ABSTRACT

Title of Thesis: A Case for Simulation: An Evaluation of the Use of Player and Gazebo to Identify Key Factors Contributing to Success During the 2004 and 2005 DARPA Grand Challenge (CNU Technical Report PCSE-2010)

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This technical report is a work of critical scholarship providing relevant technical data, justification for conclusions, and resolution of discrepancies supporting research documented by Master's Thesis “A Case for Simulation: An Evaluation of the Use of Player and Gazebo to Identify Key Factors Contributing to Success During the 2004 and 2005 DARPA Grand Challenge”. An analysis of objective evidence available through review of published records was performed. The analysis supports a conclusion that system integration was the fundamental problem of the Grand Challenge. During the analysis, key factors contributing to the success of teams participating in the 2004 and 2005 DARPA Grand Challenge were identified. The use of simulation as a tool which would have allowed teams to identify some of these key factors prior to the Grand Challenge was proposed.

A Case for Simulation: An Evaluation of the Use of Player and Gazebo to Identify Key Factors Contributing to Success During the 2004 and 2005 DARPA Grand Challenge
(CNU Technical Report PCSE-2010)

By

Jason Clair Allen

Relevant technical data, justification for conclusions, and resolution
of discrepancies supporting research documented by Master's
Thesis submitted to the Graduate Faculty of
Christopher Newport University in partial
fulfillment of the requirements
for the degree of
Master of Science
2010

DEDICATION

I would like to dedicate this research

to my wife, Lisa,

to my mother, Gloria,and

to the civilizations which flourished in the infancy of the Milky Way Galaxy, and whose stars died, giving the Earth her iron and silicon.

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CHAPTER I. INTRODUCTION

The Defense Advanced Research Projects Agency (DARPA) established the Grand Challenge to "promote innovative technical approaches that will enable the autonomous operation of unmanned ground combat vehicles." ([1] and [2], p. 4). DARPA described the Grand Challenge as a race during which autonomous vehicles would be required to "navigate from point to point in an intelligent manner so as to avoid or accommodate obstacles and other impediments to the completion of their missions." ([1]) or, worded slightly differently, to "navigate from point to point in an intelligent manner to avoid or accommodate obstacles including nearby vehicles and other impediments." ([2], p. 4).

No team successfully completed the 2004 Grand Challenge Event (GCE).

Following the 2004 GCE, DARPA reported ([3], pp. 1 - 2)[1]:

> **Rationale for Using Congressional Prize Authority for Autonomous Ground Vehicle Development**
>
> Following a series of studies, and influenced by a Congressional directive[1], DARPA determined that the first use of the Congressional prize authority would be in the area of autonomous ground vehicles with the following goals:
>
> - Increase the number of performers working on autonomous ground vehicle technologies.
> - Provide DoD access to new talent, new ideas, and innovative technologies by motivating and enlisting innovators that would not normally work on a DoD problem.
> - Accelerate autonomous ground vehicle technology development in the United States in the areas of sensors, navigation, control algorithms, vehicle systems, and systems integration.
>
> 1 Congress expressed a clear interest in accelerating unmanned vehicle capabilities and, in fact, set a goal for the Department of Defense: The Fiscal Year 2001 National Defense Authorization Act states, "It shall be the goal of the Armed Forces to achieve the fielding of unmanned remotely controlled technology such that...by 2015, one-third of the operational ground combat vehicles of the Armed Forces are unmanned." Given the aggressive timeline in the directive, DARPA determined that organizing a prize authority event would be the quickest and most cost-

effective approach to stimulate innovation and expand the research community in autonomous ground vehicle technologies.

Based on the results of the 2004 GCE, DARPA held a second Grand Challenge in 2005. On October 8, 2005, four teams successfully completed the 2005 GCE. A fifth team completed the 2005 GCE course the next day. DARPA awarded the prize of $2 million to Team 2005-16[2], the first team to complete the 2005 GCE.

The successful completion of the 2005 GCE was widely considered to be a significant achievement. DARPA stated: "The results prove conclusively that autonomous ground vehicles can travel long distances over difficult terrain at militarily relevant rates of speed." ([5]).

However, the actual goal of the Grand Challenge was concealed by the format of the Grand Challenge as a race. As noted by DARPA[1], the Fiscal Year 2001 National Defense Authorization Act stated: "It shall be a goal of the Armed Forces to achieve the fielding of unmanned, remotely controlled technology such that...by 2015, one-third of the operational ground combat vehicles are unmanned." ([4], p. 46).

DARPA published rules prior to the 2004 and 2005 GCE. The rules reported a problem statement which was revised continuously prior to the 2004 GCE, through the 2004 GCE itself, to successful completion of the 2005 GCE. DARPA published clarifications to the rules, but also revised course length, maximum corrected time, and expectation of obstacle avoidance:

- DARPA revised the maximum corrected time of the 2004 GCE from greater than 10 hours to 10 hours on April 1, 2003, several weeks after the official start of the 2004 GCE on February 22, 2003.

- DARPA revised the proposed 2004 GCE course length continuously from the official start of the 2004 GCE on February 22, 2003 through the publication of revision "5 January 2004" of the 2004 GCE rules on January 5, 2004 from 300 miles to less than 210. The reported 2004 GCE course length was 142 miles.

- DARPA stated the 2005 GCE course length would not exceed 175 miles. The reported 2005 GCE course length was 131.6 miles.

- Prior to the 2004 QID or GCE, DARPA stated: "DARPA intends to clear the Challenge Route of non-Challenge traffic and obstacles, but can not guarantee that there will be no non-Challenge traffic, obstacles, or humans on the Challenge Route. ... Sensing and processing designs must be able to avoid collisions with any obstacle, moving or static, that may exist on the route." ([1] and [6]). As a result, DARPA established an expectation that teams participating in the 2004 GCE would not encounter obstacles deliberately placed on the 2004 GCE course by DARPA to test and evaluate vehicle obstacle detection and avoidance.

- Prior to the 2005 GCE, DARPA stated: “The vehicle must avoid collisions with any obstacle, moving or static, on the route. DARPA will place obstacles along the route to test obstacle avoidance capabilities.” ([2], p. 22). DARPA later stated: “...vehicles were required to detect and avoid obstacles along the route...” ([7], p. 4) and “The 132-mile route contained a series of graduated challenges beginning with a dry lake bed, narrow cattle guard gates, narrow roads, tight turns, highway and railroad underpasses. ... Vehicles passed through tunnels and avoided more than 50 utility poles situated along the edge of the road.” ([7], p. 9). Although both of these claims are true, neither DARPA nor any of the teams reported DARPA deliberately placed obstacles on the 2005 GCE course to test obstacle avoidance capabilities.

- DARPA placed obstacles on both the 2004 Qualification, Inspection, and Demonstration (QID) and 2005 National Qualification Event (NQE) courses to evaluate challenge vehicle obstacle detection and avoidance capabilities.

In addition, a detailed course analysis reveals course difficulty changed between 2004 and 2005. For various reasons, the 2005 GCE course was not as difficult as the 2004 GCE course. For example:

- The 2005 GCE course was located on terrain with much less slope overall than the 2004 GCE course.

- The 2005 GCE RDDF eliminated extreme lateral boundary offset and course segment lengths similar to those defined by the 2004 GCE RDDF.

- The length of the 2005 GCE course was 131.6 miles, less than the 142-mile length of the 2004 GCE course. The maximum corrected time was not reduced to ensure an “average minimum speed of approximately 15-20 mph” ([3], p. 2) was achieved for either event.

- The 2005 GCE RDDF defined more waypoints than the 2004 GCE RDDF. As a result of this increase and the decrease in length of the 2005 GCE course compared to the 2004 GCE course the average distance between adjacent waypoints decreased and waypoint density increased.

- The 2005 GCE course was, overall, “smoother” than the 2004 GCE course. As a result of the increase in waypoint density, the 2005 GCE RDDF required more changes in bearing than the 2004 GCE RDDF, but these changes in bearing were less severe than those required by the 2004 GCE RDDF.

- The 2005 GCE RDDF defined forced deceleration lanes before significant terrain features.

In summary, the evidence supports a conclusion that the 2005 GCE course was engineered and "groomed" to reduce its difficulty and increase the opportunity that at least one vehicle would successfully complete the 2005 GCE.

The problem statement reported by DARPA was ostensibly one of autonomous navigation. Teams which participated in the 2004 and 2005 GCE were required to develop an autonomous vehicle with a controlling intelligence able to:

- distinguish the course from terrain that was unnavigable or was declared off-limits[3] based on detailed course information withheld until two hours prior to the event, and which identified the course and established speed limits which the controlling intelligence was required to observe, and
- navigate the course identified, while
- detecting and avoiding unintended obstacles encountered on the course,
- in less than ten hours at an average speed greater than 15 mph.

To "win", teams were required to develop the autonomous vehicle which completed the course in the least "maximum corrected time".

These problems were, to various degrees, solved prior to the Grand Challenge[4]. As a result, based on a comprehensive review of published records, the author concluded the problem statement reported by DARPA concealed the fundamental problem of the Grand Challenge ("fundamental problem"), which was *system integration*:

- The Grand Challenge required teams to integrate sensor data intelligently, and integrate computer hardware with various sensors and the research platform on which they are mounted. Some teams which focused on the fundamental problem were *potentially disruptive*.
- The vast majority of failures during the 2004 and 2005 GCE were not failures of artificial intelligence, but system integration failures.

The fundamental problem of the Grand Challenge was not software engineering or artificial intelligence, but system integration, and the conditions of the Grand Challenge favored teams with greater experience and sponsorship.

As a result, in the broader context it is important to place the Grand Challenge in perspective, and determine what, exactly, the successful teams achieved in 2005. This research documents an evaluation of the 2004 and 2005 GCE, in an attempt to provide a perspective on the successful completion of the Grand Challenge.

In general, teams which participated in the Grand Challenge described the technical details and information concerning their approach to solving the fundamental problem in published records. Some team solutions demonstrate technical achievement in system integration. Analysis reveals that most teams spent a significant amount of money on their solutions to the problem, and that the total cost of team solutions represents an investment which exceeds what the Department of Defense may reasonably be expected to pay to procure them.

In addition, team vehicles were mindless automatons incapable of true autonomous navigation, although some team vehicles were capable of autonomous obstacle detection and avoidance and path detection while following a “bread crumb” trail.

As a result, team solutions were impractical solutions to the problem of autonomous navigation.

Although DARPA concluded: “The results prove conclusively that autonomous ground vehicles can travel long distances over difficult terrain at militarily relevant rates of speed.” ([5]), significant progress toward the goal of the Department of Defense that one-third of operational ground combat vehicles are unmanned by 2015 has not been made in the years since the 2005 GCE.

The author gained a greater appreciation for the difficulty teams participating in the 2004 and 2005 GCE must have faced while completing this research. However, the perspective of this research is that the Grand Challenge was a failure, despite the fact that prize money was awarded by DARPA, for the following reasons:

- the technical achievement was consistent with the state of the art,
- the development of basic algorithms and strategies for control of an autonomous vehicle was not the focus of the Grand Challenge,
- the cost of proposed solutions far exceeds what the Department of Defense may reasonably be expected to pay to procure them,
- DARPA failed to structure the Grand Challenge to ensure long-term realization of its stated goals, and
- significant progress toward the actual goal has not been made in the years since the 2005 GCE.

The author asserts the use of simulation as a complement to the Grand Challenge would have provided teams participating in the Grand Challenge with a way to identify key factors contributing to success prior to field trials, increased focus on the development of basic strategies and algorithms to enhance the intelligence of autonomous vehicles, and provided a way to increase the competitiveness of the Grand Challenge by “leveling the playing field”, allowing teams with no experience or limited sponsorship to compete on a more even basis with teams with prior experience or significant sponsorship.

CHAPTER II. COURSE DIFFICULTY

II.A. Discussion

DARPA established the following success criteria[5] for vehicles participating in the 2004 and 2005 GCE ("challenge vehicles") ([3], p. 2):

> DoD missions require autonomous ground vehicles that not only have sensors and navigation capabilities for operations on varied terrain and with varying amounts of autonomy, but they must also be able to operate at militarily relevant speeds, defined as an average minimum speed of approximately 15 - 20 mph over some relevant distance.

DARPA selected the Mojave Desert as the general location because ([3], p. 7):

> its overall terrain characteristics best correspond to the type of operating environments U. S. military forces encounter in the Middle East.

It is not the purpose of this research to determine whether the location selected by DARPA for the 2004 and 2005 GCE courses is representative of the "varied terrain" which DOD missions require. However, U. S. military forces conduct operations in areas other than the Middle East, and the overall terrain characteristics of those areas do not correspond as closely with the Mojave Desert.

As noted in Chapter I. and throughout this technical report, for various reasons challenge vehicles were incapable of true autonomous navigation, although some challenge vehicles were capable of autonomous obstacle detection and avoidance and path detection while following a "bread crumb" trail. As a result, the author concluded true autonomous navigation was not required to successfully complete the 2004 and 2005 GCE courses.

This contradicts the problem statement reported by DARPA. However, it is not the purpose of this research to objectively evaluate the degree of autonomy required to complete the 2004 and 2005 GCE courses.

As a result, the word "successful" is used herein to refer to a challenge vehicle which:

- is autonomous, having sensors and navigation capabilities for operations on terrain at the location selected by DARPA for the 2004 and 2005 GCE courses, and

- completed the 2004 or 2005 GCE course with an average speed greater than 15 mph.

Note that the second condition for success, above, differs slightly, but significantly, from the corresponding condition for success established by DARPA via revision "April 1.2" of the 2004 GCE rules ([1]):

```
DARPA will award one million U.S. dollars to the Team
that completes the Route with the best corrected time
at or under ten hours.
```

and in 2005 via the 2005 GCE rules ([2], p. 5):

```
DARPA will award a prize ... of $2 million to the
team ... whose vehicle completes the route with the
shortest corrected time ... under 10 hours and
complies with all other eligibility requirements.
```

In retrospect, DARPA established contradictory success conditions for the 2004 and 2005 GCE. DARPA stated ([3], p. 2):

```
Using the prize authority, DARPA would award $1
million to the first team that demonstrated a fully
autonomous, unmanned ground vehicle capable of
traveling a militarily relevant distance and speed
across terrain similar to that encountered by U.S.
forces in overseas operations.  The winning vehicle
would be one that traveled 142 miles across desert
terrain in the best time under 10 hours.
```

DARPA had earlier established "militarily relevant speeds" as an "average minimum speed of approximately 15 - 20 mph". Because completion of the 142-mile 2004 or 131.6-mile 2005 GCE course in a "maximum corrected time" of ten hours would result in an average speed of 14.2 mph or 13.2 mph, respectively, the author established the second condition for success, above, to resolve the discrepancy.

Based on a review of information published by DARPA:

- No challenge vehicle completed the 2004 GCE[6] course. As a result, no challenge vehicle which participated in the 2004 GCE was successful.

- Five challenge vehicles completed the 2005 GCE[7] course. Four challenge vehicles completed the 2005 GCE course with an average speed greater than 15 mph. As a result, four challenge vehicles which participated in the 2005 GCE were successful.

To determine if advances in autonomous navigation alone resulted in success during the 2005 GCE, the author formulated the following hypothesis to explain why no vehicle was able to complete the 2004 GCE course, but five vehicles were able to complete the 2005 GCE course, four of which were successful:

- The 2004 GCE course was too difficult.

Alternately:

- The 2005 GCE course was less difficult than the 2004 GCE course.

In later sections, this evaluation was expanded to determine what other factors contributed to success during the 2005 GCE.

II.B. Analysis

Neither the 2004 nor 2005 RDDF provide direct evidence of course difficulty. Therefore, it was necessary to develop objective measures of course difficulty and then compare the 2004 and 2005 GCE courses on the basis of these objective measures to test either the hypothesis or alternate hypothesis.

The author developed an application to analyze an arbitrary RDDF conforming to the 2005 RDDF specification ([13]) using PHP and MySQL[8] [9]. The following objective measures of course difficulty were selected:

- Course length.
- Average course segment length, calculated by dividing the course length by the number of course segments defined by the RDDF.
- The number of course segments for which the speed exceeds a reportable speed.
- The number of waypoints at which the change in bearing from one course segment to the next exceeds a reportable change in bearing.
- The minimum time required to complete the course at the maximum course segment speed allowed by the RDDF.
- The average time to complete a course segment, calculated by dividing the minimum time required to complete the course by the number of course segments defined by the RDDF.

II.B.1. RDDF revision

Because the 2004 QID and GCE RDDF are no longer hosted by DARPA[10], the 2004 QID (“qid-rddf.txt”) and 2004 GCE (“race-rddf.zip”) RDDF were downloaded from

RoboSUV ([18]), an Internet repository independent of DARPA. The 2005 GCE RDDF was downloaded from the Archived Grand Challenge 2005 website ([19]).

Review of these files revealed that the 2004 QID and GCE RDDF do not conform to the 2005 RDDF specification published by DARPA. The 2004 QID and GCE RDDF each contain eight columns, in lieu of the five specified by the 2005 RDDF specification. Neither the 2004 GCE rules nor 2004 RDDF specification were hosted by DARPA via the Archived Grand Challenge 2004 website ([17]).

Copies of revisions "April 1.2" and "5 January 2004" of the 2004 GCE rules ([1] and [6]) were downloaded from the Team 2004-20 website ([20]), an Internet repository independent of DARPA. DARPA stated the three additional columns in the 2004 QID and GCE RDDF correspond to "Maximum Crossing Time for Phase Line Waypoints (Pacific Standard Time in hours, minutes, and seconds)" ([1] and [6]). DARPA stated the RDDF may contain an additional column of "remarks including specially designated Waypoints" ([1]), however revision "5 January 2004" of the 2004 GCE rules did not refer to "remarks" and neither the 2004 QID nor GCE RDDF contain remarks. DARPA stated: "Null fields will be indicated by ####." ([1] and [6]).

II.B.1.a. <u>2004 QID RDDF</u>

To produce input conforming to the 2005 RDDF specification published by DARPA, all occurrences of ",####" were deleted from the downloaded 2004 QID RDDF using the "Replace All" command of a text editor to replace ",####" with an empty string. The resulting file ("qid-rddf.CORRECTED.txt") was used for the analysis.

II.B.1.b. <u>2004 GCE RDDF</u>

Each row of the 2004 GCE RDDF contained three additional columns of "null field" values with the exception of four rows: 732, 946, 1627, and 2024. DARPA stated these rows correspond to "Phase Line Waypoints" with a "Maximum Crossing Time". DARPA defined "Phase Line Waypoints" as ([1] and [6]):

```
Phase Line Waypoints are those Waypoints that have
been assigned a Maximum Crossing Time.
```

DARPA defined the "Maximum Crossing Time" as ([1] and [6]):

```
The Maximum Crossing Time is the Pacific Standard Time
associated with a Phase Line Waypoint, and is the time
by which a Challenge Vehicle must pass that Phase Line
Waypoint in order to remain in the Challenge.
```

To produce input conforming to the 2005 RDDF specification published by DARPA, all occurrences of ",####" were deleted from the downloaded 2004 GCE RDDF using the "Replace All" command of a text editor to replace ",####" with an empty string. The Maximum Crossing Time was deleted from rows 732, 946, 1627, and 2024, corresponding to Phase Line Waypoints as follows[11]:

- Row 732: ",13,30,0" was deleted.
- Row 946: ",14,15,0" was deleted.
- Row 1627: ",15,30,0" was deleted.
- Row 2024: ",16,30,0" was deleted.

The resulting file ("race-rddf.CORRECTED.txt") was used for the analysis.

II.B.1.c. <u>2005 GCE RDDF</u>

The 2005 GCE RDDF ("2005_GCE_RDDF.txt") conformed to the 2005 RDDF specification, and required no revision. This file was used for the analysis.

II.C. Results

II.C.1. Course length

The RDDF analysis application calculates the length of the geodesic between two points represented by latitude and longitude pairs using Vincenty's Inverse Solution ([21]), which is accurate to 0.0005m[12]. Vincenty's Inverse Solution is reproduced in Appendix B.

DARPA stated, in part: "Latitude and longitude are expressed in decimal degrees based on the WGS84 coordinate system" ([13], p. 1). Therefore, values for *a* (major semiaxis), *b* (minor semiaxis), and *f* (flattening) conforming to the World Geodetic System 84 (WGS84) Coordinate System Ellipsoid were selected[13]. Table V presents a list of adopted and derived geometric constants for three major Coordinate Systems for comparison: WGS84, GRS80, and the hybrid WGRS80/84.

II.C.1.a. <u>Error in distance calculations</u>

II.C.1.a.i. <u>Error in distance calculations based on the WGS84 Ellipsoid</u>

The length of the geodesic between two adjacent waypoints ("distance") is the length on the surface of the WGS84 Ellipsoid. The true distance between two waypoints ("true distance") varies based on how closely the geometry of the earth's surface matches the geometry of the WGS84 Ellipsoid. The orthometric height of the earth's topographic surface is a function of geodetic height (height relative to the ellipsoid) and geoid undulation[14]. It is possible to calculate these values, and to use the result to construct a geometric argument allowing a more accurate distance to be calculated, but it would not be the true distance because it would be calculated from the difference in orthometric height of two adjacent waypoints located some distance apart on the WGS84 Ellipsoid, with a line or curve of known length between them.

II.C.1.a.ii. Error in distance calculations based on slope

Figure 4 depicts the error in distance calculations based on slope. If the slope between two adjacent waypoints is held to be a constant five or ten degrees, there is an increase in the true distance of approximately four millimeters per meter (0.4 percent), or 15 millimeters per meter (1.5 percent), respectively. Therefore, the true length of a course segment with a length of one kilometer (1000 m) on a notionally flat surface is approximately 1004 m if the course segment has a fixed slope of five degrees, or 1015 m if the course segment has a fixed slope of ten degrees.

To place this in perspective, the width of a course segment with a lateral boundary offset of ten feet is approximately 6.1 m. As a result, the difference in true distance due to a fixed slope of five degrees over one kilometer is less than the width of a course segment with a lateral boundary offset of ten feet, and is therefore not considered significant.

II.C.1.a.iii. Error in distance calculations based on course smoothing

Distances calculated by the RDDF analysis application reflect travel along a geodesic between adjacent waypoints, at which changes in bearing are instantaneous. This is unrealistic, although traveling along an arc tangent to both course segments reduces, rather than increases, the true distance traveled.

Based on an assessment of the vehicle risk of rollover (see Chapter III.), the author calculated the length of the 2004 and 2005 GCE course using a geometric argument for a vehicle following a path of travel along the centerline from waypoint to waypoint with a turn of radius equal to the turn radius required to complete the turn at the maximum speed allowed by the RDDF at their intersection (with the exception of 2004 GCE segment 2570-2571-2572, see paragraph III.C.1.). See paragraph II.C.1.b. for a comparison between calculated and reported course lengths.

II.C.1.b. Conformance to reported course lengths

The most accurate measurement of course length is direct measurement of the distance traveled between waypoints specified by the RDDF by navigating the course. In general, published records (e.g., [23], [24], and [25]) do not disclose the distance traveled by their respective challenge vehicles.

The course lengths calculated for the 2004 and 2005 GCE courses closely conform to the course lengths reported by DARPA. The reported length of the 2004 GCE course was 142 miles ([3], p. 7), and the calculated length was 142.3 miles (229.0 km). The reported length of the 2005 GCE course was 131.6 miles[15], and the calculated length was 131.8 miles (212.0 km). See Table VI. The error in calculated course length was approximately 0.2 percent, and may be explained by a combination of factors identified in paragraph II.C.1.a.

The course length calculated for the "smoothed" 2004 and 2005 GCE courses (see paragraph II.C.1.a.iii.) was 141.6 miles (227.8 km) and 131.3 miles (211.3 km)[16], respectively. The error in calculated course length was less than 0.3 percent, and may be explained by a combination of factors identified in paragraph II.C.1.a.

As a result, although it would have been possible to more accurately calculate course length, this was not pursued because the error in course length is not considered to be significant, and in particular not considered to be significant over the course segment lengths defined by the 2004 and 2005 GCE RDDF.

As a result, the author concluded the 2004 GCE course length was greater than the 2005 GCE course length, and that errors in distance calculations based on the WGS84 Ellipsoid, slope, and course smoothing were not significant.

II.C.2. Average course segment length

Calculated course length was divided by the number of course segments defined by the RDDF for the 2004 and 2005 GCE courses to determine the average course segment length. The number of course segments is equal to one less than the number of waypoints. The 2004 GCE RDDF defines 2586 waypoints and 2585 course segments. The 2005 GCE RDDF defines 2935 waypoints and 2934 course segments.

The average course segment length for the 2004 GCE course was 88.6 m. The average course segment length for the 2005 GCE course was 72.3 m. See Table VII. As a result, the author concluded the average course segment length for the 2005 GCE course was less than the average course segment length for the 2004 GCE course.

II.C.3. The number of course segments for which the speed exceeds a reportable speed

To evaluate the number of course segments for which the speed exceeds a reportable speed, a histogram of course segment speed was prepared to compare the 2004 and 2005 GCE courses using OpenOffice Calc from CSV files exported from the MySQL database created by the RDDF analysis application using PHP MyAdmin[17].

The 2005 GCE RDDF defines more allowable speeds than the 2004 GCE RDDF. Twelve speeds are defined by the 2004 GCE RDDF: 2, 5, 10, 15, 20, 25, 30, 40, 45, 50, 55, and 60 mph; a speed of 2 mph is specified for the last course segment, which crosses the arrival line, and is not otherwise significant. Thirty-nine speeds are defined by the 2005 GCE RDDF: 5, 6, 8 through 42, 44, and 45 mph. "Intermediate speeds" are defined herein as those speeds defined by the 2005 GCE RDDF which are not evenly divisible by five.

As a result of intermediate speeds, data from the 2004 and 2005 GCE RDDF cannot be directly compared. The data were initially divided into the nine groups presented by Table IX, but because the number of waypoints defined by the 2004 and 2005 GCE RDDF are different, direct comparison on the basis of the number of course segments is not possible. As a result, the author adopted an approach that would allow comparison based on the cumulative percentage of course segments for which the speed exceeds a reportable speed.

To better evaluate the overall impact of speed defined by the 2004 and 2005 GCE RDDF on the 2004 and 2005 GCE, the data were divided into the five groups presented by Tables X and XI. Table X presents both the number and cumulative percentage of course segments per group. The information presented by Table X is presented graphically by Figure 1, below.

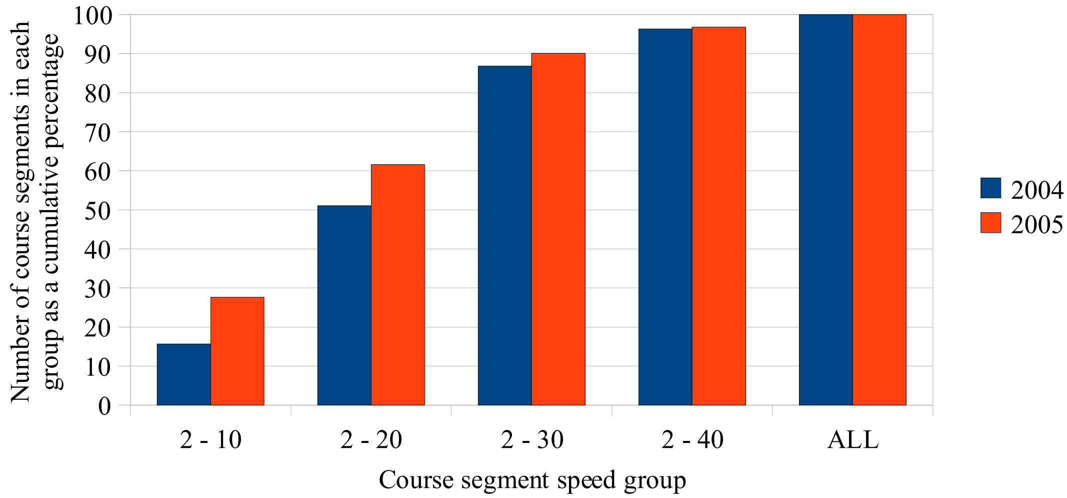

Figure 1. Number of course segments in each group versus cumulative percentage.

By itself, Figure 1 is of limited utility because it does not establish context. It is possible that the number of course segments in each group increased but not the total length of all course segments in each group as a percentage of course length. Table XI presents both the total length and cumulative percentage of course segments per group. The information presented by Table XI is presented graphically by Figure 2, below.

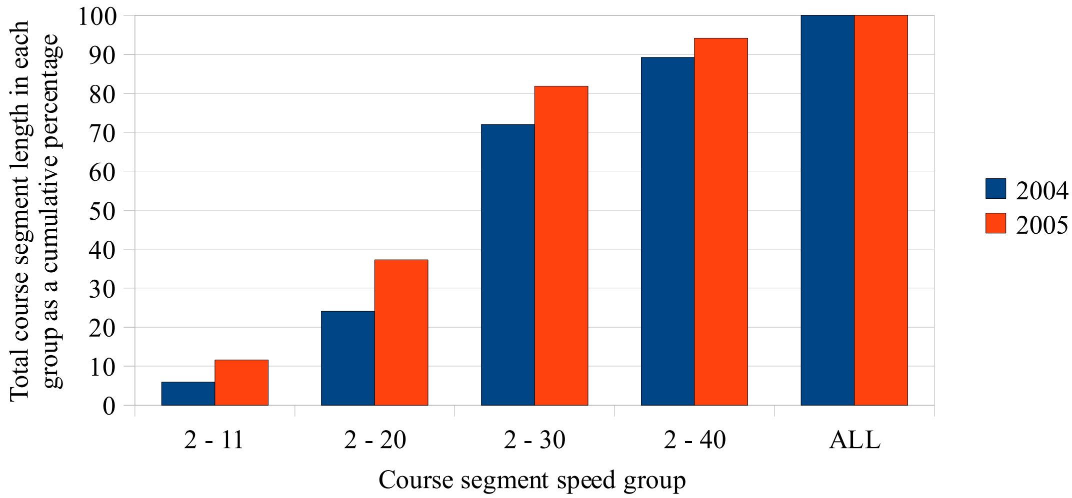

Figure 2. Total course segment length in each group versus cumulative percentage.

Figures 1 and 2 clearly illustrate a fundamental difference between the 2004 and 2005 GCE courses: the 2005 GCE course had a greater number of course segments in every group than the 2004 GCE course as a cumulative percentage of the number of course segments, the majority of which were distributed across groups representing lower course segment speeds, and the total course segment length in each group increased.

II.C.4. The number of waypoints at which the change in bearing from one course segment to the next exceeds a reportable change in bearing

To evaluate the number of waypoints at which the change in bearing from one course segment to the next exceeds a reportable change in bearing, the Inverse Solution was used to calculate the azimuth to true north of each end of each course segment. The change in bearing at each waypoint was calculated by subtracting the azimuth of the preceding course segment at the waypoint from the azimuth of the succeeding course segment at the waypoint. A positive change in bearing represents a left turn; a negative change in bearing represents a right turn.

The magnitude of the change in bearing was used to produce a histogram of change in bearing to compare the 2004 and 2005 GCE courses using OpenOffice Calc from CSV files exported from the MySQL database created by the RDDF analysis application using PHP MyAdmin. See Table XII. The information presented by Table XII is presented graphically by Figure 3 below.

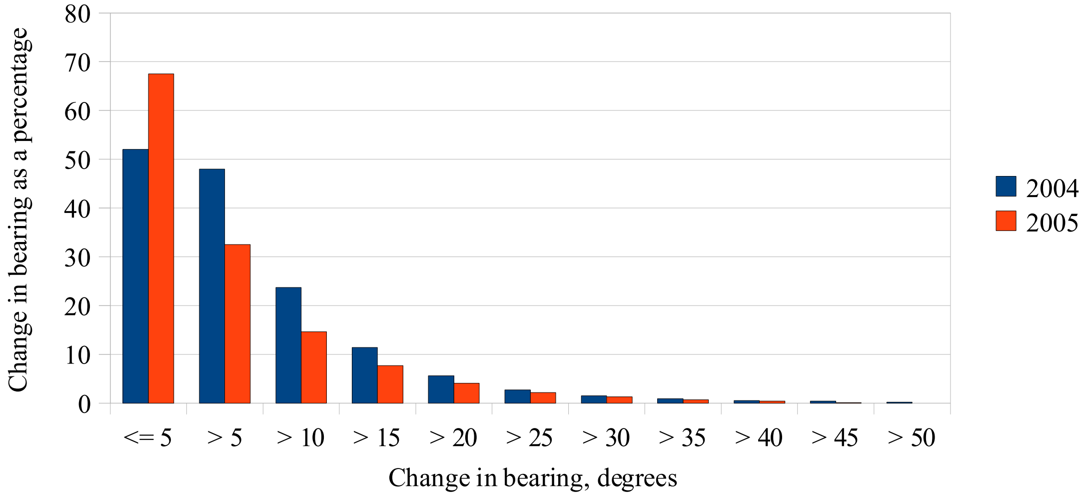

Figure 3. Change in bearing versus percentage.

This chart clearly illustrates a fundamental difference between the 2004 and 2005 GCE courses: the 2004 GCE course has an almost even distribution of *minor* (less than or equal to five degrees) changes in bearing (52 percent) and *significant* (greater than five degrees) changes in bearing (48 percent), and the 2005 GCE course has twice as many minor changes in bearing (67.5 percent) as significant changes in bearing (32.5 percent). In addition, as a percentage:

- changes in bearing defined by the 2004 GCE RDDF are more evenly distributed, and

- the 2004 GCE course has more changes in bearing in every group than the 2005 GCE course, with 348 fewer course segments.

As a result, the author concluded the 2005 GCE course was "smoothed" by increasing the number of minor changes in bearing, or decreasing the number of significant changes in bearing.

II.C.5. The minimum time required to complete the course at the maximum course segment speed allowed by the RDDF

To calculate the minimum time required to complete the 2004 and 2005 GCE courses at the maximum course segment speed allowed by the RDDF, the minimum time required to complete each course segment was first determined by dividing the course segment length by the maximum course segment speed allowed by the RDDF using OpenOffice Calc from CSV files exported from the MySQL database created by the RDDF application using PHP MyAdmin. The total time required to complete the course was then calculated by summing the minimum times required to complete each course segment.

The minimum time required to complete the 2004 GCE course was 6.42 hours (06:25:12 hours). The minimum time required to complete the 2005 GCE course was 6.20 hours (06:12:00 hours). These are *ideal* times, i.e., they are equal to the course segment distance divided by the speed of the course segment. As noted above, course segment length, and therefore the minimum time required to complete the course, will vary based on a number of factors. For example, the minimum time required to complete the smoothed 2004 GCE course (see paragraph II.C.1.a.iii.) at the maximum speed allowed by the RDDF, with the sole exception of 2004 GCE segment 2570-2571-2572 (see paragraph III.C.1.), was 6.38 hours (6:22:48 hours). The minimum time required to complete the smoothed 2005 GCE course was 6.18 hours (6:10:48 hours).

Because the difference between the ideal times and the times based on course smoothing is not significant, and in the absence of direct measurement of the distance traveled between waypoints specified by the RDDF by navigating the course, ideal times are used herein.

The minimum time required to complete the 2005 GCE course was less than the minimum time required to complete the 2004 GCE course. The author does not consider the difference of 0.22 hours (00:13:12) to be significant. However, because the 2004 GCE course length was greater than the 2005 GCE course length, the author considers this an effect of the distribution of 2005 GCE course segments across groups representing lower course segment speeds. See paragraph II.C.3.

II.C.6. The average time required to complete a course segment

The minimum time required to complete the course at the maximum course segment speed allowed by the RDDF was divided by the number of segments of the course to determine the average time required to complete a course segment. The average time required to complete a course segment for the 2004 GCE course was approximately 9.0 s (8.94 s); the average time required to complete a course segment for the 2005 GCE course was approximately 7.6 s (7.61 s). The author considers the difference to be significant. The average time required to complete a course segment for the 2005 GCE course was approximately 15 percent less than the average time required to complete a course segment for the 2004 GCE course.

Using the average course segment lengths calculated above, this corresponds to an average speed of 22.2 mph (2004) and 21.3 mph (2005). Although the author does not consider the difference of 0.9 mph to be significant, it is of interest because it supports a conclusion DARPA did not calculate the minimum time required to complete the course, at the maximum course segment speed allowed by the RDDF, using the maximum "militarily relevant speed" established by DARPA of 20 mph. Note this average speed is based on the minimum time to complete the course at the maximum course segment speed allowed by the RDDF, not the maximum "corrected time" of ten hours (see paragraph II.A.).

II.C.7. Evidence of course grooming

II.C.7.a. <u>“Taming”</u>

Teams 2005-13 and 2005-14 reported course “taming”, and stated pre-planning based on perceived high risk areas impacted their success during the 2005 GCE ([23], pp. 16 - 17, 19):

> The 2005 Grand Challenge course was much simpler than the 2004 Grand Challenge course. The specific route given by the race organizers was overall straight, wide, and had very few areas of large slope change. In many regions, the most difficult sections for an autonomous vehicle were tamed with well defined berms ... and the grooming of washouts.
>
> This taming of regions contrasts with the 2004 Grand Challenge where grading was not as widespread...
>
> As a result of grooming of washouts and the creation of berms, many areas that [Team 2005-13] identified as high risk were in fact tame. Had [Team 2005-13] known the full extent of the grooming of paths, the targeted elapsed time would have been shorter, resulting in faster targeted times for both [challenge vehicles]. This did not harm other teams as they did not use information in order to slow their vehicles down for hazardous areas such as washouts.

II.C.7.b. <u>Changes in observed slope from 2004 to 2005</u>

Teams 2005-13 and 2005-14 reported there was a significant difference in observed slope between the 2004 and 2005 GCE courses ([23], p. 17):

> Specifically last year's Grand Challenge had approximately 17.5 miles of slopes greater than 5 degrees; this year's grand challenge had less than 2 miles.

One of the consequences of the reduction in the number of miles of slope greater than five degrees was an overall “flattening” of the course, making it easier for long-range sensors such as VISION sensors and RADAR to detect obstacles at ranges consistent with challenge vehicle stopping distances, and ultimately increasing the speed at which challenge vehicles were able to travel. See paragraph VIII.C.5.

Several teams reported one of the unstated requirements for successfully completing the 2005 GCE was effective obstacle detection at long range. For example: Team 2005-16 stated: “The effective maximum range at which obstacles can be detected with the laser mapper is approximately 22 m. This range is sufficient for [the challenge vehicle] to reliably avoid obstacles at speeds up to 25 mph. Based on the 2004 Race Course, the development team estimated that [the challenge vehicle] would need to reach speeds of 35 mph in order to successfully complete the challenge. To extend the sensor range enough to allow safe driving at 35 mph, [the challenge vehicle] uses a color camera to find drivable surfaces at ranges exceeding that of the laser analysis.” ([25], p. 672).

This comment prompted the author to determine the minimum time required to complete the 2004 and 2005 GCE courses given a notional course-wide speed limit less than the maximum speed allowed by the 2004 RDDF for the 2004 GCE or less than the course-wide speed limit of 50 mph established by DARPA via the 2005 RDDF specification ([13]) for the 2005 GCE. Available sources ([1] and [6]) did not report a course-wide speed limit was imposed in 2004, and the 2004 GCE RDDF contains speeds up to and including 60 mph.

The number of course segments exceeding the notional course-wide speed limit, total length of those course segments, and resulting minimum time required to complete the course were calculated. The number of course segments exceeding the notional course-wide speed limit can be calculated from Table IX as the total number of all course segments exceeding the notional course-wide speed limit. The total length of those course segments and time required to complete the course were calculated using OpenOffice Calc from CSV files exported from the MySQL database created by the RDDF analysis application using PHP MyAdmin. Results are summarized in Table XIII. As noted in paragraph II.C.5., times are ideal.

DARPA established a requirement that successful challenge vehicles be able to travel at “militarily relevant speeds”, defined as an “average minimum speed of approximately 15 - 20 mph” ([3], p. 2). The results clearly reveal that no vehicle was required to travel at a speed which appreciably exceeded the minimum of the “average minimum speed of approximately 15 – 20 mph” of 15 mph during the 2004 GCE. Any challenge vehicle would have been able to complete the 2004 GCE course in 10.2 hours with a course-wide speed limit of 15 mph, with a single instance of acceleration during a series of ten adjacent segments with extreme lateral boundary offset greater than 4500 m in length (4555.728 m), or almost 3 miles (2.83 miles), 3896.271 m (2.42 miles) of which was at an allowed speed of 60 mph (see paragraph II.C.7.d.); or with several instances of acceleration during any of several extremely long course segments, two of which exceeded one mile in length (see paragraph II.C.7.c.). In either case, limited acceleration under controlled conditions would have resulted in a maximum corrected time of less than ten hours.

The author concluded any challenge vehicle would have been able to complete the 2005 GCE in 9.45 hours at a maximum course-wide speed limit of 15 mph. Although the

2005 GCE was arguably a “race” because more than one vehicle successfully completed the course, at the time of the 2005 GCE the outcome was uncertain. Before the first vehicle crossed the departure line, DARPA virtually guaranteed that any challenge vehicle capable of traveling at the minimum of the “average minimum speed of approximately 15 – 20 mph” of 15 mph would successfully complete the course.

Autonomous navigation and obstacle avoidance under off-road conditions at speeds of 20 mph was well within the state of the art in the year 2000. The National Institute of Standards and Technology (NIST) demonstrated an autonomous HMMWV capable of traveling at speeds up to 35 km/hr (approximately 22 mph) in “rolling grass-covered meadows where the only obstacles were large trees and shrubs” ([29]). Although this terrain does not share the overall terrain characteristics of terrain selected by DARPA for the 2004 or 2005 GCE as typical of operating environments U. S. military forces encounter in the Middle East (see paragraph II.A.), the use of LIDAR to reliably detect both positive and negative obstacles supports a conclusion sensor and computing hardware available in 2000 was able to reliably detect obstacles typical of the ones encountered during the 2004 and 2005 GCE at speeds exceeding 15 mph.

As a result, the author concluded long-range sensors typical of those in use by the teams were not required to successfully complete the 2005 GCE, but their effective use provided a sensing advantage, and determined team placement.

In addition, range and field-of-view limitations of many sensors in use by the teams during the 2004 and 2005 GCE had non-obvious consequences. Many teams overestimated the ability of the sensors in use by the team to reliably detect obstacles due to field-of-view limitations, and overestimated the speed at which the challenge vehicle could travel based on its ability to come to a complete stop before collision with a detected obstacle. See Chapter VIII.

Overall, the flattening of the 2005 GCE route supports a conclusion that DARPA groomed the course to provide a sensing advantage to teams which were able to effectively use long-range sensors, to maximize the chance that at least one challenge vehicle would successfully complete the 2005 GCE.

II.C.7.c. <u>Changes in maximum course segment length from 2004 to 2005</u>

Based on course segment length calculated by the RDDF analysis application between adjacent waypoints defined by the 2004 and 2005 RDDF, no segment defined by the 2005 RDDF exceeds approximately 305 m (304.634 m) in length. In contrast, the 2004 RDDF defines 147 segments which exceed the maximum length defined by the 2005 RDDF, including seven segments which exceed 1000 m in length, two of which exceed one mile (1609.344 m) in length: 833 - 834 (1612.826 m) and 433 - 434 (2533.834 m).

These segments were generally more than 7.4 miles from the start line. Because no challenge vehicle completed more than 7.4 miles of the course in 2004 ([30]), extreme course segment length had no practical impact on team performance during the 2004 GCE. However, the 2004 RDDF defines five course segments exceeding 305 m in length in the first 7.4 miles of the course: 28 - 29 (429.500 m), 29 - 30 (710.904 m), 49 - 50 (351.078 m), 83 - 84 (345.734 m), and 84 - 85 (313.255 m).

DARPA stated ([13], p. 2):

> The distance between successive waypoints will never exceed 1,000 feet and will never be less than 3 feet.

The maximum course segment length of 305 m defined by the 2005 RDDF, above, is approximately equal to 1000 feet. DARPA did not limit the distance between successive waypoints defined by the 2004 GCE RDDF ([1] and [6]).

II.C.7.d. Changes in lateral boundary offset from 2004 to 2005

No segment defined by the 2005 RDDF has a lateral boundary offset which exceeds 50 ft. By contrast, the 2004 RDDF defines 12 segments with a lateral boundary offset exceeding 50 ft, including a series of ten adjacent segments greater than 4500 m in length (4555.728 m), or almost 3 miles (2.83 miles), in which the lateral boundary offset increases from 50 ft, to 75, 125, 200, 400, and 800 ft, before decreasing to 600 ft, 400, 200, 100, 75, to 50 ft again (waypoints 2553 to 2563).

Because no challenge vehicle completed more than 7.4 miles of the course in 2004 ([3], p. 8 and [30]), extreme lateral boundary offset had no practical impact on team performance during the 2004 GCE.

Team 2005-06 successfully completed the 2005 GCE. Team 2005-06 indirectly attributed their failure to place first or second during the 2005 GCE to extreme lateral boundary offset. Team 2005-06 stated: "...the director of DARPA said later that if we hadn't had a bug where we slowed down in the dry lakebeds, we would have either beaten [Team 2005-16] or been very, very close to [the Team 2005-16 challenge vehicle]. The bug meant we went from 30 miles an hour to two miles an hour on all the dry lakebeds. We'd never tested in an area 100 feet wide like that. We call it the $2 million bug. Needless to say, it's been fixed." ([31]).

II.C.7.e. DARPA introduced forced deceleration lanes in 2005

A non-obvious pattern was revealed by analysis of the number of course segments for which the speed exceeds a reportable speed (see paragraph II.C.3., above) because it does not establish the context by which intermediate speeds defined by the 2005 RDDF were used. For example:

- From waypoints 76 to 84, speed decreased from 30 mph to 5 mph (30 mph to 29, 22, 17, 15, 11, and finally 5 mph) over approximately 230 m (229.764 m), then immediately increased to 40 mph at waypoint 85.

- From waypoints 1177 to 1184, speed decreased from 45 mph to 10 mph (45 mph to 40, 36, 31, 27, 23, 16, and finally 10 mph) over approximately 98 m (97.572 m), then increased to 20 mph after four segments at 10 mph approximately 82 m (81.659 m) in length.

- From waypoints 1805 to 1809, speed decreases from 20 mph to 5 mph (20 mph to 17, to 13, to 9, and finally 5 mph) over approximately 70 m (69.396 m), then immediately increases to 20 mph at waypoint 1810.

- From waypoint 2277 to 2290, speed decreased from 45 mph to 5 mph (45 mph to 39, 33, 30, 23, 16, 13, 9, and finally 5 mph) over approximately 818 m (817.997 m), then immediately increased to 30 mph at waypoint 2291.

This pattern is repeated throughout the 2005 RDDF. The 2005 RDDF defines 508 waypoints at which deceleration is required, the majority of which (266 of 508) require deceleration from an intermediate speed; 2256 waypoints at which no change in speed occurs; and 170 waypoints at which acceleration is allowed. Not a single instance of acceleration from an intermediate speed is defined by the 2005 RDDF.

By comparison, the 2004 RDDF defines 160 waypoints at which deceleration is required; 2301 waypoints at which no change in speed is required; and 124 waypoints at which acceleration is required.

As a result, the author proposed that the intermediate speeds defined by the 2005 RDDF form “deceleration lanes” which forced vehicles to decelerate to significantly lower speeds before a significant change in bearing or other terrain features, i.e., areas which were high risk. This was later confirmed. See paragraph III.D.3.

II.D. Conclusion

Based on a comparison of objective measures calculated from data defined by the 2004 and 2005 GCE RDDF using the RDDF analysis application, the 2005 GCE course was less difficult. DARPA:

- Decreased the course length from 142 miles to 131.6 miles.

- Increased the number of waypoints from 2586 to 2934.

- Increased the number of course segments in defined groups as a cumulative percentage of the total number of course segments, the majority of which were distributed across groups with lower course segment speeds.

- Increased the total length of the course in defined groups with lower course segment speeds.

As a consequence of the changes, the average course segment length decreased, the number of segments increased, and the average time required to complete each course segment decreased. The author considers these changes a consequence of the decreased course length and increased number of waypoints, and not otherwise significant.

In addition, the evidence supports a conclusion that:

- DARPA provided well-defined berms for the 2005 GCE course to make it easier for challenge vehicles to identify the edges of the path.

- DARPA groomed washouts, eliminating areas that would otherwise have been high risk.

- The location DARPA selected for the 2005 GCE course resulted in a decrease in the number of miles of observed slope greater than 5 degrees from 17.5 miles to less than two miles, which resulted in more effective obstacle detection at long range and provided a sensing advantage to teams which were able to effectively use long-range sensors.

- DARPA engineered the 2005 GCE course to eliminate the extreme course segment lengths and lateral boundary offsets defined by the 2004 GCE RDDF.

- DARPA engineered the 2005 GCE course to decrease the number of significant changes in bearing.

- DARPA engineered the 2005 GCE course to introduce deceleration lanes to force vehicles to decelerate to significantly lower speeds before negotiating areas which were high risk.

The author was not able to confirm the hypothesis that the 2004 course was difficult. To confirm this hypothesis, it would have been necessary for the challenge vehicles which successfully completed the 2005 GCE course to have attempted to complete the 2004 GCE course but fail while conclusively demonstrating that the course, not the challenge vehicles, was the cause. The author has no evidence this occurred. Several teams reported completing portions of the 2004 GCE course in preparation for the 2005 GCE. For example:

- Team 2005-02

Team 2005-02 alternately stated: "We setup to run the first part of the Grand Challenge 04 route." and "We ran the GC04 route several times. The first time it appeared that the GPS was off and the vehicle moved off to one side of the road until it could no longer fit between what was left of the road and the bushes on the side of the road. The second run was perfect all the way to the gate (approx 2 miles). The third run was a bit off but made it all the way to the gate again." ([32]). As a result, the author concluded Team 2005-02 completed two miles of the 2004 GCE course.

- Team 2005-03

Team 2005-03 stated: "We had planned on rerunning the original GC I course but since the area has been closed we are seeking alternative desert-condition test sites." ([33], p. 12). As a result, the author concluded Team 2005-03 did not complete the 2004 GCE course.

- Team 2005-16

Team 2005-16 stated: "The race preparation took place at... the 2004 Grand Challenge Course between Barstow and Primm..." ([25], p. 685). However, although Team 2005-16 stated the 2004 GCE course was used as a test location for their challenge vehicle, the team did not report the challenge vehicle was able to successfully complete the 2004 GCE course.

As a result, the author was unable to confirm a team was able to complete the entire 2004 GCE course in preparation for the 2005 GCE.

However, the author confirmed the hypothesis that the 2005 GCE course was less difficult than the 2004 GCE course. Therefore, it was proposed that some function of speed and change in bearing, particularly significant changes in bearing, motivated DARPA to reduce the difficulty of the 2005 GCE course, and a rationale for the change was sought.

CHAPTER III. VEHICLE RISK OF ROLLOVER

III.A. Discussion

The dominant vehicles selected as challenge vehicle platform by teams which participated in the 2004 QID and GCE and 2005 GCE were commercially-available sport-utility vehicles (SUVs) and trucks purpose-modified for the event[18]. See Table XIV. Prior to the 2005 GCE, DARPA stated: “The route can be traversed by a commercial 4X4 pickup truck.” ([2], p. 5), which may provide some insight into the decision of the majority of teams to select a commercially-available SUV or truck as challenge vehicle platform despite the increased susceptibility of these vehicles to rollover at high speed compared to other commercially-available passenger vehicles. For example: Team 2005-05 stated: “...our vehicle in the 2004 Grand Challenge, was based on a 1994 Ford F-150 truck with off-road suspension modifications. We believe this was a good choice of platform for several reasons. By design, the Grand Challenge route was well-matched to the capabilities of a commercial 4x4 pickup truck, such as the ones used by DARPA as chase vehicles.” ([34], p. 2).

The author formulated the following hypothesis:

- DARPA reduced the difficulty of the 2005 GCE course to reduce the risk of rollover to the dominant platforms.

The “rollover condition” may be expressed as a function of four variables ([35] and [36]): vehicle speed, turn radius, track width, and height of vehicle center of gravity (CG) above the road surface. The rollover condition is given by:

$$\frac{t}{2h} = \frac{v^2}{rg}$$

where $\frac{t}{2h}$ = the Static Stability Factor (see below),

v = vehicle speed,

r = turn radius, and

g = acceleration due to gravity

The term on the left-hand side of the equation, the Static Stability Factor (SSF), is determined by vehicle geometry, whereas the term on the righthand side is determined by the motion of the vehicle. The SSF describes the relationship between the track width and height of vehicle CG above the road surface:

$$SSF = \frac{t}{2h}$$

where

t = track width (the center-to-center distance between the right and left tires along the axle), and

h = height of vehicle CG above the road surface

Without restricting the geometry of the vehicle, DARPA was able to control two of the variables on the righthand side of the equation: vehicle speed and turn radius. DARPA established course boundaries ("lateral boundary offset") and provided guidance on how to interpret course segment speed: as a speed limit or as a speed advisory ([2] and [13]). The 2004 and 2005 GCE RDDF establish the latitude and longitude of waypoints, lateral boundary offset, and course segment speed.

The author established the following conditions for evaluation of rollover risk (see Figures 5 through 8):

- if the turn radius, *r*, corresponding to vehicle speed, *v*, during any change in bearing equals or exceeds the maximum turn radius allowed by course geometry, or

- if the course speed entering the intersection of two adjacent course segments equals or exceeds the maximum vehicle speed allowed by course geometry,

the vehicle cannot make the turn without satisfying the rollover condition or exiting the course.

III.B. Analysis

To better visualize the actual course geometries involved, the RDDF analysis application was modified to use the Google Maps™ mapping service to re-create the 2004 and 2005 GCE courses. DARPA published an image of the 2004 GCE course ([3], p. 7, Figure 5) and an image of the course marked with the final positions of the vehicles ([17]). DARPA published an image of the 2005 GCE course ([37]). Alternate images were published by Teams 2005-13 and 2005-14 ([24], p. 501, Figure 37) and Team 2005-16 ([25], p. 686, Figure 27).

Images from published records conform closely to the map output generated by the RDDF analysis application using the Google Maps™ mapping service. See Figures 9 through 29.

At first glance, the 2005 GCE course appears significantly more difficult than the 2004 GCE course because it crosses or overlaps itself in several locations, and because, at the scale at which all of the course is visible, changes in bearing appear to be sudden and significant (see Figures 21 and 22). However, when the scale is increased (see Figures 23 through 29), it is apparent that the changes in bearing are neither sudden nor significant. Therefore, visual analysis alone cannot provide an objective measure of difficulty.

The number of changes in bearing at which a vehicle satisfies the rollover condition is an objective measure which is a function of speed and change in bearing. Comparing the number of changes in bearing at which a vehicle satisfies the rollover condition therefore allows direct comparison of the difficulty of the 2004 and 2005 GCE courses.

As noted above, the rollover condition is also a function of g, acceleration due to gravity, and SSF. A survey of manufacturers revealed that very few manufacturers disclose both the track width and height of vehicle CG. The author proposes this is because the height of vehicle CG, and therefore SSF, has been publicly correlated with rollover risk.

The U.S. National Highway Transportation Safety Administration (NHTSA) documented the result of a survey of the industry conducted in 2005 ([36]). The purpose of this survey was to document trends in SSF of passenger cars, light trucks, and vans. The NHTSA reported SSF values for vehicles which are considered typical of vehicles purpose-modified by teams participating in the Grand Challenge.

As a result, published technical papers from the 2004 and 2005 GCE were reviewed to determine the specific make and model of the vehicles participating in the 2004 and 2005 GCE, and SSF values considered typical for those vehicles.

Generally, SSF values for types “Commercially-available ATV” and “Military Service Vehicle” were unpublished, and could not be calculated or accurately estimated using reported figures and dimensions for type “Purpose-built vehicles”, because the height of vehicle CG could not be determined from available information.

SSF values for vehicles considered typical for 2004 and 2005 challenge vehicles fell in the range 1.02 to 1.29 in 2004 (see Table XVII) and 1.02 to 1.20 in 2005 (see Table XVIII). Rather than determine an average SSF, the minimum SSF reported (1.02) was selected as the worst case scenario. Ironically, DARPA, by stating: “The route can be traversed by a commercial 4X4 pickup truck.”, may have inadvertently caused some teams to select vehicles with high ground clearance and low SSF as challenge vehicle platform due to their off-road capabilities. In addition, at least one team proposed modifying the team challenge vehicle to increase ground clearance, compounding the problem. Team 2004-09 stated: "...the suspension may be modified to increase ground clearance." ([38], p. 2).

The RDDF analysis application was modified to evaluate the risk of rollover. A geometric analysis was conducted to determine the maximum allowed turn radius, which is defined as the radius of a circular arc tangent to both course segments representing the path of travel, which falls completely within the course boundaries established by DARPA.

III.B.1. Law of Sines approach

The initial attempt involved utilizing the spherical Law of Sines to determine the maximum allowed turn radius as the best possible estimate. However, the distances between some adjacent waypoints are extremely small compared to the radius of the Earth, and rounding error in calculation caused the final result to exceed the range of legal arguments for the inverse sine function (i.e., the result was greater than one). The Law of Sines approach did not reliably produce valid results, and was abandoned.

III.B.2. Plane tangent to the ellipsoid approach

As a result, the author decided to concentrate on determining the maximum allowed turn radius using a circular arc in a plane tangent to the ellipsoid at a waypoint representing the intersection of two course segments. The maximum allowed turn radius passes through a point representing the intersection of the entering lateral boundary offset with a line bisecting the angle formed between adjacent course segments, and is therefore representative of the worst case scenario. See Figure 30. See paragraph III.D.2. for a comparison of the maximum allowed turn radius to the minimum design turn radius (also referred to by vehicle manufacturers as "curb-to-curb diameter" or "turning circle diameter").

Figure 31 visually presents the 2004 QID course with RDDF-allowed turn radius based on course segment speed as a red circle tangent to each course segment at the intersection of two course segments. The radius of the circle was calculated using the plane tangent to the ellipsoid approach. In general, larger red circles correspond to higher speeds defined by the RDDF and smaller red circles correspond to lower speeds. Visual analysis reveals a challenge vehicle with a minimum design turn radius equal to or less than the RDDF-allowed turn radius could completely turn around without exceeding the lateral boundary offset at the intersections marked with the smallest red circles, and that no turns required a change in bearing which placed the challenge vehicle at risk of rollover. For example, the largest red circle denotes segment 17-18-19. The 2004 QID RDDF-allowed speed for this segment was 50 mph, however the required change in bearing at the intersection was less than one degree.

The error in the radius of a circle in a plane tangent to the ellipsoid at an intersection of two course segments will increase with increasing radius. However, over the distances involved (typically less than several hundred meters), error resulting from using this method is not expected to be significant, and the maximum allowed turn radius well exceeded the RDDF-allowed turn radius for all but a single intersection defined by the 2004 GCE RDDF. See paragraphs III.C. and III.D.

III.C. Results

III.C.1. Segment 2570-2571-2572

At the minimum SSF reported of 1.02, the maximum turn radius allowed by the 2004 GCE RDDF for segment 2570-2571-2572 was 72 m, corresponding to a speed of 60 mph; the maximum turn radius allowed by course geometry was 46.1 m, corresponding to a speed of 48.0 mph. At the maximum SSF during the 2004 GCE of 1.29, the maximum allowed turn radius for segment 2570-2571-2572 was 56.8 m. At the maximum SSF reported during the 2005 GCE of 1.20, the maximum allowed turn radius was 61.1 m.

III.D. Conclusion

DARPA stated ([2], p. 22):

> A maximum speed limit is specified for each segment of the route. Any vehicle that exceeds the speed limit may be disqualified. A specified speed limit does not imply that it is a safe or achievable speed. Speed limits are specified in the RDDF and apply to the route segment defined by the associated waypoint to the next sequential waypoint.

and

> Segments with unspecified maximum speed are indicated by 999.

The 2004 GCE RDDF defined no segments with unspecified maximum speed.

DARPA stated ([13], p. 6):

> Course speeds that are less than 25 mph are mandatory speed limits. In addition, a 50 mph mandatory course-wide speed limit is in effect under all conditions at all points on the route. The minimum course speed in the RDDF is 5 mph. Course speeds that are between 26mph and 50 mph (inclusive) are advisory and are

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provided for guidance purposes.  No course speed will
exceed 50 mph.
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Because the 2005 RDDF specification ([13]) was published after the 2005 GCE rules ([2]) it is clear that DARPA revised its guidance prior to the 2005 GCE and after publishing the 2005 GCE rules. The 2004 GCE rules published by DARPA are no longer hosted by DARPA via the Archived Grand Challenge 2004 website ([17]). However, revision "April 1.2" of the 2004 GCE rules downloaded from the Team 2004-20 website stated ([1]):

```
Speed limits will be mandatory for certain segments of
the Challenge Route for safety and environmental
reasons.  Speed limits will be specified in the RDDF
in miles per hour, and will apply from the associated
Waypoint to the next sequential Waypoint.  A specified
speed limit does not imply that it has been tested or
that it is a safe or achievable speed.  Exceeding a
speed limit will be cause for disqualification.
```

A speed of 48.0 mph was within the course-wide speed limit of 50 mph imposed by DARPA for the 2005 GCE. Available sources ([1] and [6]) did not report a course-wide speed limit was imposed by DARPA for the 2004 GCE. The 2004 GCE RDDF defined speeds up to, and including, 60 mph.

The author concluded no challenge vehicle would have been able to make this turn at the maximum speed allowed by the 2004 GCE RDDF of 60 mph and would have either satisfied the rollover condition or exceeded the lateral boundary offset and consequently exited the course less than one kilometer (890.1 m), or less than two minutes (100 seconds), from the finish line. Because no vehicle completed more than 7.4 miles of the course in 2004 ([3], p. 8 and [30]), this had no practical impact on the successful completion of the 2004 GCE. The potential impact, however, was significant.

In 2004 no intersection had a maximum allowed turn radius of less than 27.1 m (27.147 m) (segment 73-74), corresponding to a speed of 36.8 mph, and in 2005 no intersection had a maximum allowed turn radius of less than 20.9 m (20.897 m) (segment 1672-1673), corresponding to a speed of 32.3 mph, both of which were well within the maximum speed realized by Team 2004-10 during the 2004 GCE of 36 mph ([39], p. 31) and Team 2005-16 during the 2005 GCE of 38.0 mph ([25], p. 688). However, neither team achieved a speed of 48.0 mph, nor is it evident that a challenge vehicle would have been traveling at this speed when it approached segment 2570-2571-2572.

Following the 2004 GCE, Team 2004-10 stated ([39], p. 39):

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The backup Riegl laser scanner (installed after the
pre-race rollover) was used on race day.  This
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> operated at only 15 Hz, instead of the specified 50Hz, and only 3⁄4 of the line rate achieved by the original Riegl scanner. The onboard filtering of the laser data was designed to operate with a laser scan rate of 20 Hz. Though it appears to have played no role in any of the incidents during race day, the decreased laser scan rate did cause the onboard system to disregard the laser data several times when [the challenge vehicle] accelerated to high speed. Had any of these accelerations occurred in more challenging terrain, this weakness may have led to a failure.

and:

> The impact of robot dynamics can be significant- Though not discussed in this report, during testing [the challenge vehicle] rolled while driving at roughly 50mph. The root cause of the role [*sic*] was an overlap in the route [the challenge vehicle] was tracking at the time. The roll occurred because [the challenge vehicle] turned very sharply to respond to inconsistent path tracking commands. Had there been a better model of the robots [*sic*] safety margin, the control output could have been limited to prevent the roll over from happening.

The author considers this supports a conclusion that a rollover was possible due to speed and change in bearing at speeds up to the maximum RDDF-allowed speed even though the challenge vehicle's controlling intelligence may have been designed to limit the speed of the vehicle to mitigate the risk of rollover, and that the potential impact due to rollover was significant, for example, requiring the replacement of an expensive sensor.

III.D.1. Effect of slope, friction, and suspension and tire effects

Realistically, the rollover condition is also dependent on slope, friction, and suspension and tire effects ([35]).

III.D.1.a. <u>Effect of slope</u>

The rollover condition for a challenge vehicle on a slope may be expressed as a function of five variables: vehicle speed, turn radius, track width, height of vehicle CG above the road surface, and slope. The rollover condition on a slope is given by ([35]):

$$\frac{\frac{t}{2h} - \tan(\phi)}{\frac{t}{2h}\tan(\phi) + 1} = \frac{v^2}{rg}$$

where $\frac{t}{2h}$ = the Static Stability Factor (see paragraph II.A.),

v = vehicle speed,

r = turn radius,

g = acceleration due to gravity, and

ϕ = slope of the road surface, to the outside of the turn

As discussed (see paragraph II.C.1.a.ii.), the RDDF does not provide sufficient information to determine the slope between waypoints and consequently the effect of slope on challenge vehicles. However, the rollover condition on a slope was evaluated for a notional slope of five, ten, 20, and 30 degrees to the outside of the turn at each waypoint with no impact on reported results. No additional waypoints defined by either the 2004 or 2005 RDDF were identified at which the effect of slope would have resulted in a challenge vehicle being at risk of rollover on a slope of five, ten, 20, or 30 degrees.

The required turn radius for segment 2570-2571-2572 defined by the 2004 RDDF was 86 m at a slope of five degrees and 103 m at a slope of ten degrees. The minimum turn radius allowed by course geometry was 46.1 m. For comparison, the required turn radius for segment 2570-2571-2572 was 60.3 m at a slope of negative five degrees and 50.3 m at a slope of negative ten degrees.

As a result, the author concluded the effect of slope did not contribute additional rollover risk.

III.D.1.b. Effect of friction

There are two kinds of rollovers: “tripped” and “untripped”. A tripped rollover occurs when the vehicle's wheels hit an obstacle such as a curb or pothole, most commonly during lateral motion such as a slide, causing vehicle CG to move beyond the balance point above the leading tires. The vehicle then rolls over ([40]). An untripped rollover results solely from friction forces acting on the outside wheels of the vehicle during a turn, and is also called a “friction rollover”. The rollover condition for a sliding vehicle is given by ([35]):

$$SSF < \mu_k$$

where SSF = the Static Stability Factor, and

μ_k = the kinetic coefficient of friction

If $SSF > \mu_k$ then the challenge vehicle will slide sideways instead of rolling over. Review of SSF values for vehicles considered typical for 2004 and 2005 challenge vehicles (see Tables XVII and XVIII) revealed that no challenge vehicle had a SSF less than published estimates for μ_k on asphalt (dry) or concrete (dry) (see Table XIX), and certainly not less than reasonable estimates for μ_k on road surfaces considered typical for the 2004 and 2005 GCE (see paragraph VIII.A.1.).

Although, in general, teams mounted additional equipment above their challenge vehicle CG, such as inside the vehicle or on the roof, which would make the vehicles top-heavy and ultimately decrease SSF, the weight of this equipment is not expected to be significant compared to the weight of the challenge vehicle itself, and its contribution to a reduction in SSF is not expected to be significant.

As a result, the author concluded the most likely form of rollover was a tripped rollover, during which the effect of friction would cause a challenge vehicle to slide into an obstruction sufficient to cause the vehicle's lateral or sideways motion to stop, and causing vehicle CG to move beyond the balance point above the leading tires, and therefore roll over.

III.D.1.c. Suspension and tire effects

Suspension and tire effects vary depending on team selection of challenge vehicle platform. Suspension and tire effects have been estimated ([35]) to contribute to a ten percent reduction in SSF (herein referred to as “effective SSF”). The RDDF analysis application was used to evaluate the risk of rollover with an effective SSF of 0.92, which is a ten percent reduction of the minimum SSF reported of 1.02. No additional waypoints defined by either the 2004 or 2005 GCE RDDF were identified at which the required turn radius exceeded the maximum turn radius allowed by course geometry.

In addition, the rollover condition on a slope was evaluated for a notional slope of five, ten, 20 and 30 degrees to the outside of the turn at each waypoint with an effective SSF of 0.92. As before, the required turn radius for segment 2570-2571-2572 defined by the 2004 RDDF was 95 m at a slope of five degrees and 115 m at a slope of ten degrees; the minimum turn radius allowed by course geometry was 46.1 m. No additional waypoints defined by either the 2004 or 2005 RDDF were identified at which the effect of slope and suspension and tire effects combined would have resulted in a challenge vehicle with an effective SSF of 0.92 being at risk of rollover on a slope of five, ten, 20 or 30 degrees. As a result, the author concluded the effect of slope and suspension and tire effects combined did not contribute additional rollover risk.

III.D.1.d. Safety factor

The author calculated the equivalent of a safety factor by dividing the maximum allowed turn radius by the RDDF-allowed turn radius and noted that the minimum safety factor in the course design was:

- 8.4 for the 2004 GCE (segment 1368-1369)
- 9.8 for the 2005 GCE (segment 2306-2307)

with the exception of 2004 GCE segment 2570-2571-2572 which had a safety factor of 0.64. See paragraph III.C.1.

III.D.2. Minimum design turn radius

The author conducted a survey of commercial used vehicle search services ([41], [42], and [43]) to determine the minimum design turn radius of vehicles identical or similar to the platforms selected as challenge vehicle platform by teams participating in the 2004 and 2005 GCE (see Table XX). The minimum design turn radius was then used to calculate the corresponding rollover speed using SSF values from the vehicle closest match (see Tables XVII and XVIII) because vehicles cannot turn at a radius smaller than their minimum design turn radius without modification, no matter what the maximum allowed turn radius is. Therefore, if a vehicle entered a turn at a speed greater than or equal to the rollover speed calculated from the minimum design turn radius, and the minimum design turn radius is greater than the maximum allowed turn radius, the vehicle is at risk of rollover. See Table XXI.

In 2004, no challenge vehicle was required to make a turn at a radius of less than 27.1 m (27.147 m) at the maximum speed allowed by the RDDF. No vehicle had a minimum design turn radius greater than half the maximum turn radius allowed by course geometry (Team 2004-23: 42.7 ft or 13.0 m).

In 2005, no challenge vehicle was required to make a turn at less than 20.9 m (20.897 m) at the maximum speed allowed by the RDDF. Again, no vehicle had a minimum design turn radius greater than half the maximum turn radius allowed by course geometry (Team 2005-21: 29.0 ft or 8.8 m).

Because no challenge vehicle was required to make a turn at a turn radius less than the minimum design turn radius at an allowed speed greater the corresponding rollover speed, the author concluded the minimum design turn radius of vehicles similar, or identical, to 2004 and 2005 challenge vehicles did not contribute additional rollover risk.

III.D.3. Confirmation of forced deceleration lanes

Markers were placed on the map of the 2005 GCE course using the RDDF analysis application representing waypoints at the beginning and end of the four proposed deceleration lanes referred to in paragraph II.C.7.e. to attempt to confirm these lanes forced deceleration before a significant change in bearing or other terrain features.

Review of the 2005 GCE course supports the conclusion that the four proposed deceleration lanes were forced deceleration lanes, although in one example the author was unable to determine, based on review of map data alone, why:

- From waypoints 76 to 84, the 2005 GCE RDDF forced challenge vehicles to reduce speed continuously through a right turn of more than 45 degrees, then allowed the vehicles to increase speed at the next waypoint (85) to 40 mph. See Figure 32.

- From waypoints 1177 to 1184, the 2005 GCE RDDF forced challenge vehicles to reduce speed prior to a left turn of more than 45 degrees from paved road to what appears to be dirt road, maintain a speed of 10 mph through the turn, then allowed the vehicles to increase speed at waypoint 1188 to 20 mph after the turn was completed. See Figure 33.

- From waypoints 1805 to 1809, the 2005 GCE RDDF forced challenge vehicles to reduce speed on approaching an intersection, then allowed the vehicles to increase speed at the next waypoint (1810) to 20 mph. See Figure 34.

- From waypoints 2277 to 2290, it is unclear why the 2005 GCE RDDF forced challenge vehicles to reduce speed while approaching what appear to be railroad tracks, then allowed the the vehicles to increase speed at the next waypoint (2291) to 30 mph, with no significant change in either terrain or distance from the railroad tracks. See Figure 35.

CHAPTER IV. TEAM EVALUATION OF VEHICLE RISK OF ROLLOVER

IV.A. Discussion

Several teams described specific strategies to mitigate vehicle risk of rollover in their 2004 technical papers, 2005 technical papers, and articles published in the Journal of Field Robotics, either directly by addressing vehicle risk of rollover or indirectly by describing, for example, speed setting or steering algorithms.

In addition, several teams addressed vehicle risk of rollover when describing the safety systems in use by the team, such as sealed fuel cells and lead-acid batteries, or the selection of tires, but did not describe their strategy to mitigate the vehicle risk of rollover, or referred to turn radius in the context of platform selection by stating that their selection was influenced by turn radius. Those descriptions are not included herein.

Several teams referred to turn radius in the context of manually or automatically smoothing the path of travel or editing the path. See Chapter XII.

IV.B. Analysis

The author performed a comprehensive review of published records to determine if team strategies to mitigate rollover risk were successful, and if team strategies could be compared to determine which was more successful.

- Team 2004-01

Team 2004-01 stated: “Speed setting algorithms will take into consideration the following and reduce speed appropriately: ... Turn radius.” ([8], p. 7).

- Team 2004-04

Team 2004-04 stated: “The speed sensor feedback will be used to limit the allowable steering angle to prevent rollovers at high speeds.” ([44], p. 9).

- Team 2004-05

Team 2004-05 stated: “The tilt measurements are also used to determine the vehicle’s risk for a roll-over.” ([9], p. 5).

- Team 2004-07

Team 2004-07 stated: “At all times after the vehicle passes the Departure Line, it should have an estimate of its current location and heading, and nominal desired headings and speeds for locations at its sensor horizon. Given possibly new information about obstacles in sensor range, it will use another version of the wavefront-propagation path planner to find the optimal obstacle-free trajectory that will take it to a point on the sensor horizon with as close as possible to the precomputed nominal desired heading and speed. This second algorithm will be adapted to the local planning problem in that it will more finely differentiate (x,y,theta) space and take more account of the vehicle kinematics and dynamics (e.g., steering linkage position, *turning radius as a function of speed*).” ([10], pp. 5 - 6, *emphasis added*).

- Team 2004-09

Team 2004-09 stated ([47], p. 4):

> Objects that are taller than vehicle clearance need to be avoided completely. These objects require an adequate detection range so that, at the vehicle velocity, there is sufficient turn radius for the vehicle to safely steer at an angle that combines the vehicle size with the half width of the vehicle. Such steering will involve significant turning radii, which will need to be compared to limits that depend on vehicle attitude and speed. This feature will prevent unintentionally rolling the vehicle. ... These algorithms take into account vehicle attitude, which imposes a speed-dependent lower bound on the turn radius.
>
> Figure 3 is a chart of the effect of attitude and speed on allowable turn radius for a sample vehicle. The chart shows the minimum allowable uphill turn radius for the given speed and roll angle (the angle of the terrain across the vehicle path) to prevent vehicle rollover. A safety factor is built into the algorithm, which provides an additional 15% margin in radius.

- Team 2004-18

Team 2004-18 stated: “The stability control system limits the curvature commanded as a function of speed to minimize the risk of vehicle rollover.” ([48], p. 6).

- Team 2004-25

Team 2004-25 stated: “Speed is kept within the specified course limits and may be further limited by the current turning radius of the vehicle.” ([49], p. 9).

- Team 2005-02

Team 2005-02 stated ([50], p. 615):

> As an additional measure for vehicle stability, a steering constraint was added to limit the maximum steering angle as a function of speed (v) and roll angle (Φ) (due to uneven terrain). The goal of this constraint was to limit the maximum lateral acceleration (n_y) incurred by the vehicle due to centripetal acceleration and acceleration due to gravity (g). Thus, if the vehicle were traveling on a gradient that caused it to roll toward any one direction, the steering wheels would be limited in how much they could turn in the opposite direction. Additionally, as the vehicle increased in speed, this constraint would restrict turns that could potentially cause [the challenge vehicle] to roll over.
>
> The value for maximum lateral acceleration was determined experimentally with the following procedure. A person driving [the challenge vehicle] would turn the wheels completely to one direction, and then proceed to drive the vehicle in a tight circle slowly increasing in speed. The speed in which the driver felt a lateral acceleration that was reasonably safe or borderline comfortable was recorded, and the acceleration value was calculated. This was done for both left and right turns, and the minimum of the two values were taken for conservatism.

- Team 2005-04

Team 2005-04 stated: “The speed controller’s main aim is to avoid the [*sic*] collision into the [*sic*] obstacles. Moreover, due to the physical constraint [*sic*] of the vehicle, sharp turning at high speed should be avoided to prevent [the challenge vehicle] from rolling over.” ([51], p. 738).

- Team 2005-06

Team 2005-06 stated: “If [minimum distance from the virtual sensor to the reference path] were ever to cross a given threshold, meaning the vehicle is severely off path, the speed was instantly reduced to 2 mph. This allowed the vehicle to return to the desired path and prevented a possible rollover.” ([28], p. 521).

- Team 2005-09

Team 2005-09 stated: “In addition to path geometry, several additional mechanisms regulate vehicle speed. While speed is important for competing in the Grand Challenge, it increases risks inherent in a large moving vehicle... Simply increasing the speed - without addressing safety, stability, and sensor range - fails to recognize the dangers inherent in large robots. Higher speed reduces the distance available to react to an obstacle, decreases sensor fidelity as samples are taken over a larger area, and consequently decreases confidence in a selected action. At higher speeds, vehicles are more likely to tip over or swerve off the road from an unexpected steering correction. In the event of a collision, higher speed increases the momentum of a vehicle; increasing the likelihood of damage. This is evident from the damage to the parked cars at the NQE from robots colliding with them at low speeds.” ([52], p. 820).

- Teams 2005-13 and 2005-14

Teams 2005-13 and 2005-14 stated: “In this approach to high-speed navigation, three principal risks are considered: Hitting large obvious obstacles that can destroy a vehicle, driving on avoidable rough terrain that will damage a vehicle over prolonged periods of time, and dynamic effects—such as sliding and rollovers—which cause a loss of control and can also potentially destroy a vehicle.” ([24], p. 481).

Teams 2005-13 and 2005-14 stated: “The speed planner is responsible for ensuring driving speeds are safe. As vehicle speed increases, dynamics become important. Speed induces side-slip ... and can cause rollover ... in vehicles with a high center of gravity.” ([24], p. 490).

Teams 2005-13 and 2005-14 stated: “Many effects which are functions of the terrain and environment decrease tractive force. A wheel bouncing on washboard terrain has less contact with the ground, and as a result cannot apply as much force. On side slopes and in banked turns, gravity and the 'up force' generated by the curvature of the terrain changes the maximum possible speed before rollover and breakaway.” ([24], p. 491).

Teams 2005-13 and 2005-14 stated: “The human editing process removes unnecessary curvature from the smoothed path. Smooth paths are also generally faster since decreasing the amount of curvature in a path reduces concerns for dynamic rollover and side slip.” ([24], p. 492).

- Team 2005-15

Team 2005-15 stated: “The vehicle speed in sharp curves is limited, to limit lateral g-forces dependent on the curve’s radius, to an actual speed, which would be less than the RDDF file allowed maximum speed.” ([53], p. 11).

- Team 2005-18

Team 2005-18 stated: “In the rollover constraint expression, *W* is the track of the vehicle (distance between left and right wheels), *hcg* is the height of the center of gravity of the vehicle above ground, and *g* is the acceleration due to gravity. This expression is derived from assuming flat ground and rollover due purely to a centripetal force. In reality, on many surfaces, sideslip will occur much before rollover, so this constraint has an adjustment factor.” ([54], p. 797).

- Team 2005-19

Team 2005-19 stated: “Dynamic checks for rollover, side slip, and front slip ... are also used to penalize or eliminate paths that are more hazardous.” ([55], p. 12).

- Team 2005-20

Team 2005-20 stated: “The curving speed is also defined by the path planner. It assumes a maximum lateral acceleration allowed and defines the speed required to meet that acceleration. This is to minimize the rollover risk.” ([56], p. 12).

- Team 2005-21

Team 2005-21 stated: “The lateral stability of the truck was evaluated through constant-radius tests. Tire forces were monitored to detect tire lift-offs. The results of these simulations ... were used to evaluate the capability of the truck to take a particular turn at different speeds without rolling over.” ([57], p. 695).

- Team 2005-22

Team 2005-22 stated: “The Motion Control program receives these speed and steering commands and determines if they are safe from causing a rollover.” ([58], p. 10).

Team 2005-22 also stated: “Brake percent is controlled by the current steering angle, roll angle, amount of speed reduction, and urgency. These controls prevent a rollover from occurring...” ([58], p. 11)

- Teams 2005-22 and 2005-23

Teams 2005-22 and 2005-23 stated: “After experiencing two vehicle rollovers, one during [Team 2005-23 challenge vehicle's] DARPA site visit, attention was focused on preventing another rollover. A simple dynamic model of the vehicle, that considers gravity and centripetal force, was developed. ... To account for the rollover effects of unpredictable terrain, a factor of safety is implemented in each calculation...” ([59], p. 713)

Teams 2005-22 and 2005-23 also stated: “A rollover condition exists when the resultant of the centripetal force and the weight vector point outside the footprint of the vehicle. Stability can be achieved by slowing the vehicle’s forward velocity and reducing the magnitude of the steering angle.” ([59], p. 713)

IV.C. Results

- 2004

Four of 25 teams (16 percent) referred specifically to the vehicle risk of rollover in their 2004 technical papers: Teams 2004-04, 2004-05, 2004-09, and 2004-18. Six of 25 referred to turn radius as a function of speed.

- 2005

Three of 23 teams (approximately 13 percent) referred specifically to the vehicle risk of rollover in their 2005 technical papers: Teams 2005-19, 2005-20, and 2005-22. Four of 23 referred to turn radius as a function of speed. However, an additional nine teams referred specifically to the vehicle risk of rollover or turn radius as a function of speed in articles published in the Journal of Field Robotics, for a 2005 GCE total of 12 of 23 teams (approximately 52 percent).

IV.C.1. Mitigation of rollover risk

Only one team experienced a rollover event during either the 2004 or 2005 GCE: Team 2004-18. DARPA stated: “The vehicle began smoothly, but at mile 0.2, when making its first 90-degree turn, the vehicle flipped. The vehicle was removed from the course.” ([3], p. 8). Team 2004-18 was one of four teams participating in the 2004 GCE which referred to the vehicle risk of rollover specifically.

Via their 2004 technical paper, dated March 3, 2004, Team 2004-18 described their “Second Stage Planned Testing” as taking place in the future: “The second stage will be in the company parking lot to determine the performance of … rollover protection and correction...” ([48], p. 8). The 2004 GCE was held March 13, 2004. As a result, the author concluded Team 2004-18 may not have completed planned testing due to time constraints. Insufficient time to complete planned testing was cited by a number of teams as a factor impeding their success. Inadequate test and evaluation was the leading cause of team failure during the 2004 and 2005 GCE, and was the cause of failure of four of six (66 percent) potentially-disruptive teams to complete the 2005 GCE.

Only one team (Team 2005-06) stated their strategy successfully prevented a rollover event: “If [minimum distance from the virtual sensor to the reference path] were ever to cross a given threshold, meaning the vehicle is severely off path, the speed was instantly reduced to 2 mph. This allowed the vehicle to return to the desired path and prevented a possible rollover. The algorithm was repeatedly tested by manually overriding the steering controller and taking the vehicle off path, then allowing it to regain control." ([28], p. 521).

Several teams stated their challenge vehicles experienced a rollover event during field testing prior to the 2005 GCE: Team 2004-10 reported one rollover event ([39], p. 39); Team 2005-14 reported one rollover event ([24], pp. 499 - 500) occurred on September 19, 2005, nine days before the first day of the 2005 NQE; and Teams 2005-22 and 2005-23 reported two rollover events ([59], p. 713).

IV.C.2. Comparison of team strategies to mitigate rollover risk

In general, teams did not report sufficient technical detail to independently evaluate their strategies. For example, based on a review of technical papers submitted in 2004 and 2005:

- The strategy described by Team 2004-05 was incomplete: "...tilt measurements are ... used to determine the vehicle's risk for a roll-over.". However, it is unclear this strategy would have been sufficient; although Team 2004-05 reported state sensors would provide both steering angle and speed, the team did not describe how either steering angle or speed are monitored for the purpose of mitigating vehicle risk of rollover.

- Team 2004-09 provided the most comprehensive description of any team which participated in the 2004 GCE, but did not report sufficient technical detail to evaluate the algorithm described by the team.

- Teams 2005-02 and 2005-21 described experimental evaluation of the vehicle risk of rollover ([50], p. 615 and [57], p. 695), but their methods are not reproducible without the challenge vehicle.

- Of all published records, Teams 2005-22 and 2005-23 provided the most comprehensive description of rollover prevention of any team which participated in the 2004 or 2005 GCE, and were the only teams to describe a reproducible method ([59], pp. 713 - 714, paragraph 4.2).

IV.D. Conclusion

Review of published records supports a conclusion that some teams considered vehicle risk of rollover and developed specific strategies to mitigate it. However, only two of 48 teams reported sufficient technical detail to determine what strategy was adopted to mitigate vehicle risk of rollover. The author concluded no meaningful comparison between team strategies was possible, and that insufficient evidence is available to conclude that team strategies to mitigate vehicle risk of rollover were successful.

Some teams variously referred to the relationship between turn radius and vehicle speed, the relationship between steering angle and speed, the use of vehicle state information (e.g., "tilt measurement" and "vehicle attitude"), the rate of change of steering angle (e.g., "sharp turning at high speed"), and speed reduction. None of these strategies was complete. Maximum safe vehicle speed is a function of turn radius, vehicle attitude, and angular rate of change of the steering angle.

The general failure to identify the variables which must be controlled to mitigate vehicle risk of rollover, or universal acknowledgement that a strategy to mitigate the risk is required, supports a conclusion that DARPA recognized the danger to challenge vehicles and reduced the difficulty of the 2005 GCE course to mitigate vehicle risk of rollover. See Chapter II. and Chapter III.

Given the considerable but unreported cost of some challenge vehicles (see paragraph V.E.), and the potential for catastrophic damage as the result of a rollover event, the author concluded the risk of rollover was very real. However, the author considers it more likely that the course grooming and forced deceleration lanes referred to in Chapter II. more successfully mitigated vehicle risk of rollover during the 2005 GCE than any action on the part of the teams themselves.

CHAPTER V. TOTAL COST

V.A. Discussion

Section 2374a of Title 10 of the United States Code ([60]) authorized the Secretary of Defense: “acting through the Director of Defense Research and Engineering and the service acquisition executive for each military department, may carry out programs to award cash prizes in recognition of outstanding achievements in basic, advanced, and applied research, technology development, and prototype development that have the potential for application to the performance of the military missions of the Department of Defense.”[19]

Section 220 of House Report 106-945 (“Enactment of Provisions of H. R. 5408, The Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001”) stated, in part: “It shall be a goal of the Armed Forces to achieve the fielding of unmanned, remotely controlled technology such that … by 2015, one-third of the operational ground combat vehicles are unmanned.” ([4]). Section 220(d)(4) defines the term “operational ground combat vehicles”: “The term 'operational ground combat vehicles' means ground combat vehicles acquired through the Future Combat System acquisition program of the Army to equip the future objective force, as outlined in the vision statement of the Chief of Staff of the Army.”

As of March 2, 2009, the U. S. Army stated the Future Combat System (FCS) Brigade Combat Team (BCT) systems included: “Two classes of unmanned ground vehicles, the XM1216 Small Unmanned Ground Vehicle (SUGV), and Multifunction Utility/Logistics and Equipment Vehicle (MULE) variants” ([61]).

The FCS was a modernization-through-acquisition program[20]. Department of the Army Fiscal Year (FY) 2009 Budget Estimates ([64]) did not report per-unit costs for the three planned Multifunction Utility/Logistics and Equipment Vehicle (MULE) variants. However, it is unlikely the production cost of the basic MULE variant, the XM1217 MULE-Transport (MULE-T) ([65]), would have far exceeded the current production cost of the High Mobility Multipurpose Wheeled Vehicle (HMMWV).

Production cost estimation information for several “generations” of HMMWV is available, including the current base model M1097A2 “heavy variant” and the “up-armored” M1151A1/M1152A1:

- The Department of Defense FY 2009 Budget Request Summary Justification ([66]) stated the Department of Defense plans to acquire 5249 units at a total cost of $989.7 million, for an average unit cost of approximately $189,000. However, this figure includes procurements of advanced models based on the Extended Capacity Vehicle (ECV2) Chassis with unit costs ranging from $134,000 to $248,000, which increases the average unit cost.

- The Department of the Army Fiscal Year (FY) 2009 Budget Estimates ([64]) reported a "Unit Cost" of $168,000 for the "Armored" version of the M1151A1, and $103,000 and $129,000 for the "Armor Ready" and Armored versions, respectively, of the M1152A1, and $150,000 for the Armored version of the M1165A1. These models comprise the bulk of FY 2009 procurement, and represent 4126 of 5065 units procured, with an average unit cost of approximately $148,000. From FY 2007 to FY 2009 the unit cost for these units increased by $2000 to $3000 for each version. Prior years' data indicated procurement of 122,522 units with a total "Gross Cost" of $7,420.4 million, for a unit cost of approximately $61,000. However, this unit cost includes prior models such as the M998 and M1097A2 which were less expensive than the current up-armored variants.

- At the 2003 Tactical Wheeled Vehicles Conference the Army National Guard (ARNG) reported a unit cost of $77,000 for the HMMWV ([67]). This is most likely the M1097A2 which was based on the A2 series modification package introduced in 1995, and which figures prominently in the FY 2003 budget ([68]), with 752 of 2154 units procured at a unit cost of $63,000. However, it is unclear how the ARNG arrived at a unit cost of $77,000, since the average unit cost for all 2154 units procured in FY2003 was approximately $68,000. During this conference, the ARNG also reported a unit cost of $185,000 for an up-armored HMMWV. As before, it is unclear how the ARNG arrived at a unit cost of $185,000, since the unit cost of the up-armored M1114 variant was $71,000.

- At the 2008 Tactical Wheeled Vehicles Conference the Department of the Army reported a unit cost of $60,000 for the M998 HMMWV and $150,000 for a "UA HMMWV" (up-armored HMMWV) ([69]). These figures correspond roughly with the Department of the Army Fiscal Year (FY) 2009 Budget Estimates prior years' data unit cost of $61,000 and average unit cost of approximately $148,000, respectively.

- And in 2005, the Maine Military Authority estimated the unit cost of a "new basic HMMWV" at "approximately $77,000" ([70]). This number is used to calculate the "Savings Per HMMWV" for vehicles refurbished by the Maine Military Authority from 1997 to 2005, and corresponds to the unit cost of $75,000 and $77,000 for the up-armored M1151 and M1152, respectively, in the FY 2005 budget ([68]).

Based on the available data, the unit cost of a HMMWV will be estimated at $150,000 herein, corresponding to the average unit cost of the models comprising the bulk of FY 2009 procurement.

It is unlikely that the Department of Defense will choose, as its autonomous ground vehicle control technology, a solution the hardware cost of which represents a significant portion of the unit cost of FCS unmanned ground vehicles. Far more likely, in fact, is that the Department of Defense, in an era of declining defense spending and increased global demand for resources, will seek a cost-effective solution.

To offer a sense of perspective, the Abrams Upgrade Program upgrades M1/M1A1 Abrams Main Battle Tanks (MBT) to the M1A2 System Enhancement Package (SEP) configuration. The SEP upgrades both the Gunner's Primary Sight (GPS) and The Commander's Independent Thermal Viewer (CITV) on the M1A2 SEP tank to include the improved thermal imaging capabilities of new Block I 2nd Generation Forward Looking Infra-Red (FLIR) technology. The sights "allow gunners and field commanders to see, identify and target enemy platforms 24 hours a day, regardless of obscurants such as smoke, fog, and dust." The M1/M1A1 MBT "Basic Vehicle" has a FY 2009 unit cost of $3,988,000. The FLIR upgrade has a FY 2009 unit cost of $407,000, or approximately ten percent of the basic vehicle cost ([71]).

Ten percent of the basic vehicle cost is a realistic estimate of the cost of a sensor technology that provides a distinct advantage in combat. Therefore, the author does not anticipate the cost of the sensor technology that provides "semiautonomous and leader-follower capability" to unmanned ground vehicles to exceed ten percent of the basic vehicle cost, or $15,000 of the $150,000 estimated unit cost of the HMMWV.

Neither detailed technical information nor cost information was available from General Dynamics Robotic Systems ([72]), which was awarded the contract for the FCS Autonomous Navigation System (ANS):

> General Dynamics Robotic Systems (GDRS) is responsible for the design, development, manufacture, integration, and testing of the Autonomous Navigation System (ANS) for the Army's Future Combat System (FCS) program. The ANS system is capable of autonomously controlling any of several vehicles designated by the Army, including the Multi-functional Utility Logistics Equipment (MULE) platform, the Armed Reconnaissance Vehicle (ARV), as well as Manned Ground Vehicles (MGVs).
>
> ANS, a major subsystem in the FCS manned combat system, will provide navigational, perception, path-planning and vehicle-following algorithms and the requisite onboard sensor package for autonomous mobility.

V.B. Analysis

V.B.1. Comprehensive review of technical papers for 2004 QID and GCE participants

Although a variety of sensors were in use by teams which participated in the 2004 and 2005 GCE, sensors in use by the teams can broadly be classified as state, environment, and navigation sensors. It is difficult to classify some sensors, such as driveshaft or wheel encoders, because they provide both state (e.g., vehicle or ground speed) and navigation (e.g., incremental distance) information. Other sensors, such as GPS or DGPS receivers, are easier to classify based on their primary purpose as a geolocation sensor, but geolocation estimates reported by GPS or DGPS receivers can also be used to determine state information (e.g., vehicle or ground speed), and some COTS components containing a GPS or DGPS receiver provide reliable estimates of instantaneous or average vehicle or ground speed. These issues were generally resolved as described in paragraphs V.B.3., V.B.5., and V.B.5.b., below.

The author completed a comprehensive review of technical papers submitted by teams participating in the 2004 QID and GCE. In general, this was accomplished by searching for key words related to the sensor technologies in use by the teams, for example: “video”, “camera”, and “stereo” for cameras; or “LIDAR”, “LADAR”, and “laser” for LIDAR sensors. The purpose of this review was to determine if team technical papers reported sufficient technical detail to identify the quantity, manufacturer, and model number for state, environment, and navigation sensors in use by the teams. Based on the state, environment, and navigation sensors identified, the author could then produce a reliable estimate of the total cost of the sensor technology in use by each team, which could be used to answer the following research questions:

- Did the cost of the sensor technology exceed the cost of the platform for which it was designed?
- Was it possible to relatively rank vehicles by use of a metric such as total cost per mile and determine which solutions were more cost effective?
- Was the cost of the sensor technology alone a reliable predictor of success?

V.B.2. Review of 2005 GCE technical papers

The author did not complete a comprehensive review of 2005 NQE and GCE technical papers. The technical papers for teams which participated in the 2005 GCE were reviewed to determine if team technical papers reported sufficient technical detail to identify the quantity, manufacturer, and model number for environment and navigation sensors in use by the teams, and to provide a basis for comparison between results for teams participating in the 2004 and 2005 GCE.

The author did not attempt to determine if 2005 technical papers reported enough information to identify the quantity, manufacturer, and model number for state sensors in use by the teams. DARPA, in establishing the requirements for technical papers submitted by teams expressing interest in participating in the 2004 and 2005 GCE, asked each team to respond to standard questions which were presented in outline format. See Tables XXII and XXIII. Although the standard questions asked by DARPA prior to the 2004 GCE were revised before the 2005 GCE, 2004 GCE Standard Question (SQ) 1.f.1 does not differ significantly from 2005 GCE SQ 2.3.3. In general, teams participating in the 2005 GCE reported less technical detail for state sensors than teams participating in the 2004 QID or GCE.

The author considers this supports conclusions that solutions offered by some teams were unnecessarily complex, that for some teams, excessive attention to detail was evidence of distraction, and that some teams recognized the risk of, and attempted to reduce, complexity where possible. See paragraph XIV.B. The changing problem definition reported by DARPA may also have been a contributing factor. See Appendix C.

V.B.3. Classification of state sensors

For the purposes of classification herein, state sensors are considered to be those sensors which provide information about the state of the challenge vehicle. The author does not consider navigation sensors to be state sensors. See paragraph V.B.5.b. Examples of state sensors include:

- engine RPM (or tachometer) sensors
- brake pressure or brake position sensors
- fuel level sensors
- temperature sensors
- throttle position sensors
- transfer case sensors
- transmission position sensors
- steering angle or steering position sensors

V.B.3.a. <u>Estimation of quantity of state sensors</u>

Where a team reported insufficient technical detail to determine the quantity of state sensors in use by the team, the author estimated the quantity as follows:

- one brake pressure sensor
- one brake position (also “settings”) sensor
- one engine RPM (also “engine running” or “engine condition”) sensor
- one driveshaft RPM sensor
- one intake manifold pressure sensor per intake manifold
- one fuel level sensor
- one water temperature (or radiator temperature) sensor
- one transmission shifter position (or gear position) sensor
- one transfer case position sensor
- one throttle position sensor
- one steering position (or angle or rate) sensor (two if for front and rear steering)
- one oil pressure sensor
- one air conditioning sensor

V.B.4. Classification of environment sensors

For the purposes of classification herein, environment sensors are considered to be those obstacle- and path-detection sensors in use by the teams. Sensors which did not, in the author's estimation, provide the controlling intelligence with useful obstacle- or path-detection information at the 2004 and 2005 GCE average speeds of 22.2 mph and 21.3 mph, respectively, or the maximum “militarily relevant speed” established by DARPA of 20 mph (see paragraph II.C.6.), were not considered environment sensors for the purposes of determining total cost. These sensors were “discounted”, and are denoted by an “X” in the “Sensor Type” column in Tables XXV and XXVII. Examples include:

- ultrasonic (or SONAR) sensors
- touch (or tactile) sensors
- depth sensors
- conductivity (or water) sensors
- ground whiskers or vibration sensors

- photoelectric sensors

Some observations concerning discounted sensors are documented in the paragraphs which follow because they support conclusions which will be discussed in later sections.

V.B.4.a. Clarification of terminology

V.B.4.a.i. Laser range finders

Teams alternately referred to "laser range finder", "scanning laser range finder", and "line scanner" for various environment sensors utilizing lasers, which made it difficult to determine what sensors were in use by some teams. Examples have been noted throughout the text.

V.B.4.b. SICK LMS 291 LIDAR sensor model numbers

Seventeen teams which participated in the 2004 and 2005 GCE referred to SICK "LMS 291" LIDAR sensors, or some variant thereof. Only four teams reported the complete model numbers of the SICK LMS 291 product family LIDAR sensors in use by the team: Teams 2004-12, 2005-02, 2005-08, and 2005-18.

The author notes manufacturer product literature published prior to the 2004 GCE referred to SICK LMS 291-S05 and LMS 291-S14 LIDAR sensors ([73]), while manufacturer product literature published prior to the 2005 GCE referred to a SICK LMS 291-S15 LIDAR sensor ([74]). This inconsistency may explain why teams did not report a complete model number for these sensors. Manufacturer product literature published since the 2005 GCE referred to SICK LMS 291-S05, LMS 291-S14, and LMS 291-S15 LIDAR sensors ([75]).

V.B.5. Classification of navigation sensors

For the purposes of classification herein, navigation sensors are considered to be those which collectively allow the controlling intelligence to determine challenge vehicle geolocation, attitude, and speed. Examples include:

- accelerometers
- gyroscopes
- compasses, digital compasses, or electronic compasses
- magnetometers or "northfinding" modules
- OE, AOE, encoders such as potentiometers or rotary sensors, or wheel speed sensors used in odometry, including differential odometers

- speed sensors
- one- or two-axis inclinometers or sensors which determine challenge vehicle attitude relative to the horizon
- IMU
- INS
- GPS or DGPS

V.B.5.a. Clarification of terminology

V.B.5.a.i. Geolocation

Although DARPA and the teams variously referred to “position”, “localization data” or “localization information”, and “geolocation”, “geolocation” is used exclusively herein to refer to latitude, longitude, and altitude.

V.B.5.a.ii. IMU and INS

The teams and some manufacturers alternately referred to an IMU as an INS, and vice versa. The author draws a clear distinction between an IMU and an INS: an IMU provides attitude data only: rotation (roll, pitch, and yaw) and acceleration in three axes; an INS estimates geolocation after initialization, typically using GPS, based on navigation data from other sensors, such as an IMU, odometry, and magnetic compass.

For example, the ISI ISIS-IMU is an INS, even though ISIS-IMU includes the acronym “IMU” in its name (see paragraph V.C.18.c.).

V.B.5.a.iii. Speed

The teams variously referred to “speed”, “vehicle speed”, “ground speed”, “velocity”, and “velocity state”. All of these terms are used herein to refer to the vehicle or ground speed in the direction the vehicle is traveling.

V.B.5.b. Navigation sensors do not provide state information, and they are not state sensors

Navigation sensors do not provide state information, and they are not state sensors. This is inconsistent with the interpretation of some teams.

Responses to 2004 GCE standard questions revealed some teams included interpretation of navigation data in the state sensing sections, and vice versa. For some teams, this was due to the use of a COTS IMU or INS which provided navigation data such as heading, speed, roll, pitch, and yaw, and for others because their sensor integration solution fused a combination of inputs from navigation sensors such as compasses, gyroscopes, and odometers into a custom INS developed by the team. For example:

- Team 2004-02

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-02 stated: "[The challenge vehicle] will use the American GNC Coremicro Land Navigator (LN) AHRS/DGPS/INS system to determine the geolocation of [the challenge vehicle]. Heading, roll, and pitch will be introduced into [the challenge vehicle's] computer systems through the Coremicro's serial port (RS232) interface to the servers." ([9], p. 9).

- Team 2004-08

In a section titled "State Sensing", Team 2004-08 stated: "The truck's speed is sensed by POS LV." ([76], p. 5). This is a reference to the Applanix POS LV, which is a geolocation sensor not specifically referred to in the Team 2004-08 technical paper "Localization" section. The POS LV is referred to as a "specific device" in the "Processing" section of their technical paper, which provides input into the team's sensor integration solution: "The computer, which will be used for high level route planning, will use GPS and INS inputs. The device being used contains both GPS and INS internally. It will run off of the INS with updates to the current location using the GPS when available. The specific device is model number POS LV built by Applanix Corporation." ([76], p. 3).

- Team 2004-09

In a section titled "External Sensors", Team 2004-09 stated: "The vehicle state includes engine speed, wheel rotation speed, ground speed, current direction and current steering wheel position. In addition, sensors will provide vehicle attitude with respect to the horizon and 3-axis acceleration. The EMC AEVIT system interfaces with the vehicle control module providing some of these parameters. Additional sensors will be identified or designed to provide the rest." ([47], p. 7).

- Team 2004-10

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-10 stated: "Vehicle state is sensed via optical encoders, potentiometers, rotational variable differential transformers (RVDT), current and voltage sensors. Vehicle state is reported by GPS (latitude, longitude, and altitude), vehicle Pose (roll, pitch, yaw), and vehicle velocity. Onboard software calculates vehicle's speed and acceleration." ([77], p. 4).

V.B.5.c. Estimation of quantity of navigation sensors

Where a team reported insufficient technical detail to determine the quantity of navigation sensors in use by the team, the author estimated the quantity as follows:

- one heading sensor
- one accelerometer
- one wheel rotational position sensor per wheel or axle, as described by the team

V.B.6. Corrections and standardization

In general, corrections were made to manufacturer names and model numbers reported by the teams where the author was able to determine they were in error, and to standardize the use of acronyms. Corrections have been noted throughout the text. These corrections are reflected in Tables XXIV, XXV, XXVI, XXVII, XXVIII, and XXIX. Table XXXV provides a list of acronyms used herein.

V.B.7. Elimination of state sensors from total cost

After a preliminary analysis, it was evident that team technical papers reported the least identifying information for state sensors. See Table XXIV. Available cost information indicated that many state sensors are low-cost. In general, environment and navigation sensors are much more expensive. As a result, the author concluded it may be possible to produce a reliable estimate of the total cost of the sensor technology in use by each team using the cost of environment and navigation sensors only.

V.B.8. Known, unknown, and estimated sensors

In the paragraphs which follow (see paragraphs V.C. and V.D.), the author uses the words "known", "unknown", and "estimated" to classify sensors described by 2004 and 2005 technical papers. In general, a sensor was considered "known" if the author was able to identify the quantity, manufacturer, and model number of the sensor in use by review of published records (see Chapter XVI.). If either the quantity, manufacturer, or model number could not be determined by review of published records, the author concluded the sensor was "unknown", and the specific reason the author was unable to determine the quantity, manufacturer, or model number was reported.

Because they do not contribute additional cost to procure, all OEM sensors (i.e., sensors which were part of the challenge vehicle) were considered known.

Teams which participated in the 2004 QID and GCE did not generally publish their results following the 2004 GCE, and review of published records for teams which participated in the 2005 GCE indicated that there was a significant difference between the configuration of the challenge vehicle described by some team technical papers prior to the 2005 GCE and the configuration described by published records after the 2005 GCE. Sixteen teams which participated in the 2005 GCE published their results via the Journal of Field Robotics; twelve of which also participated in the 2004 GCE. As a result, the published record for the 2005 GCE is more complete. Where necessary, the author has attempted to err on the side of "most conservative", based on a review of the published record.

V.C. Resolution of discrepancies in the published record

In the course of performing the review, the author was required to resolve many discrepancies in the published record to identify the quantity, manufacturer, and model number for environment and navigation sensors in use by the teams. The paragraphs which follow support that resolution, as noted, where published records conflict or are self-contradictory, and provide justification for the information presented by Tables XXIV, XXV, XXVI, XXVII, XXVIII, and XXIX. The author acknowledges the possibility that additional information may be available from published records which the author was unable to review while documenting the results of this analysis.

Where the words "in use by the team", or words to that effect, are used herein, they mean in use by the team during the 2004 QID, 2004 GCE, or 2005 GCE if the team participated in those events. The words "during the 2005 GCE", or words to that effect, are used herein if necessary to highlight a difference between the technical paper and final written report.

V.C.1. Team 2004-01

- The Team 2004-01 website reported limited additional identifying information for the sensors in use by the team.
- Team 2004-01 passed on their turn on the first day of the 2004 QID ([78]), and terminated within the starting chute area on the last day of the 2004 QID ([79]).
- Team 2004-01 was not selected to participate in the 2004 GCE ([80]).

V.C.1.a. <u>Unknown other sensors</u>

Team 2004-01 stated: "Other sensors monitor engine RPM, intake manifold pressure, brake settings, brake hydraulic pressure, fuel level, water temperature, individual wheel speed, transmission gear position, throttle position, and steering angle[.]" ([8], p. 4), but reported no additional identifying information for the "other sensors" in use by the team. The author estimated the quantity of state and navigation sensors in use by Team 2004-01 in accordance with paragraphs V.B.3.a. and V.B.5.c., but otherwise considers these sensors unknown.

V.C.1.b. Unknown cameras

Team 2004-01 stated: “Two cameras will be used. For color analysis a Fire wire digital camera with 1280 x 980 resolution will be used. For texture analysis a monochrome camera, sensitive to near IR will be used.” ([8], p. 3), but reported no additional identifying information. The author concluded one camera of each type was in use by Team 2004-01, but otherwise considers these sensors unknown.

V.C.1.c. Unknown SICK LIDAR sensors

Team 2004-01 alternately stated: “Two Sick LMS211 LIDAR units will scan a 100-degree field of view in front of the vehicle providing terrain contour data.” ([8], p. 3) and “The laser scanner is a Sick LMS220.” ([8], p. 9), but reported no additional identifying information.

Photographs of the challenge vehicle hosted by Team 2004-01 via the Team 2004-01 website ([81]) revealed two LIDAR units were in use by the team. Both the SICK LMS 211-30106 and 211-30206 have a scanning angle of 100 degrees ([74]); the SICK LMS 220-30106 has a scanning angle of 180 degrees ([73]).

The author concluded either two SICK LMS 211-30106 or two SICK LMS 211-30206 LIDAR sensors were in use by Team 2004-01, in lieu of one SICK LMS 220, and considers the manufacturer of these sensors known, but model number unknown.

V.C.1.d. Unknown ultrasonic sensors

Team 2004-01 stated: “Close range ultrasonic sensors will be mounted around the perimeter of the vehicle, at wheel level, to provide 360-degree hazard detection at crawl speeds when other sensors are inoperative or unable to see.” ([8], pp. 3 - 4), but reported no additional identifying information. The author considers these sensors unknown.

V.C.1.e. Unknown gyroscopes and unknown accelerometers

Team 2004-01 stated: “The vehicle uses 3 axis rate gyros and 3 axis accelerometers to determine attitude and speed changes.” ([8], p. 4), but reported no additional identifying information. The author considers the gyroscopes and accelerometers in use by Team 2004-01 unknown.

V.C.1.f. Unknown compass

Team 2004-01 stated: “The odometry system uses odometry, inertial, GPS, and digital compass data to determine its location.” ([8], p. 4), but reported no additional identifying information. Throughout the team technical paper ([8]), Team 2004-01 variously referred to a “compass”, “digital compass”, or “electronic compass”. The author concluded one compass was in use by Team 2004-01, but otherwise considers this sensor unknown.

V.C.1.g. Trimble AgGPS 114

Team 2004-01 stated: “The DGPS receiver is a Trimble AGPS 114.” ([8], p. 4). Trimble did not manufacture a DGPS receiver with model number “AGPS 114”; the corresponding model number was “AgGPS 114” ([82]). The author concluded “AGPS 114” was an error, that one Trimble AgGPS 114 was in use by Team 2004-01, and considers this sensor known.

V.C.2. Team 2004-02

- Team 2004-02 participated in the 2005 GCE as Team 2005-01. See paragraph V.C.26.
- The Team 2004-02 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-02 website reported no additional identifying information for the sensors in use by the team.
- Team 2004-02 partially completed the 2004 QID course on the second and third day of the 2004 QID ([84] and [85]), and completed the 2004 QID course on the last day of the 2004 QID ([79]).
- Team 2004-02 was selected to participate in the 2004 GCE ([80]).

V.C.2.a. Unknown state sensors

In response to 2004 SQ 1.c.2 (see Table XXII), Team 2004-02 stated: “Some of the above-mentioned sensors are used to sense the state of [the challenge vehicle].” ([9], p. 7). This appears to be a reference to Figure 2 (“System hardware configuration”) of the team technical paper ([9], p. 6), which lists several environment and navigation sensors.

Team 2004-02 did not report sufficient technical detail to determine what environment and navigation sensors were in use by the team to sense the state of the challenge vehicle or what state information they provide, and the author does not consider navigation sensors to be state sensors (see paragraph V.B.5.b.). As a result, the author considers these sensors unknown.

V.C.2.b. OBD-II

Team 2004-02 stated: “ODB-II Information: Utilizing the ability for a 1994 Jeep Grand Cherokee to attempt to deliver vehicle data to a COTS monitor has proven to be less than useful information. The team continues to do cost analysis of the race use of this information.” ([9], p. 12).

The author concluded Team 2004-02 was referring to information provided by the OEM On-Board Diagnostic (OBD) system, commonly referred to as OBD-II, in lieu of "ODB-II". The author considers all OEM sensors known (see paragraph V.B.8.). However, Team 2004-02 did not report sufficient technical detail to determine what "vehicle data" OBD-II provided.

V.C.2.c. Team 2004-02 MetalSense B1 touch sensors

In response to 2004 SQ 1.e.2 (see Table XXII), Team 2004-02 stated: "Three touch sensors will be mounted in the front of the vehicle." ([9], p. 9). However, via Table 1 ("Sensor Descriptions") of the team technical paper ([9], p. 8) Team 2004-02 reported that four "MetalSense B1" touch sensors were mounted on the challenge vehicle. Neither the Team 2005-01 technical paper ([10]) nor the team website ([86]) reported touch sensors were in use by the team, or reported additional, clarifying information. The author concluded four Team 2004-02 MetalSense B1 touch sensors were in use by Team 2004-02, and considers these sensors known; the difference in cost between three and four touch sensors is not expected to be significant.

V.C.2.d. Point Grey Bumblebee cameras

Team 2004-02 alternately stated three and four Point Grey Bumblebee cameras were in use by the team. In response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-02 reported three Bumblebee cameras were in use by the team via an un-numbered table of computer hardware ([9], p. 5). Via Table 1 ("Sensor Descriptions") of the team technical paper ([9], p. 8), Team 2004-02 reported four Bumblebee cameras were in use by the team.

Via Table 1 ("Computing Hardware") and Figure 4 ("Sensing & Stopping Distances") of the Team 2005-01 technical paper ([10], pp. 4 and 9), Team 2005-01 reported five Bumblebee cameras were in use by the team. Via the team website, Team 2005-01 stated: "[The challenge vehicle] uses Bumblebee stereo vision cameras for obstacle detection." ([86]), but reported no additional identifying information. The author concluded a different quantity of Bumblebee cameras were in use by Team 2005-01 than were in use by Team 2004-02.

The author estimated the quantity of Bumblebee cameras in use by Team 2004-02 to be three, but otherwise considers these sensors known.

V.C.2.e. FLIR A20M and unknown AVT camera

Via Table 1 ("Sensor Descriptions") of the team technical paper ([9], p. 8), Team 2004-02 reported one FLIR A20M and one "Allied Vision Systems Dolphin" color camera were in use by the team. The use of these descriptions is consistent throughout the text of the technical proposal, with the exception of Figure 2. Figure 2 ("System hardware configuration") of the team technical paper ([9], p. 6) reported two "EMX

Raytheon Thermal Cameras" were in use by the team; Figure 2 did not report either the FLIR A20M or color camera were in use by the team. The author concluded the EMX Raytheon Thermal Cameras were not in use by Team 2004-02, and considers the FLIR A20M in use by the team known.

The author was unable to locate a manufacturer named "Allied Vision Systems" with a "Dolphin" color camera product, but a manufacturer named "Allied Vision Technologies GmbH" exists. AVT had a product line named "Dolphin", which has since been discontinued ([87]). The Dolphin product line had multiple model numbers with different capabilities: "F-145B/C" and "F-201B/C" ([88]). These model numbers now correspond to the "Pike" and "Marlin" product lines, respectively.

The author concluded one AVT camera was in use by Team 2004-02, but considers the model number of this sensor unknown.

V.C.2.f. <u>Epsilon Lambda ELSC71-1A</u>

Team 2004-02 stated: "One other terrain sensor [Team 2004-02] is using is a 77 GHz three dimensional tracking obstacle detection RADAR. This sensor is built by Epsilon Lambda Electronics (Model #ELSC71-1B)..." ([9], p. 8).

No RADAR with model number "ELSC71-1B" exists, and the author was otherwise unable to locate manufacturer product literature for the Epsilon Lambda ELSC71-1B ([89]). However, the capabilities reported by Team 2004-02 for the ELSC71-1B do not differ significantly from the capabilities of the Epsilon Lambda ELSC71-1A, and the description reported by Team 2004-02 is virtually identical to the manufacturer's description of the ELSC71-1A. Review of 2004 technical papers revealed the ELSC71-1B was not in use by any other team, but the ELSC71-1A was in use by three other teams.

The author concluded "ELSC71-1B" was an error and that one Epsilon Lambda ELSC71-1A was in use by Team 2004-02, and considers this sensor known.

V.C.2.g. <u>AGNC Land Navigator</u>

Via Table 1 ("Sensor Descriptions") of the team technical paper ([9], p. 8), Team 2004-02 reported an "American GNC coremicro UNUCN1" was in use by the team. Throughout the text of the technical proposal, Team 2004-02 referred to the "American GNC Coremicro Land Navigator". Figure 2 ("System hardware configuration") of the Team 2004-02 technical paper ([9], p. 6) reported an "AGNC CoreMicro GPS/INS" was in use by the team, but reported no additional identifying information. An alternate INS was in use by Team 2005-01 during the 2005 GCE.

AGNC does not manufacture a product with a model number "UNUCN1" ([90]). AGNC manufactures several "Universal Navigation and Control Units" (UNCU), and model number UNCUN1 includes a GPS chipset. AGNC stated: "Based on AGNC's coremicro IMU and proprietary GPS/IMU integration technology, the Land Navigator is designed for land navigation." ([90]). Information reported by manufacturer product literature was of limited utility. For example, the author was unable to determine if the AGNC Land Navigator requires the use of an external GPS or DGPS antenna. Team 2004-02 did not report an external GPS or DGPS antenna was in use by the team.

AGNC reported the current AGNC "Palm Navigator" product series is a "wrapper" around the UNCUN1, which itself is a wrapper around a UNCU, which is a wrapper around the coremicro IMU ([91]). The author concluded the AGNC Land Navigator was also a wrapper around the UNCUN1 and that the AGNC Land Navigator was in use by Team 2004-02, and considers this sensor known.

V.C.3. Team 2004-03

- The Team 2004-03 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- Various sources direct the public to three different domains for Team 2004-03 information: www.roboticinfantry.com ([92], p. 1), www.insidiarobot.com ([92], p. 3), and www.ghostriderrobot.com ([17]). Only the latter is currently active, although the others may have been valid at the time of the 2004 QID and GCE. Neither of the other two domains are currently accessible from the Internet, although the domain www.roboticinfantry.com was used to host the Team 2004-03 website through 2007 ([93]). The current Team 2004-03 website reported no additional identifying information for the sensors in use by the team.
- Team 2004-03 passed on their turn on the second day of the 2004 QID ([84]), and terminated their attempts on the third day of the 2004 QID ([85]), but did not withdraw.
- Team 2004-03 was selected to participate in the 2004 GCE ([80]). On the day of the 2004 GCE, Team 2004-03 officially withdrew prior to start [30].

V.C.3.a. Unknown AOEs and unknown potentiometer

Team 2004-03 stated: "Steering position is determined by an Absolute Optical Encoder (AOE) and a potentiometer. Wheel rotational positions are determined by AOEs." ([92], pp. 5 - 6), but reported no additional identifying information. The author estimated the quantity of AOEs in use by Team 2004-03 in accordance with paragraphs V.B.3.a. and V.B.5.c., but otherwise considers these sensors unknown.

V.C.3.b. Unknown Cognex cameras and unknown other camera

Throughout the team technical paper, Team 2004-03 referred to an indeterminate quantity of “cameras” ([92], pp. 4, 5, and 7). Via the team website, Team 2004-03 stated: “The are two types of cameras used onboard. First, a pair of high resolution 1600x1200 ethernet cameras manufactured by Cognex used for creating realtime 3D scene of the obstacles in front of the vehicle. Second a single CCD, high speed (40 Hz), color camera is used for road detection.” ([94]). Team 2004-03 reported no additional identifying information for the cameras in use by the team.

The author concluded two Cognex cameras were in use by Team 2004-03, but considers the model number of these sensors unknown; and concluded one color camera was in use by Team 2004-03, but otherwise considers this sensor unknown.

V.C.3.c. Unknown DGPS receiver

Throughout the team technical paper ([92]) Team 2004-03 referred to “GPS” and “DGPS”, but reported no additional identifying information for the DGPS receiver in use by the team. Via the team website, Team 2004-03 stated: “Beyond DGPS, we are using only high speed camera as sensor input.” ([94]), but reported no additional identifying information for the DGPS receiver in use by the team. The author concluded one DGPS receiver was in use by Team 2004-03, but otherwise considers this sensor unknown.

V.C.3.d. Unknown Crossbow gyroscopes

Team 2004-03 stated: “The attitude of the vehicle is determined by two Crossbow MEMS gyro [*sic*] (VG 400, AHRS400).” ([92], p. 5). Crossbow reported “VG400” and “AHRS400” were function and series designators ([95]) for products which have since been discontinued, and neither VG400 nor AHRS400 is a complete model number ([96]). The author considers the quantity and manufacturer of these sensors known, but model numbers unknown.

V.C.3.e. Unknown Crossbow IMU

Team 2004-03 stated: “Crossbow Inertial Measurement Unit (IMU) integrated Kalman filter and angular bias elimination to provide direct roll, pitch and heading angles.” ([92], p. 4), but reported no additional identifying information. Crossbow manufactures several models of IMU ([95]). Crossbow reported at least five products with different function and series designators have an integrated Kalman filter and either integrated GPS or GPS as an option ([96]): NAV420, VG440, AHRS440, NAV440, and AHRS500. Although Crossbow has since discontinued products which were available at the time of the 2004 QID and GCE, the author considers it likely that multiple products with the capabilities reported by Team 2004-03 were available at the time of the 2004 QID and GCE, and concluded one Crossbow IMU was in use by Team 2004-03, but considers the model number of this sensor unknown.

V.C.4. Team 2004-04

- Team 2004-04 participated in the 2005 GCE as Team 2005-02. See paragraph V.C.27.
- The Team 2004-04 website was updated prior to the 2005 GCE and reflects the challenge vehicle configuration during the 2005 GCE.
- Team 2004-04 had an unsuccessful attempt to start due to instrumentation problems on the first day of the 2004 QID ([78]), nearly completed the 2004 QID course on the third day of the 2004 QID ([85]), and partially completed the 2004 QID course on the last day of the 2004 QID ([79]).
- Team 2004-04 was selected to participate in the 2004 GCE ([80]).

Team 2004-04 stated: "[The challenge vehicle perception system] consists of a suite of sensor hardware including a fixed SICK LADER [*sic*], a 3D SICK LADAR, three (3) video cameras, three (3) short range radar units, a long range radar unit, and a Videre Design stereo vision system." ([44], pp. 5 - 6).

Team 2004-04 also stated: "[The challenge vehicle] determines its geolocation by filtering and fusing a combination of sensor data. The sensors used include a NavCom Starfire 2050 GPS, a Garmin WAAS GPS, a quadrature shaft encoder, and a Smiths Industries Northfinding Module, an inertial/magnetic orientation sensor." ([44], pp. 9 - 10).

V.C.4.a. <u>Honeywell ML500PS1PC pressure transducer</u>

Team 2004-04 alternately stated: "Honeywell pressure transducers read the brake pressure..." ([44], p. 9), and "The brake system is also equipped with a Honeywell pressure transducer, ML500PS1PC..." ([44], p. 1). Although the author does not consider the cost of a pressure transducer to be significant, Team 2004-04 reported that both one and more than one pressure transducer were in use by the team. The author estimated one Honeywell ML500PS1PC was in use by Team 2004-04 in accordance with paragraph V.B.3.a., but otherwise considers this sensor known.

V.C.4.b. <u>Unknown Videre Design stereo camera pair</u>

Videre Design manufactures multiple "Stereo System Products", each with a unique model number and capabilities, some of which have been discontinued ([97]). The author concluded one Videre Design stereo camera pair was in use by Team 2004-04, but considers the model number of this sensor unknown.

V.C.4.c. Unknown other cameras

In addition to the stereo camera pair, Team 2004-04 alternately referred to three "cameras", "video cameras", "additional cameras", and "stationary cameras" throughout the team technical paper ([44]), but reported no additional identifying information for the cameras in use by the team.

The author considers it likely Team 2004-04 was referring to the same three cameras, and concluded three other cameras were in use by Team 2004-04, but otherwise considers these sensors unknown.

V.C.4.d. Unknown PRECO RADAR and unknown long-range RADAR

Team 2004-04 alternately stated: "Due to their limited 26-foot range, the three short-range radar units will act collectively as a virtual bumper switch providing a last line of defense to prevent the [the challenge vehicle] from colliding with obstacles in its path." and "The long-range radar unit provides additional information to the arbiter on free or blocked space. The PRECO Preview long range RADAR system provides range data at distances up to 100 feet." ([44], p. 6).

Team 2004-04 did not report the model number for either the "short-range" RADAR or Preco PreView RADAR in use by the team ([44]). At least three different product families exist: "Standard PreView" (model numbers SPV 2010, SPV 2015, and SPV 2020 with 10-, 15-, and 20-ft "detection range", respectively) ([98]), "Xtreme PreView" (model numbers XPV 4020, XPV 4026, and XPV 4032 with 20-, 26-, and 32-ft "coverage", respectively) ([99]), and "High Resolution PreView" (model numbers HRPV 3010, HRPV 3015, and HRPV 3020 with 10-, 15, and 20-ft "coverage", respectively) ([100]). No Preco PreView unit has a range of 100 ft, and the use of three matched sensors is consistent with automotive anti-collision RADAR, or short-range RADAR, not long-range RADAR.

The author concluded three Preco RADAR sensors were in use by Team 2004-04, but considers the model number of these sensors unknown, although the "limited 26-foot range" of the "short-range radar units" described by Team 2004-04 matches the 26-ft coverage of Preco PreView XPV 4026.

The author concluded one long-range RADAR sensor was in use by Team 2004-04, but otherwise considers this sensor unknown.

V.C.4.e. Unknown Garmin GPS receiver

Team 2004-04 stated: "[The challenge vehicle] determines its geolocation by filtering and fusing a combination of sensor data. The sensors used include ... a Garmin WAAS GPS..." ([44], p. 9), but reported no additional identifying information.

Garmin manufactures dozens of GPS receivers with unique model numbers and capabilities ([101]). The author concluded one Garmin GPS receiver was in use by Team 2004-04, but considers the model number of this sensor unknown.

V.C.4.f. Unknown NavCom GPS receiver

Team 2004-04 stated: "[The challenge vehicle] determines its geolocation by filtering and fusing a combination of sensor data. The sensors used include a NavCom Starfire 2050 GPS..." ([44], p. 9), but reported no additional identifying information.

The NavCom StarFire SF-2050 GPS receiver and StarFire network were in use by 12 of 40 NQE semifinalists ([102]) and 6 of 23 GCE finalists ([103]). At least two different model numbers of NavCom StarFire GPS receiver existed at the time of the 2004 QID and GCE, and they targeted different markets: "The SF-2050G is designed for backpack GIS and mapping applications while the SF-2050M is ideal for vehicle mounting to suit a wide variety of machine guidance and control applications." ([104]). NavCom launched both the SF-2050G and SF-2050M receivers in 2002 ([105]). The author concluded one NavCom GPS receiver was in use by Team 2004-04, but considers the model number of this sensor unknown.

V.C.4.g. Unknown quadrature shaft encoder

Team 2004-04 stated: "[The challenge vehicle] determines its geolocation by filtering and fusing a combination of sensor data. The sensors used include ... a quadrature shaft encoder..." ([44], p. 9), but reported no additional identifying information. The author concluded one quadrature shaft encoder was in use by Team 2004-04, but otherwise considers this sensor unknown.

V.C.4.h. Smiths Aerospace North Finding Module

Team 2004-04 stated: "[The challenge vehicle] determines its geolocation by filtering and fusing a combination of sensor data. The sensors used include a ... Smiths Industries Northfinding Module..." ([44], p. 9), but reported no additional identifying information. The author was unable to locate a manufacturer named "Smiths Industries", but a manufacturer named "Smiths Aerospace" existed at the time of the 2004 QID and GCE, and has since been acquired by GE. The author concluded one Smiths Aerospace North Finding Module was in use by Team 2004-04, and considers this sensor known.

V.C.5. Team 2004-05

- The Team 2004-05 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-05 website was no longer available.

- Team 2004-05 was delayed awaiting parts for the challenge vehicle until the third day of the 2004 QID ([85]), and officially withdrew on the last day of the 2004 QID ([79]).

- Team 2004-05 was not selected to participate in the 2004 GCE.

V.C.5.a. Unknown state sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-05 reported a list of state sensors in use by the team, including the quantity of each sensor in use, but reported no additional identifying information ([45], p. 5). The author considers the quantity of these sensors known, but the manufacturers and model numbers unknown.

Team 2004-05 stated: "Certain other sensors are present in self regulating systems (i.e [*sic*] alternator, ignition, gps)" ([45], p. 5), but reported no additional identifying information for these sensors. The author considers these sensors unknown.

V.C.5.b. Unknown SONAR sensors

Team 2004-05 stated: "Sonar array: 3 front, 4 per side, 3 rear. 40 kHz. Range 1 -15 ft, cone angle 15 degrees. Purpose: low speed collision avoidance." ([45], p. 4), but reported no additional identifying information. The author concluded fourteen SONAR sensors were in use by Team 2004-05, but otherwise considers these sensors unknown.

V.C.5.c. Unknown depth finders

Team 2004-05 stated: "Depth finders: (2) 200 kHz sonic sensor) [*sic*] to detect water depth in front of each wheel." ([45], p. 4), but reported no additional identifying information. The author concluded two depth finders were in use by Team 2004-05, but otherwise considers these sensors unknown.

V.C.5.d. Unknown conductivity sensors

Team 2004-05 stated: "Conductivity sensors: (2) for water presence sensing." ([45], p. 4), but reported no additional identifying information. The author concluded two conductivity sensors were in use by Team 2004-05, but otherwise considers these sensors unknown.

V.C.5.e. Unknown tactile sensors

Team 2004-05 stated: "Tactile sensors: 3 front, 2 per side, spring loaded, front sensors with single micro switch, side sensor with dual position micro switches. Purpose: front sensors back up for sonar in close range maneuvering. Side sensors to detect and track close range distance to objects like barbed wire and chain link fencing." ([45], p. 4), but reported no additional identifying information. The author concluded seven tactile sensors were in use by Team 2004-05, but otherwise considers these sensors unknown.

V.C.5.f. Unknown SICK LIDAR sensors and trinocular camera system

Team 2004-05 referred to both "Main Ladar unit" and "Side Ladar units" in use by the team ([45], p. 4). Via an addendum, Team 2004-05 stated: "Ladar units: 2 SICK LMS 291." ([45], p. 12). Pages 1 through 11 pre-date pages 12 and 13 of the addendum. However, it is unclear if the addendum referred to either the "Main Ladar unit" or "Side Ladar units" previously described ([45], p. 4), or if the "2 SICK LMS 291" LIDAR sensors were intended to replace both. Paragraph 2.a.4 of the team technical paper ([45], p. 7) referred to a "Ladar system from Laseroptronix", but it is unclear if this unit was intended to be the main LIDAR unit or if it supplements the SICK LIDAR sensors referred to in the addendum.

In response to 2004 SQ 2.a.1 (see Table XXII), Team 2004-05 referred to a "trinocular camera system", but reported no additional identifying information ([45], p. 6). This is the only reference to a trinocular camera system made by Team 2004-05.

The "Computational System Block Diagram" ([45], p. 11) is of little help resolving these difficulties because it referred to sensors by type only: "Ladar", "Radar", "Sonar", etc. However, because neither the Laseroptronix LIDAR sensor nor trinocular camera system were referred to in response to 2004 SQ 1.e (see Table XXII), the author concluded the two SICK LIDAR sensors replaced both the "Main Ladar unit" and "Side Ladar units" and considers the quantity and manufacturer of these sensors known, but model number unknown, and concluded no trinocular camera system was in use by Team 2004-05.

V.C.5.g. Unknown Eaton RADAR

Team 2004-05 alternately stated: "Radar unit: (Epsilon Lambda Electronics) Selectable 40/16 degrees azimuth field of view, 2 degrees resolution, range 400 ft. Purpose: detect large obstacles far away, detect and track moving large objects (other vehicles, trains), back up for main Ladar unit." ([45], p. 4); and via their addendum: "Radar unit: Eaton Vorad VBOX 83001-001 Field of view 12 degrees. Range 300 ft. 2 degrees resolution." ([45], p. 12).

The "VBOX 83001-001" referred to by Team 2004-05 was part of the "Eaton VORAD Radar Development Toolkit" designed to interface with the Eaton VORAD RADAR antenna ([106]): Team 2004-20 reported their "Eaton VORAD anti-collision radar system" was "a standard Eaton VORAD unit ... interfaced to computers using an Eaton VBOX." ([107], p. 5).

The author concluded the Epsilon Lambda RADAR was not in use by Team 2004-05, and that one Eaton RADAR was in use by Team 2004-05, but considers the model number of this sensor unknown.

V.C.5.h. Point Grey Bumblebee stereo camera pair

Team 2004-05 stated: "Stereo camera: (Point Grey Bumblebee)" ([45], p. 4), but reported no additional identifying information.

Point Grey had multiple product lines: "Bumblebee", "Dragonfly", "Flea", etc. ([108]). Each product line had multiple model numbers. For example, the two current model numbers for the Bumblebee product line are "Bumblebee 2" and "Bumblebee XB3" ([109]).

The Point Grey website requires a login to download technical manuals for their products. The author does not consider access-controlled manufacturer product literature to be part of the published record. See Chapter XVI. Although the author was unable to determine what model numbers were available at the time of the 2004 and 2005 GCE, the Bumblebee 2 was introduced August 23, 2006 ([110]). The author concluded "Bumblebee" was the model number of this sensor during the 2004 and 2005 GCE, and considers this sensor known.

V.C.5.i. Unknown navigation sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-05 reported a list of navigation sensors in use by the team, including the quantity of each sensor in use, but reported no additional identifying information ([45], p. 5). The author considers the quantity of these sensors known, but otherwise considers these sensors unknown.

V.C.5.j. Unknown gyroscopes

Team 2004-05 stated: "One gyro determines yaw rate and in combination with the front wheel speed sensors are [*sic*] used to correct steering maneuvers as well as for odometric localization in areas of poor gps reception." and "Two gyros are used to measure rate of change in vehicle tilt during pitch and roll, inputs also used for stability control." ([45], p. 5), but reported no additional identifying information.

The author concluded two gyroscopes were in use by Team 2004-05: the first to "correct steering maneuvers as well as for odometric localization in areas of poor gps reception" and to "measure rate of change in vehicle tilt during pitch and roll"; and a second to "measure rate of change in vehicle tilt during pitch and roll", but otherwise considers these sensors unknown.

V.C.5.k. CSI Wireless Vector, CSI Wireless DGPS MAX, and unknown DGPS receivers

Team 2004-05 stated: "The primary method of geolocation used during the mission is a system of multiple Differential GPS receivers, including a Real-Time Kinematic receiver (CSI Vector) that is used for heading determination at zero velocity." ([45], p. 5). The CSI Wireless Vector is a DGPS receiver which uses multiple antennas to function as a compass as well as provide position data ([111] and [112]). In response to 2004 SQ 2.g.1 (see Table XXII), via their addendum, Team 2004-05 stated: "A CSI DGPS MAX sensor has been added..." ([45], p. 12). The CSI Wireless DGPS MAX is also a DGPS receiver ([113]). However, it is unclear if the two DGPS receivers were the "multiple Differential GPS receivers" in use by Team 2004-05.

The author concluded one CSI Wireless Vector and one CSI Wireless DGPS MAX were in use by Team 2004-05, and that additional DGPS receivers may have been in use by Team 2004-05, but considers these sensors unknown.

V.C.6. Team 2004-06

- Team 2004-06 participated in the 2005 GCE as Team 2005-03. See paragraph V.C.28.

- The Team 2004-06 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).

- The Team 2004-06 website was no longer available.

- Team 2004-06 had an unsuccessful attempt to start due to instrumentation problems on the first day of the 2004 QID ([78]), partially completed the 2004 QID course on the third day of the 2004 QID ([85]), and completed the 2004 QID course on the last day of the 2004 QID ([79]).

- Team 2004-06 was selected to participate in the 2004 GCE.

V.C.6.a. Team 2004-06 stereo camera pair

In response to 2004 SQ 1.e (see Table XXII), Team 2004-06 stated: "Please refer to Appendix A. No additional sensors will be used." ([114], p. 2). Appendix A of the Team 2004-06 technical paper ([114]) describes a proprietary stereo camera pair similar to commercially-available stereo camera pairs in use by other teams participating in the 2004 GCE. Team 2004-06 reported very little additional identifying information for the components comprising their proprietary stereo camera pair, and no additional identifying information for the cameras in use by the team.

The author considers the proprietary stereo camera pair in use by Team 2004-06 known, but concluded the cost of this sensor cannot be independently determined.

V.C.6.b. Honeywell HMC1002

Team 2004-06 alternately stated: “two Honeywell dual axis compass sensors” ([114], p. 1) were in use by the team and “The compass is a Honeywell HMC-1002” ([114], p. 2). The author estimated one Honeywell HMC1002 two-axis magnetic sensor was in use by Team 2004-06 as a compass, but otherwise considers this sensor known.

V.C.6.c. NavCom SF-2050G

Team 2004-06 stated: “The GPS unit is a Navcom 2050G unit.” ([114], p. 2). The author concluded Team 2004-06 was referring to the NavCom SF-2050G, and considers this sensor known.

V.C.7. Team 2004-07

- Team 2004-07 participated in the 2005 GCE as Team 2005-05. See paragraph V.C.30.
- The Team 2004-07 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-07 website reported limited additional identifying information for the sensors in use by the team.
- Team 2004-07 passed on their turn on the first day of the 2004 QID ([78]), and partially completed the 2004 QID course on the second, third, and last day of the 2004 QID ([84], [85], and [79]).
- Team 2004-07 was selected to participate in the 2004 GCE ([80]).

V.C.7.a. Unknown potentiometer

In response to 2004 SQ 1.a.3 (see Table XXII), Team 2004-07 stated: “A potentiometer measures the absolute servomotor position.” ([46], p. 2); and in response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-07 stated: “A potentiometer senses the position of the steering column.” ([46], p. 7). Team 2004-07 reported no additional identifying information for the potentiometer in use by the team. The author concluded one potentiometer was in use by Team 2004-07, but otherwise considers this sensor unknown.

V.C.7.b. Unknown ground whisker

In response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-07 stated: “One Ground Whisker. This passive sensor consists of a whisker which trails (or bounces) along the ground. The resulting vibration is picked up by a microphone to evaluate ground roughness." ([46], p. 7), but reported no additional identifying information. The author concluded one ground whisker was in use by Team 2004-07, but otherwise considers this sensor unknown.

V.C.7.c. Unknown SICK LIDAR sensor

In response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-07 stated: "We are evaluating an active SICK ladar mounted at the front of the truck. This ladar system has at least 10 meters range and 180-degree arc of sweep. It is intended to supplement the radar system in detecting positive obstacles. It is not certain yet whether this system will be available for use in the race, so in evaluating this technical paper we would like you to allow for the possibility that the ladar will not be present." ([46], p. 7), but reported no additional identifying information.

Photographs hosted by Team 2004-07 via the Team 2004-07 website revealed one SICK LIDAR sensor was in use by the team ([115]), but the Team 2004-07 website reported no additional identifying information. The author concluded one SICK LIDAR sensor was in use by Team 2004-07, but considers the model number of this sensor unknown.

V.C.7.d. FLIR Omega

In response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-07 stated one "Indigo Omega Infrared Camera" ([46], p. 7) was in use by the team. Indigo and FLIR completed a merger January 6, 2004 ([116]). The "Product Name" for this camera was "Micron/A10/Omega" ([117]). The author concluded the manufacturer of this sensor was FLIR, and considers this sensor known.

V.C.7.e. Unknown Rotomotion IMU and unknown Rotomotion magnetometer

In response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-07 stated: "Changes in the vehicle's angular orientation will be measured by a Rotomotion 6-degree-of-freedom inertial measurement unit and a Rotomotion 3-axis magnetometer." ([46], p. 7), but reported no additional identifying information. The author concluded one Rotomotion IMU and one Rotomotion magnetometer were in use by Team 2004-07, but considers the model numbers of these sensors unknown.

V.C.7.f. Unknown Hall Effect sensor

Team 2004-07 stated: "A magnetic encoder using a Hall Effect sensor measures rotation of the rear axle." ([46], p. 7), but reported no additional identifying information. The author concluded one Hall Effect sensor was in use by Team 2004-07, but otherwise considers this sensor unknown.

V.C.8. Team 2004-08

- Team 2004-08 participated in the 2005 GCE as Team 2005-07. See paragraph V.C.32.

- The Team 2004-08 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).

- The Team 2004-08 website reported no additional identifying information for the sensors in use by the team.

- In a press release published after Team 2005-07 was selected to participate in the 2005 GCE, Team 2005-07 stated: "...last year [Team 2004-08 was] unable to compete due to lack of funding." ([118]). Team 2004-08 did not participate in the 2004 QID or GCE.

V.C.8.a. Unknown optical sensor

Team 2004-08 stated: "An optical sensor is mounted on the sprocket connected to the steering motor. This sensor detects the presence of gear teeth between the emitter and collector to determine the position of the steering wheel. By counting teeth as they pass through the optical sensor we are able to tell how far the steering wheel is turned left or right." ([76], p. 5), but reported no additional identifying information.

The author concluded one optical sensor was in use by Team 2004-08, but otherwise considers this sensor unknown.

V.C.8.b. Unknown ten-turn potentiometers

Team 2004-08 stated: "The position of the braking linear actuator is determined by a ten-turn potentiometer. We will use the data gathered about the position of the brake pedal to control the amount of pressure applied to the brakes. Both actuators automatically disengage when they reach the end of their travel due to built in limit switches." ([76], p. 5). Team 2004-08 also stated: "The accelerator and brake pedals are pulled down by steel cables, which run through tubes in the engine bay where two linear actuators are mounted." ([76], p. 2).

As a result, the author concluded linear actuators were in use by the team to control both the accelerator and brake pedals, and that these are "both actuators" to which the team referred. Although Team 2004-08 did not affirmatively state the position of the accelerator pedal was also determined by a ten-turn potentiometer, the author concluded one ten-turn potentiometer was also in use to determine the position of the accelerator pedal and concluded two ten-turn potentiometers were in use by Team 2004-08, but otherwise considers these sensors unknown.

V.C.8.c. Laseroptronix LDM 800-RS232 laser range finders

Team 2004-08 stated: "Laser range finders will be mounted on the front, back, and sides of the vehicle... The range finders will be model number LDM 800-RS232 from Laseroptronix..." ([76], p. 5), but did not report the number of laser range finders in use by the team. The author concluded four Laseroptronix LDM 800-RS232 laser range finders were in use by Team 2004-08, one each for the front, back, and sides of the vehicle.

V.C.8.d. Unknown Applanix INS

Team 2004-08 stated: "The specific device is model number POS LV built by Applanix Corporation." ([76], p. 3), and reported via an un-numbered table ("GPS Outage Duration") that the model number was "POS LV 320" ([76], p. 6).

Applanix does not currently manufacture a model number "POS LV 320". Applanix manufactures a model number "POS MV 320" for marine applications ([119]), and several model numbers of the POS LV for land navigation (200, 220, 420, and 610) ([120]).

Although the author was unable to locate a reference to the Applanix POS LV 320 on the Applanix website, one of the results of an Internet search using the key words "+applanix +'pos lv' +320" as the search string is a document titled "POS LV", which reported the Applanix POS LV 320 was a model number at the time of the 2004 GCE ([121]). This reference has no revision information, no copyright notice, and is not dated. However, the file attributes indicate it was created April 23, 2004, and last modified December 22, 2005. The author considers April 23, 2004 the date of the reference.

The "IARTK", "PP", and "DGPS" figures given by the team technical paper ([76]) for the "POS LV 320" do not match the "IARTK", "PP", and "DGPS" figures reported by Applanix ([120]) for any current Applanix POS LV model number. The "IARTK", "PP", and "DGPS" figures given by the team technical paper ([76]) for the "POS LV 320" substantially match the "IARTK", "PP", and "DGPS" figures given by the undated reference ([121]) for the Applanix POS LV 320, but are not identical. The author concluded one Applanix INS was in use by Team 2004-08, but considers the model number of this sensor unknown.

V.C.9. Team 2004-09

- The Team 2004-09 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-09 website was no longer available.

- Team 2004-09 partially completed the 2004 QID course before stopping to make mechanical adjustments on the first day of the 2004 QID ([78]), and partially completed the 2004 QID course on the third and last day of the 2004 QID ([85] and [79]).

- Team 2004-09 was selected to participate in the 2004 GCE ([80]).

Team 2004-09 stated: "[The challenge vehicle] will be using a laser range finding system, a video camera, a gyroscope, GPS, and a vibration sensor to determine the location of the path being taken, location of the vehicle, obstacles in the path, and the condition of the road/path surface." ([47], p. 7).

V.C.9.a. Unknown state and navigation sensors

Team 2004-09 stated: "The vehicle state includes engine speed, wheel rotation speed, ground speed, current direction and current steering wheel position. In addition, sensors will provide vehicle attitude with respect to the horizon and 3-axis acceleration. The EMC AEVIT system interfaces with the vehicle control module providing some of these parameters. Additional sensors will be identified or designed to provide the rest." ([47], p. 7), but reported no additional identifying information.

The author estimated the quantity of state and navigation sensors in use by Team 2004-09 in accordance with paragraphs V.B.3.a. and V.B.5.c., but otherwise considers these sensors unknown.

V.C.9.b. Unknown gyroscope

Team 2004-09 reported no additional identifying information for the gyroscope in use by the team. The author concluded one gyroscope was in use by Team 2004-09, but otherwise considers this sensor unknown.

V.C.9.c. Unknown vibration sensor

Team 2004-09 reported no additional identifying information for the vibration sensor in use by the team. The author concluded one vibration sensor was in use by Team 2004-09, but otherwise considers this sensor unknown.

V.C.9.d. Unknown SICK LIDAR sensor

Team 2004-09 stated: "The laser system will be a LMS 211 or 221 device manufactured by SICK, Inc." ([47], p. 7), but reported no additional identifying information. The author concluded one SICK LIDAR sensor was in use by Team 2004-09, but considers the model number of this sensor unknown.

V.C.9.e. Unknown camera

Team 2004-09 stated: “The video camera is a generic, high-resolution color digital camera...” ([47], p. 7), but reported no additional identifying information. The author concluded one camera was in use by Team 2004-09, but otherwise considers this sensor unknown.

V.C.9.f. MiTAC Navman TU60-D120 and MiTAC Ashtech DG16

Team 2004-09 stated: “The GPS units are NAVMAN TU60-D120 12 channel GPS, ASHTECH DG16, and GARMIN GPS16A...” ([47], p. 8). The Navman GPS product line is currently manufactured by MiTAC ([122]). The author concluded one MiTAC Navman TU60-D120 sensor was in use by Team 2004-09, and considers this sensor known. The Ashtech DG16 was a product of Thales Navigation. Through a series of mergers and acquisitions Thales Navigation was ultimately purchased by MiTAC ([123]). The author concluded one MiTAC Ashtech DG16 was in use by Team 2004-09, and considers this sensor known.

V.C.10. Team 2004-10

- Team 2004-10 participated in the 2005 GCE as Team 2005-13. See paragraph V.C.38.
- The Team 2004-10 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-10 website was updated prior to the 2005 GCE and reflects the challenge vehicle configuration during the 2005 GCE.
- Team 2004-10 was one of only a few teams to publish their results following the 2004 GCE.
- Team 2004-10 completed the 2004 QID course on the second and last day of the 2004 QID ([84] and [79]).
- Team 2004-10 was selected to participate in the 2004 GCE ([80]).

V.C.10.a. Unknown state sensors

Team 2004-10 stated: “Vehicle state is sensed via optical encoders, potentiometers, rotational variable differential transformers (RVDT), current and voltage sensors.” ([77], p. 4), but reported no additional identifying information. The author was unable to estimate the quantity of state sensors in accordance with paragraph V.B.3.a. because Team 2004-10 reported no information about the intended use of the sensors, and considers these sensors unknown.

V.C.10.b. Riegl LMS-Q140i and unknown SICK LIDAR sensors

Throughout the team technical paper ([77]), Team 2004-10 referred to “LIDAR”, “LIDAR scanner”, “LIDAR line scanner”, “long range LIDAR line scanner”, and “short range LIDAR line scanner” as sensors in use by the team, but reported no additional identifying information for either long-range or short-range LIDAR sensors in use by the team.

Team 2004-10 later stated: “A Riegl Q140i scanning laser range finder was selected as the primary sensor...” ([39], p. 13) and “Three SICK LMS laser scanners are used to provide short range supplemental sensing.” ([39], p. 14). Team 2004-10 did not report the model number of the SICK LIDAR sensors in use by the team.

The author concluded one Riegl LMS-Q140i was in use by Team 2004-10, and considers this sensor known, and concluded three SICK LIDAR sensors were in use by Team 2004-10, but considers the model number of this sensor unknown.

V.C.10.c. Navtech DS2000

Throughout the team technical paper ([77]), Team 2004-10 referred to “RADAR”, “RADAR scanner”, and “FMCW RADAR scanner” as sensors in use by the team, but reported no additional identifying information.

Team 2004-10 later stated: “To fill the role of complementary sensor, the NavTech DS2000 Continuous Wave Frequency Modulated (CWFM) radar was selected.” ([39], p. 14) and “The RADAR was not integrated with the primary navigation system due to difficulties extracting noise free data.” ([39], p. 14). Team 2004-10 did not refer to the RADAR sensor in use by the team in subsequent pages and throughout the section titled “Navigation Software”, including Figure 11, which is a block diagram showing the Riegl and SICK LIDAR sensors provide input to the navigation software ([39]).

The author considers this sensor known, but concluded the Navtech DS2000 RADAR was not in use by Team 2004-10 during the 2004 GCE.

V.C.10.d. Unknown SAIC stereo camera pair

Throughout the team technical paper ([77]), Team 2004-10 referred to both a “Stereo video camera pair” and “stereovision camera pair” as sensors in use by the team, but reported no additional identifying information.

Team 2004-10 later stated: “To complement the low density, long range stereo vision system, [the challenge vehicle] incorporates a high speed stereo vision system. The stereo system, provided by SAIC...” ([39], p. 14). Although, unlike the RADAR sensor, Team 2004-10 did not affirmatively state that the stereo camera pair was not integrated with the primary navigation system, Team 2004-10 stated: “After reviewing the logged stereo imagery from race day, it is apparent that the onboard stereo system would have been of little benefit during the early portions of the race.” ([39], p. 39). Team 2004-10 did not refer to the stereo camera pair in use by the team in subsequent pages and throughout the section titled “Navigation Software”, including Figure 11, which is a block diagram showing the Riegl and SICK LIDAR sensors provide input to the navigation software ([39]).

The author considers the quantity and manufacturer of this sensor known, but model number unknown, and concluded the SAIC stereo camera pair was not in use by Team 2004-10 during the 2004 GCE.

V.C.10.e. Unknown other navigation sensors

Team 2004-10 stated: “Vehicle state is reported by … vehicle Pose (roll, pitch, yaw), and vehicle velocity.) ([77], p. 4). The author estimated the quantity of other navigation sensors in accordance with paragraph V.B.5.c., but otherwise considers these sensors unknown.

V.C.10.f. Unknown Applanix sensor

Team 2004-10 stated: “Applanix POS unit is utilized for inertial/GPS/DMI instrumentation.” ([77], p. 5), but reported no additional identifying information. Team 2004-10 later stated: “The Applanix POS-LV provides position estimates...” ([39], p. 14), but did not report the model number of the Applanix POS LV sensor in use by the team.

Applanix currently manufactures several model numbers of the POS LV for land navigation: 200, 220, 420, and 610 ([120]). At least two of these model numbers were available at the time of the 2004 QID and GCE: 220 and 420 ([124]), and the author concluded 320 was an existing model number at the time of the 2004 GCE based on review of manufacturer product literature (See paragraph V.C.8.d.). Applanix later confirmed an Applanix sensor was in use by Team 2004-10 during the 2004 GCE, but reported no additional identifying information ([125]).

The author concluded one Applanix sensor was in use by Team 2004-10, but considers the model number of this sensor unknown.

V.C.11. Team 2004-11

- The Team 2004-11 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).

- The Team 2004-11 website was updated in anticipation of the 2005 NQE, and stated: “we continue to work to finish and perfect the system” ([126]), but reported no additional identifying information for the sensors in use by the team.

- Team 2004-11 did not participate in the 2004 QID or GCE.

V.C.11.a. Unknown tachometer

Team 2004-11 stated: “A tachometer consisting of an induction sensor/counter on the IC engine ignition system provides engine speed data to the engine/transmission microcontroller.” ([127], p. 6), but reported no additional identifying information. The author concluded one tachometer was in use by Team 2004-11, but otherwise considers this sensor unknown.

V.C.11.b. Unknown long-range laser ranger and unknown scanning laser range finder

Team 2004-11 alternately referred to both a “long-range laser ranger” and “scanning laser rangefinder” ([127], p. 4). When referring to a “laser range finder”, Team 2004-11 stated: “This instrument is a standard industrial laser rangefinder...” ([127], p. 5). However, it is unclear to which laser sensor Team 2004-11 was referring as a “laser range finder”, and Team 2004-11 reported no additional identifying information for either sensor.

The author concluded one long-range laser ranger and one scanning laser range finder was in use by Team 2004-11, but otherwise considers these sensors unknown.

V.C.11.c. Unknown Omnivision sensor

Team 2004-11 stated: “...an Omnivision digital image sensor array will also be employed for path identification.” ([127], p. 5), but reported no additional identifying information. Omnivision manufactures several “digital image sensors” ([128]). The author concluded one Omnivision sensor was in use by Team 2004-11, but considers the model number of this sensor unknown.

V.C.11.d. MiTAC A12 and unknown CSI Wireless DGPS receiver

Team 2004-11 stated: “...a Thales A12 GPS receiver, in tandem with a CSI Wireless differential beacon receiver...” ([127], p. 6), but reported no additional identifying information. Through a series of mergers and acquisitions Thales Navigation was ultimately purchased by MiTAC ([123]). The author concluded one MiTAC A12 GPS receiver was in use by Team 2004-11, and considers this sensor known. The author concluded one CSI Wireless DGPS receiver was in use by Team 2004-11, but considers the model number of this sensor unknown.

V.C.11.e. Unknown other navigation sensors

Team 2004-11 stated: “[The challenge vehicle] will derive pitch and roll relative to ground from the scanning laser rangefinder.”, “Ground speed is now derived from an optical interrupter linked to the transmission output shaft.”, and “A solid-state magnetic compass module will be used in conjunction with the odometer...” ([127], p. 6), but reported no additional identifying information for the other navigation sensors in use by the team. The author concluded one of each sensor was in use by Team 2004-11, but otherwise considers these sensors unknown.

V.C.12. Team 2004-12

- The Team 2004-12 website was no longer available.
- Team 2004-12 partially completed the 2004 QID course on the second day of the 2004 QID ([84]), terminated their attempt on the third day of the 2004 QID ([85]), and partially completed the 2004 QID course on the last day of the 2004 QID ([79]).
- Team 2004-12 was not selected to participate in the 2004 GCE ([80]).

V.C.12.a. Ultra Motion 2-B.125-DC426_12-4-P-/4-300

In response to 2004 SQ 1.a.3 (see Table XXII), Team 2004-12 reported one "Ultramotion 2-B.125-DC426_12-4-P-/4-300 linear actuator" was in use by the team "for each axle" ([129], p. 3). A company named "Ultra Motion" manufactures linear actuators with similar model numbers. The author concluded "Ultramotion" was an error.

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-12 stated linear potentiometers were in use by the team to determine "Wheel Angle for Front and Rear" ([129], p. 5), but reported no additional identifying information. Ultra Motion's online product catalog ([130]) reported an integrated linear potentiometer is denoted by the letter "P" in the model number, above; the same linear actuator without an integrated linear potentiometer is "2-B.125-DC426_12-4-/4-300". The author concluded two Ultra Motion 2-B.125-DC426_12-4-P-/4-300 linear actuators were in use by Team 2004-12 with integrated linear potentiometers, and considers these sensors known.

V.C.12.b. Omron E2E-CR8B1 proximity sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-12 stated two Omron "Omron E2E-CR8BI" sensors were in use by the team as a speedometer and to determine engine speed ([129], p. 5). However, the Omron Corporation "E2E Model Number Legend" ([131]) reported no such model number is possible. The author concluded the model number was "E2E-CR8B1" and that this error was likely to be the result of the similarity between "I" (the capital letter "i") and "1" (the number one) in some sans-serif fonts, and considers these sensors known.

V.C.12.c. Ultrasonic sensors

In response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-12 stated three short-range ultrasonic distance sensors were in use by the team ([129], p. 4), but reported no additional identifying information. The author concluded three ultrasonic sensors were in use by Team 2004-12, but otherwise considers these sensors unknown.

V.C.12.d. SICK LMS 291-S05

Team 2004-12 stated their "Forward radar distance sensor" was a "SICK Laser Measurement System (LMS) 291-S05" ([129], p. 4). However, the SICK LMS 291-S05 is a LIDAR sensor, not a RADAR sensor. The author concluded this was an error and considers this sensor known.

V.C.13. Team 2004-13

- Team 2004-13 participated in the 2005 GCE as Team 2005-15. See paragraph V.C.39.
- Teams 2004-13 and 2004-14 were co-participants during the 2004 QID and GCE, and many of the technical details of their challenge vehicles were the same.
- The Team 2004-13 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-13 website was no longer available.
- Team 2004-13 partially completed the 2004 QID course on the second day of the 2004 QID ([84]), terminated their attempt on the third day of the 2004 QID ([85]), and partially completed the 2004 QID course on the last day of the 2004 QID ([79]).
- Team 2004-13 was selected to participate in the 2004 GCE ([80]).

V.C.13.a. Unknown state sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-13 stated: "...there will be direct sensing of the state of the vehicle's transmission (reverse, neutral, or forward), the steering angle, the throttle position, and the braking pressure." ([132], p. 4), but reported no additional identifying information. The author estimated the quantity of state sensors in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.13.b. Unknown Hall Effect sensor and unknown absolute encoder

Team 2004-13 variously stated: "Differential odometer. The incremental distance traveled by the vehicle during a steering maneuver will be measured using a Hall effect sensor on the drive shaft..." ([132], p. 4); "For steering, the speed will be obtained from the Hall effect sensor." ([132], p. 5); "The pinion shaft also has attached an absolute encoder in order to determine exact position of the steering." ([132], p. 1); and "Steering rate and angle. This will be measured using an encoder on the steering servo." ([132], p. 5).

Team 2004-13 did not report enough information to determine the quantity of Hall Effect sensors used in the differential odometer, or even if a differential odometer was in use by the team (at least two sensors are required, and they cannot both be attached to the vehicle drive shaft); to determine if a Hall Effect sensor is used to measure vehicle speed in addition to the Hall Effect sensors used in the differential odometer; or to determine the quantity of absolute encoders used in the steering system, one of which is attached to the "pinion shaft" and the other to the "steering servo".

The author concluded no differential odometer was in use by the team, that one Hall Effect sensor was in use to determine the "incremental distance traveled by the vehicle during a steering maneuver" and "speed", and that one "absolute encoder" was in use to determine "steering rate and angle", but otherwise considers these sensors unknown.

V.C.13.c. Unknown compass

Team 2004-13 stated: "A digital compass will provide an absolute orientation clue for maintaining overall correct direction." ([132], p. 5), but reported no additional identifying information. The author concluded one compass was in use by Team 2004-13, but otherwise considers this sensor unknown.

V.C.13.d. Unknown camera

Team 2004-13 stated, in part: "A video camera (pinhole lens, NTSC video, 30 fps) will be ... used..." ([132]], p. 3), but reported no additional identifying information.

Team 2005-15 did not report a video camera was in use by the team.

The author concluded one camera was in use by Team 2004-13, but otherwise considers this sensor unknown.

V.C.13.e. Unknown SICK LIDAR sensors

Teams 2004-13 stated: "*As many as four* LADAR units (SICK LMS) will be used for long-range obstacle detection. In this configuration, two of the units will be used for detecting obstacles within a 180º sector of the horizontal plane directly in front of the vehicle and two units will be mounted vertically so that the laser beam is directed forward and scanned in elevation." ([132], p. 3, *emphasis added*).

Team 2005-15 stated: "The main obstacle sensing is based on SICK LIDAR sensors. Two of these sensors are used to scan horizontally, to detect objects that are in the path to be driven. Two other LIDAR sensors scan vertically, to detect surface continuity and discontinuity (negative obstacles)." ([53], p. 9) and "Five sensors were used to search for obstacles within the corridor: The stereo vision system (SVS) from Seibersdorf Research and four SICK LMS-221 light detection and ranging device (LIDAR) units..." ([133], p. 586).

Although Team 2004-13 stated “as many as four” LIDAR sensors would be used by the team, the author concluded four LIDAR sensors were in use. However, neither Team 2004-13 nor Team 2004-14 reported a model number for the SICK LIDAR sensors in use by the team. The technical capabilities of any of the SICK LMS 2XX LIDAR sensors match the “maximum range”, “angular range”, angular resolution, and “frame update time” reported by Teams 2004-13 and 2004-14 ([74] and [73]).

The author was unable to determine what Teams 2004-13 and 2004-14 were describing by “range resolution”. This may correspond to “Resolution/typ. measurement accuracy” ([73]) or “Resolution/systematic error” ([74]). The resolution of LMS 2XX LIDAR sensors is either “10 mm/± 35 mm” or “10 mm/± 15 mm” ([74] and [73]), with a potential error of -25 to 45 mm and -5 to 25 mm, respectively, or an “error range” of 70 mm (0.07 m) or 30 mm (0.03 m), neither of which correspond to the “range resolution of ~0.3 m” reported by Teams 2004-13 and 2004-14.

The author concluded four SICK LIDAR sensors were in use by Team 2004-13, but considers the model numbers of these sensors unknown.

V.C.13.f. Unknown Epsilon Lambda RADAR

Team 2004-13 stated: “The RADAR system (from Epsilon Lambda) may be used, primarily for detecting obstacles at large distances in front of the vehicle. It is capable of detecting targets at a maximum range of 110 m with a range resolution of 1 m. The microwave beam is mechanically scanned horizontally over a maximum angular range of ± 20º with an azimuth angular resolution of 1.8º. It will also have a capability to provide target elevation data over a range of 7.6º with a resolution of 1º.” ([132], p. 3), but reported no additional identifying information.

The Team 2004-21 technical paper contains a specification sheet for the Epsilon Lambda ELSC71-1A as an appendix. The technical capabilities of the Epsilon Lambda ELSC71-1A match the “maximum range”, “range resolution”, “maximum angular range”, and “azimuth angular resolution” reported by Teams 2004-13 and 2004-14 ([74] and [73]).

However, due to the limited availability of manufacturer product literature, the author was unable to determine what other products manufactured by Epsilon Lambda have similar technical capabilities. The author concluded one Epsilon Lambda RADAR was in use by Team 2004-13, but considers the model number of this sensor unknown.

V.C.13.g. Unknown ultrasonic sensors

Team 2004-13 stated: “The ultrasonic range finder will be primarily used for detecting obstacles at short distances on the sides, in front of the vehicle, and to the rear of the vehicle. ... There will be several ultrasonic units located around the vehicle with a fixed pointing direction for each one.” ([132], p. 4), but reported no additional identifying information. The author considers these sensors unknown.

V.C.13.h. Unknown Rockwell Automation photoelectric sensors

Team 2004-13 stated: “The photoelectric sensors (Rockwell Automation types commonly used in industrial automation) may be used. ... The majority of the approximately 24 photoelectric sensors to be used around our vehicle...” ([132], p. 4), but reported no additional identifying information. The author estimated 24 Rockwell Automation photoelectric sensors were in use by Team 2004-13, but considers the model number of these sensors unknown.

V.C.13.i. Unknown accelerometer

Team 2004-13 stated: “An accelerometer capable of sensing movements in the vertical direction will be used to monitor the roughness of the terrain.” ([132], p. 5), but reported no additional identifying information. The author concluded one accelerometer was in use by Team 2004-13, but otherwise considers this sensor unknown.

V.C.14. Team 2004-14

- Teams 2004-13 and 2004-14 were co-participants during the 2004 QID and GCE, and many of the technical details of their challenge vehicles were the same.
- The Team 2004-14 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-14 website was no longer available.
- Team 2004-14 partially completed the 2004 QID course on the second day of the 2004 QID ([84]), and completed the 2004 QID course on the third day of the 2004 QID ([85]).
- Team 2004-14 was selected to participate in the 2004 GCE ([80]).

V.C.14.a. Unknown state sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-14 stated: “...there will be direct sensing of the state of the vehicle’s transmission (reverse, neutral, or forward), the steering angle, the throttle position, and the braking pressure.” ([134], p. 5), but reported no additional identifying information. The author estimated the quantity of state sensors in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.14.b. Unknown Hall Effect sensor and unknown angular encoder

Team 2004-14 variously stated: "Differential odometer. The incremental distance traveled by the vehicle during a steering maneuver will be measured using a Hall effect sensor on the drive shaft..." ([134], p. 5); "For steering, the speed will be obtained from the Hall effect sensor." ([134], p. 5); and "Steering rate and angle. This will be measured using an angular encoder on the steering column." ([134], p. 5).

Team 2004-14 did not report enough information to determine the quantity of Hall Effect sensors used in the differential odometer, or even if a differential odometer was in use by the team (at least two sensors are required, and they cannot both be attached to the vehicle drive shaft); or to determine if a Hall Effect sensor is used to measure vehicle speed in addition to the Hall Effect sensors used in the differential odometer.

The author concluded no differential odometer was in use by the team, that one Hall Effect sensor was in use to determine the "incremental distance traveled by the vehicle during a steering maneuver" and "speed", and that one "angular encoder" was in use to determine "steering rate and angle", but otherwise considers these sensors unknown.

V.C.14.c. Unknown magnetometer

Team 2004-14 stated: "In the absence of GPS data due to communication outages the IND/DGPS [*sic*] system is aided by a 3D-magnetometer and the vehicle's odometer." ([134], p. 6), but reported no additional identifying information. The author concluded one magnetometer was in use by Team 2004-14, but otherwise considers this sensor unknown.

V.C.14.d. Unknown cameras

Team 2004-14 stated, in part: "A set of video cameras (pinhole lens, NTSC video, 30 fps) will be ... used..." ([134], p. 3), but reported no additional identifying information. The author considers these sensors unknown.

V.C.14.e. Unknown SICK LIDAR sensors

Team 2004-14 stated: "*As many as four* LADAR units (SICK LMS) will be used for long-range obstacle detection. In this configuration, one of the units will be used for detecting obstacles within a 100º sector of the horizontal plane directly in front of the vehicle and *either one or two units* will be used for detecting obstacles in the horizontal plane of the left and right forward quadrants to provide obstacle detection when maneuvering to the left or right. One of the LADAR systems will be mounted so that the laser beam is directed forward and scanned in elevation." ([134], pp. 3 - 4, *emphasis added*).

Although Team 2004-14 reported that either three or four LIDAR sensors were in use by the team, the author considers it likely that Team 2004-14 used the same quantity of LIDAR sensors as Team 2004-13, and concluded four SICK LIDAR sensors were in use by Team 2004-14.

Neither Team 2004-13 nor Team 2004-14 reported a model number for the SICK LIDAR sensors in use by the team. See paragraph V.C.13.e. The author considers the model number of these sensors unknown.

V.C.14.f. Unknown Epsilon Lambda RADAR

Team 2004-14 stated: "The RADAR system (from Epsilon Lambda) will be primarily used for detecting obstacles at large distances in front of the vehicle. It is capable of detecting targets at a maximum range of 110 m with a range resolution of 1 m. The microwave beam is mechanically scanned horizontally over a maximum angular range of ± 20º with an azimuth angular resolution of 1.8º. It will also have a capability to provide target elevation data over a range of 7.6º with a resolution of 1º." ([134], p. 4), but reported no additional identifying information.

Neither Team 2004-13 nor Team 2004-14 reported the model number for the Epsilon Lambda RADAR in use by the team. See paragraph V.C.13.f. The author concluded one Epsilon Lambda RADAR was in use by Team 2004-14, but considers the model number of this sensor unknown.

V.C.14.g. Unknown ultrasonic sensors

Team 2004-14 stated: "The ultrasonic range finder will be primarily used for detecting obstacles at short distances on the sides, in front of the vehicle, and to the rear of the vehicle. ... There will be several ultrasonic units located around the vehicle with a fixed pointing direction for each one." ([134], p. 4), but reported no additional identifying information. The author considers these sensors unknown.

V.C.14.h. Unknown Rockwell Automation photoelectric sensors

Team 2004-14 stated: "The photoelectric sensors will be Rockwell Automation types commonly used in industrial automation... ... The majority of the approximately 24 photoelectric sensors to be used around our vehicle..." ([134], p. 4), but reported no additional identifying information. The author estimated 24 Rockwell Automation photoelectric sensors were in use by Team 2004-14, but considers the model number of these sensors unknown.

V.C.14.i. Unknown tactile sensors

Team 2004-14 stated: "Flexible bumper tactile sensors will be able to detect contact with objects at ≤8 inches around the vehicle." ([134], p. 4), but reported no additional identifying information. The author considers these sensors unknown.

V.C.14.j. Unknown accelerometer

Team 2004-14 stated: "An accelerometer capable of sensing movements in the vertical direction will be used to monitor the roughness of the terrain." ([134], p. 5), but reported no additional identifying information. The author concluded one accelerometer was in use by Team 2004-14, but otherwise considers this sensor unknown.

V.C.14.k. Rockwell Collins GNP-10

Team 2004-14 alternately stated: "The primary navigation will be through a Navcom Starfire SF-2050G DGPS receiver. It will be hooked up to a IMU (Rockwell Collins, GMC-10, alternatively a Systron Donner C-Migit III)." ([134], p. 5) and "The vehicle determines its geo-location using El-Op's GemiNav INS/DGPS system that uses the Northrop Grumman LN-200 IMU and Trimble Pathfinder DGPS unit." ([134], p. 6).

Rockwell Collins reported no IMU with the model number "GMC-10" existed (see Figure 36). An IMU with model number "GNP-10" exists (see Figure 37), and it is to this model number that Team 2004-13 referred ([132], p. 4). Team 2004-13 did not refer to either a Systron Donner C-Migit III IMU, El-Op's GemiNav INS/DGPS system, or Northrop Grumman LN-200 IMU, and neither Team 2004-13 nor Team 2004-14 later stated these sensors were in use during the 2004 GCE ([135]).

The author concluded neither a Systron Donner C-Migit III IMU, El-Op GemiNav INS/DGPS system, nor Northrop Grumman LN-200 IMU were in use by Team 2004-14, that "GMC-10" was an error, and that the IMU in use by Team 2004-14 was identical to the IMU in use by Team 2004-13. As a result, the author considers this sensor known.

V.C.15. Team 2004-15

- The Team 2004-15 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-15 website reported no additional identifying information for the sensors in use by the team.
- Via an "An Important Message from the Team Leader", dated March 1, 2004, Team 2004-15 stated: "Although the team has worked diligently and sacrificed much in our effort to have [the challenge vehicle] ready for the [2004 GCE], it is not to be. We made great strides and were on the right track as evidenced by our

inclusion in the first group invited to the QID. Unfortunately, we fell victim to everyone's problem of 'not enough time' and 'not enough money'." ([136]).

- Team 2004-15 did not participate in the 2004 QID or GCE.

V.C.15.a. Unknown state sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-15 stated: "Vehicle sensors are … steering position, brake position, throttle position, RPM, low oil pressure, transmission shifter position, transfer case shifter position, air conditioning information which is used for temperature management in the water tight electronics enclosure..." ([137], p. 3), but reported no additional identifying information. The author estimated the quantities of the state sensors in use by Team 2004-15 in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.15.b. Polaroid 6500 SONAR sensors

Team 2004-15 stated: "Active 50KHz ultrasonic sonar with a sensing horizon of 10 meters will be used for near obstacle detection to the front, rear and sides of the vehicle." ([137], p. 3). Via "Attachment A" ([137], p. 7), Team 2004-15 identified one fixed mount point each for the left side, front, and right side SONAR sensors in use by the team, and two mount points for the rear SONAR sensors. In response to 2004 SQ 3.e.1 (see Table XXII), Team 2004-15 stated a "POLAROID 6500 Ultrasonic Ranger, 50 KHz" was in use by the team ([137], p. 6). The author concluded five Polaroid 6500 SONAR sensors were in use by Team 2004-15, and considers these sensors known.

V.C.15.c. Unknown tactile sensors

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-15 stated "front and rear tactile sensors" were in use by the team ([137], p. 3), but reported no additional identifying information. The author considers these sensors unknown.

V.C.15.d. Unknown wheel encoders

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-15 stated "encoders on all 4 wheels" were in use by the team ([137], p. 3), and in response to questions 1.g.1 and 1.g.2, Team 2004-15 stated: "Wheel encoders on the vehicle are used to compute distance traveled." ([137], p. 4), but reported no additional identifying information. The author concluded four wheel encoders were in use by Team 2004-15, but otherwise considers these sensors unknown.

V.C.15.e. Unknown accelerometer

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-15 stated a "3-axis accelerometer" was in use by the team ([137], p. 3), but reported no additional identifying information. The author concluded one accelerometer was in use by Team 2004-15, but otherwise considers this sensor unknown.

V.C.16. Team 2004-16

- Team 2004-16 participated in the 2005 GCE as Team 2005-17. See paragraph V.C.41.
- The Team 2004-16 website was updated prior to the 2005 GCE, but reported limited additional identifying information for the sensors in use by the team.
- Team 2004-16 aborted its run due to a minor malfunction by a course transmitter on the first day of the 2004 QID ([78]), and partially completed the 2004 QID course on the third and last day of the 2004 QID ([85] and [79]).
- Team 2004-16 was selected to participate in the 2004 GCE ([80]).

V.C.16.a. Unknown state sensors

Team 2004-16 reported no detailed state sensor information in response to questions specifically requesting state sensor information. In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-16 stated: "Vehicle state sensed by interface with engine electronics (e.g., stalled engine)." ([138], p. 4); and in response to 2004 SQ 1.f.2 (see Table XXII), Team 2004-16 stated: "Data is monitored using custom software via a GPS." ([138], p. 4).

V.C.16.b. Unknown compass

Throughout the team technical paper ([138]), Team 2004-16 variously referred to a "compass", "digital compass", and "electronic compass", but reported no additional identifying information. The author concluded one compass was in use by Team 2004-16, but otherwise considers this sensor unknown.

V.C.16.c. Unknown cameras

Team 2004-16 stated: "Passive cameras, 2 fixed front wide-angle IR sensitive CCD cameras for visual acquisition of terrain, obstacles, other vehicles (1-90m)..." ([138], p. 4), but reported no additional identifying information. The challenge vehicle description on the Team 2004-16 website did not report "cameras" of any kind were in use by the team ([139]). The author concluded two cameras were in use by Team 2004-16, but otherwise considers these sensors unknown.

V.C.16.d. Unknown RADARs

In addition to a number of generic references to the use of RADAR for obstacle detection, Team 2004-16 stated: “The radars ... use beams that will be reflected back from the road.” ([138], p. 7) and “Radar devices operate at 24.725 GHz with a maximum power output of less than 5mW.” ([138], p. 8), but reported no additional identifying information.

Team 2005-17 stated: “The radar and sonar sensors are removed.” ([140], p. 2), but reported no additional identifying information.

The author concluded more than one RADAR was in use by Team 2004-16, but otherwise considers these sensors unknown.

V.C.16.e. Unknown SONAR sensors

Team 2004-16 stated: “The system classifies objects acquired through sonar and radar using filtering techniques applicable to sonar and radar target identification.” ([138], p. 3), but reported no additional identifying information.

Team 2005-17 stated: “The radar and sonar sensors are removed.” ([140], p. 2), but reported no additional identifying information.

The author concluded SONAR sensors were in use by Team 2004-16, but otherwise considers these sensors unknown.

V.C.16.f. Unknown SICK LIDAR sensors

Team 2004-16 stated: “...laser range finders for distance determination between own vehicle and obstacle/other vehicles (1-100m).” ([138], p. 4), but reported no additional identifying information.

Team 2004-16 reported “Two scanning laser systems” were in use by the team, but reported no additional identifying information ([139]).

Team 2005-17 stated: “The single (functional) SICK LMS 221 is augmented by four SICK LMS 291s.” ([140], p. 2).

In the absence of an affirmative statement by Team 2005-17 that the “single (functional) SICK LMS 221” LIDAR sensor referred to via the team technical paper ([140]) was one of the “laser range finders” in use by Team 2004-16 during the 2004 QID and GCE, the author concluded two SICK LIDAR sensors were in use by Team 2004-16, but considers the model number of these sensors unknown.

V.C.16.g. Unknown C&C Technologies C-Nav and unknown INS

Team 2004-16 stated: "Software integrates GPS/inertial/compass/pitch/yaw data for navigation. Sensor data are combined (inertial and GPS using Kalman filtering)..." ([138], p. 3), but reported no additional identifying information.

Team 2004-16 reported the "C-Nav differential GPS" and "an Oxford inertial navigation sensor" were in use by the team ([139]). The C-Nav DGPS receiver is a product of C&C Technologies. C&C Technologies manufactured several model numbers of the C-Nav at the time of the 2005 GCE ([141]). The author concluded one C&C Technologies C-Nav DGPS receiver was in use by Team 2004-16, but considers the model number of this sensor unknown.

Team 2005-17 stated: "The POS/MV INS from Applanix has been replaced by RT3102 from Oxford Technologies." ([140], p. 2). As a result, the author concluded the Oxford RT3102 was not in use by the team during the 2004 QID and GCE. In the absence of an affirmative statement that the Applanix POS MV was in use by the team during the 2004 QID and GCE, the author concluded one INS was in use, but otherwise considers this sensor unknown.

V.C.16.h. Unknown solar sensors

Team 2004-16 stated: "Navigation sensors include ... solar sensors..." ([138], p. 10), but reported no additional identifying information. The author concluded solar sensors were in use by Team 2004-16, but otherwise considers these sensors unknown.

V.C.17. Team 2004-17

- Team 2004-17 participated in the 2005 GCE as Team 2005-18. See paragraph V.C.42.
- The Team 2004-17 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-17 website was updated prior to the 2007 Urban Challenge, but reported no additional identifying information for the sensors in use by the team.
- Team 2004-17 partially completed the 2004 QID course before stopping to make mechanical adjustments on the first day of the 2004 QID ([78]), and completed the 2004 QID course on the third and last day of the 2004 QID ([85] and [79]).
- Team 2004-17 was selected to participate in the 2004 GCE ([80]).

V.C.17.a. OBD-II

In response to 2004 SQ 1.f.1 (see Table XXII), Team 2004-17 stated: "Vehicle diagnostic state will be provided by the car's built-in On-Board Diagnostic system, which will provide, among other data, engine temperature, engine RPM, and present gear." ([142], p. 8). In response to 2004 SQ 2.a (see Table XXII), Team 2004-17 stated: "We found the data from OBD-II to be less than reliable. Further testing is required to determine if any of the OBD-II data will be useful." ([142], p. 11). As a result, it is unclear if OBD-II data was in use by Team 2004-17. However, in the absence of an affirmative statement by the team that OBD-II data was not in use by the team during the 2004 GCE, the author concluded the OBD-II system was in use as a state sensor, and considers this sensor known.

V.C.17.b. Indigo Omega

Team 2004-17 stated: "The end result of the test was the decision to purchase [an Indigo Omega] long-wave infrared camera." ([142], p. 12). However, the table of environmental sensors reported by the team technical paper ([142], p. 7) does not list this sensor as one in use by the team. The author concluded the Indigo Omega was not in use by Team 2004-17.

V.C.17.c. Point Grey Dragonfly cameras

Team 2004-17 stated Point Grey Dragonfly cameras were in use by the team as a "long-range forward-looking stereo camera pair", "short-range forward-looking stereo camera pair", and "road following camera" ([142], p. 7).

Point Grey has product lines named "Bumblebee", "Dragonfly", "Flea", etc. ([108]). Each product line has multiple model numbers. The current model number for the Dragonfly product line is "Dragonfly 2" ([143]). The Dragonfly 2 was introduced January 20, 2005 ([144]). Point Grey did not manufacture a Dragonfly or Dragonfly 2 stereo camera pair ([145], [143], and [146]).

The author concluded each "stereo camera pair" was comprised of two Dragonfly cameras, that the total quantity of Dragonfly cameras in use by the team was five, and that "Dragonfly" was the model number at the time of the 2004 QID and GCE, and considers these sensors known.

V.C.18. Team 2004-18

- Team 2004-18 participated in the 2005 GCE as Team 2005-20. See paragraph V.C.44.
- The Team 2004-18 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).

- The hyperlink hosted by DARPA via the Archived Grand Challenge 2004 website ([17]) to the Team 2004-18 website is actually a hyperlink to the ENSCO, Inc. corporate website, which reported no additional identifying information for the sensors in use by the team.

- The team technical paper ([48]) referred to missing Figures “1”, “2”, “3”, and “5”, but did not refer to confidential or proprietary appendixes (see paragraph V.E.2.f.).

- Team 2004-18 partially completed the 2004 QID course on the second day of the 2004 QID ([84]), nearly completed the 2004 QID course on the third day of the 2004 QID ([85]), and partially completed the 2004 QID course on the last day of the 2004 QID ([79]).

- Team 2004-18 was selected to participate in the 2004 GCE ([80]).

V.C.18.a. Unknown state sensors

Team 2004-18 stated: “There are also sensors to detect if the engine is running, if brakes are applied, if acceleration is applied, and the position of the steering motor.” ([48], p. 6), but reported no additional identifying information. The author estimated the quantity of these sensors in accordance with paragraph V.B.3.a., but otherwise considers them unknown.

Team 2004-18 also stated: “There are also temperature sensors to monitor engine and other critical components.” ([48], p. 6), but reported no additional identifying information. The author considers these sensors unknown.

V.C.18.b. Unknown compass

Team 2004-18 stated a “magnetic compass” was in use by the team, but reported no additional identifying information ([48], pp. 6 - 7). The author concluded one magnetic compass was in use by Team 2004-18, but otherwise considers this sensor unknown.

V.C.18.c. Unknown ISI INS

Team 2004-18 stated: “The vehicle has an inertial navigation system (INS-Inertial Science Inc. RRS75). This device has 3 accelerometers and 3 rate gyros that will provide the control system with information for 6 degrees-of-freedom of the vehicle state. This is integrated into the dead reckoning and the vehicle navigation control system. The purpose of the INS is to determine vehicle stability as well as to assist with determining vehicle position.” ([48], p. 6).

Concerning the RRS75, ISI stated: “The RRS (Resonator Rate Sensor) is a new technology sensor that has been developed by Inertial Science, Inc. (ISI) and Sandia

National Laboratory, for angular rate measurement applications." ([147]). ISI also stated: "ISI has designed a complete Inertial Navigation System (ISIS-IMU) utilizing the RRS for its rate sensors. This system allows GPS integration." ([147]).

The ISIS-IMU more closely matches the description of the "inertial navigation system" referred to by Team 2004-18: "ISIS-IMU is a six-degree of freedom inertial mesurement [*sic*] unit designed for commercial use." and "It consists of three RRS75 (solid state rate sensors) and three solid state accelerometers." ([148]). In addition, ISIS-IMU integrates with GPS.

The author concluded Team 2004-18 did not report sufficient technical detail to determine to which "inertial navigation system" Team 2004-18 referred via the team technical paper ([48]), concluded one ISI INS was in use by the team, and considers the model number of this sensor unknown.

V.C.18.d. Unknown RADAR

Team 2004-18 stated: "The primary sensors are one LIDAR systems [*sic*], 3 doppler radars, and a stereo camera system." ([48], p. 5); "The Doppler radar sensors are planned to be DRS 1000 units from GMH engineering." ([48], p. 12); and "Modifications of the tested system will be done to meet the final configuration presented in this paper." ([48], p. 8). The author concluded three Doppler RADAR sensors were in use by the team, but does not consider the manufacturer and model number known in the absence of an affirmative statement by Team 2004-18 that GMH Engineering DRS 1000 RADAR was in use, because alternate RADAR sensors were in use by other teams which participated in the 2004 GCE with similar characteristics, e.g., PRECO PreView.

V.C.18.e. NovAtel ProPak-LBplus

Team 2004-18 stated: "Anovatel Pro-Pack LB will be used for the challenge vehicle." ([48], p. 6). NovAtel is the manufacturer name. The author concluded this was a typographical error and considers this sensor known[21].

V.C.18.f. SICK LMS 220-30106

Team 2004-18 stated: "The primary sensors are one LIDAR systems [*sic*], 3 doppler radars, and a stereo camera system." ([48], p. 5) and "One SICK model LMS 220-30106 scanning LIDAR will be fitted to the front of the vehicle. Each [*sic*] will scan a 180 deg arc with some overlap at the extended centerline of the vehicle. The lasers [*sic*] maximum range is approximately 150m..." ([48], p. 11).

Team 2005-20 stated: "Obstacle avoidance is achieved using LIDAR, Millimeter Wave Radar, and Stereo Vision Camera systems." ([56], p. 2). However, Team 2005-20 reported no additional identifying information for the LIDAR in use by the team.

Through their repeated use of the word "one" to describe "LIDAR systems", and use of the plural "lasers" and word "each", Team 2004-18 alternately stated that both one and more than one SICK LMS 220-30106 were in use by the team. The author concluded this was an error, that one SICK LMS 220-30106 was in use by Team 2004-18, and considers this sensor known.

V.C.18.g. <u>Unknown stereo camera pair</u>

Team 2004-18 stated: "The primary sensors are one LIDAR systems [*sic*], 3 doppler radars, and a stereo camera system." ([48], p. 5) and "The Team will purchase and use an implementation of SRI's Small Vision System (SVS) software that comes standard with certain brands of stereo vision hardware." ([48], p. 5), but reported no additional identifying information for the stereo camera system in use by the team.

Team 2005-20 stated: "Obstacle avoidance is achieved using LIDAR, Millimeter Wave Radar, and Stereo Vision Camera systems." ([56], p. 2). However, Team 2005-20 reported no additional identifying information for the stereo camera pair in use by the team.

The author concluded one stereo camera pair was in use by Team 2004-18, but otherwise considers this sensor unknown.

V.C.19. Team 2004-19

- The Team 2004-19 technical paper was one of 19 technical papers described by DARPA as "completely acceptable" on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- The Team 2004-19 website was no longer available.
- The team technical paper ([151]) referred to a missing figure "4", but did not refer to confidential or proprietary appendixes (see paragraph V.E.2.f.).
- Team 2004-19 passed on their turn the second day of the 2004 QID ([84]), and terminated within the starting chute area the last day of the 2004 QID ([79]).
- Team 2004-19 was not selected to participate in the 2004 GCE ([80]).

V.C.19.a. <u>Unknown stereo camera pair</u>

Team 2004-19 stated: "The system uses ... a stereo vision system." ([151], p. 2). Via their response to 2004 SQ 2.a.1 (see Table XXII), Team 2004-19 stated: "We are still working on our stereo vision system, and have not yet interfaced it with the vehicles [*sic*] computing system." ([151], p. 4).

The author concluded one stereo camera pair was in use by Team 2004-19, but otherwise considers this sensor unknown.

V.C.19.b. Unknown ultrasonic sensors

Team 2004-19 stated: “The system uses three ultrasonic rangefinders...” ([151], p. 2), but reported no additional identifying information. The author concluded three ultrasonic sensors were in use by Team 2004-19, but otherwise considers these sensors unknown.

V.C.19.c. Unknown Electro Switch OEs

Team 2004-19 stated: “The DRS is comprised of a Precision Navigation Vector-2X digital compass module integrated with two Oak Grigsby 900 Series optical encoders.” ([151], p. 3). Oak Grigsby was acquired by Electro Switch ([152]). Electro Switch reported “900 Series” is not a complete model number ([152]). The author concluded two Electro Switch OEs were in use by Team 2004-19, but considers the model number of these sensors unknown.

V.C.19.d. PNI Vector 2X

Team 2004-19 stated: “The DRS is comprised of a Precision Navigation Vector-2X digital compass module integrated with two Oak Grigsby 900 Series optical encoders.” ([151], p. 3). Precision Navigation, Inc. became PNI Sensor Corp. in 2000 ([154]). The author concluded PNI was the manufacturer and considers this sensor known.

V.C.20. Team 2004-20

- The Team 2004-20 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- Team 2004-20 maintained an extensive online repository, which is accessible from the Internet but variously marked “Members Only (now public)” and “For participants only. Not for public distribution.”, and which was a rich source of background information for the 2004 and 2005 GCE.
- Team 2004-20 did not participate in the 2004 QID or GCE.

V.C.20.a. Unknown state sensors

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-20 stated: “Engine RPM and driveshaft RPM are monitored, along with some voltages and temperatures.” ([107], p. 6), but reported no additional identifying information. The author estimated the quantity of the engine RPM and driveshaft RPM sensors in use by

Team 2004-20 in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.20.b. Eaton EVT-300

Team 2004-20 stated: "An Eaton VORAD anti-collision radar system is fitted to detect collisions with other vehicles and large obstacles. … The radar unit is a standard Eaton VORAD unit, the widely used truck anti-collision radar, interfaced to computers using an Eaton VBOX." ([107], p. 5), but reported no additional identifying information.

The repository contains several documents which identify the specific model number of the Eaton RADAR in use by Team 2004-20 as "EVT-300". The author considers this sensor known.

V.C.20.c. Unknown water sensors

Team 2004-20 stated: "Water sensors at two heights are provided to detect when the vehicle has entered water." ([107], p. 5), but reported no additional identifying information. The author considers these sensors unknown.

V.C.20.d. Unknown ultrasonic sensors

Team 2004-20 stated: "The usual ring of ultrasonic sonars is provided, with overlapping sensing fields surrounding the vehicle." and "In addition, there are narrow-angle sonars pointing down ahead of each leading wheel and behind each trailing wheel." ([107], p. 5), but reported no additional identifying information. The author considers these sensors unknown.

V.C.20.e. Unknown Crossbow INS

Team 2004-20 stated: "We are currently planning to use a ... Crossbow AHRS inertial system." ([107], p. 7), but reported no additional identifying information. Crossbow manufactured several models of "AHRS inertial system" ([96]). The author concluded one Crossbow INS was in use by Team 2004-20, but considers the model number of this sensor unknown.

V.C.20.f. Unknown DICKEY-john RADAR

Team 2004-20 reported one "Dickey-John doppler radar speedometer" was in use by the team ([107], pp. 6, 13), but reported no additional identifying information. The author concluded one DICKEY-john RADAR was in use by Team 2004-20, but considers the model number of this sensor unknown.

V.C.20.g. Unknown compass

Team 2004-20 stated one “magnetic compass” was in use by the team ([107], pp. 6 - 7), but reported no additional identifying information. The author concluded one compass was in use by Team 2004-20, but otherwise considers this sensor unknown.

V.C.21. Team 2004-21

- The hyperlink hosted by DARPA via the Archived Grand Challenge 2004 website ([17]) to the Team 2004-21 website redirects to another domain, which reported no additional identifying information for the sensors in use by Team 2004-21.
- Team 2004-21 passed on their turn on the first day of the 2004 QID ([78]), terminated their attempt on the third day of the 2004 QID ([85]), and officially withdrew on the last day of the 2004 QID ([79]).
- Team 2004-21 was not selected to participate in the 2004 GCE ([80]).

V.C.21.a. Unknown state sensors

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-21 stated: “Fuel, temperature, electrical output, etc.” ([155], p. 6), but reported no additional identifying information. The author estimated the quantity of fuel sensors in use by Team 2004-21 in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.21.b. Epsilon Lambda ELSC71-1A

In response to 2004 GCE SQ 1.e.1 (see Table XXII), Team 2004-21 stated: “We will use a Radar system for long range sensing...” ([155], p. 6), but reported no additional identifying information. The team technical paper contains a specification sheet for the Epsilon Lambda ELSC71-1A as an appendix. The author considers this sensor known.

V.C.21.c. SensComp Developer's Kit

In response to 2004 GCE SQ 1.e.1 (see Table XXII), Team 2004-21 stated: “We will use … sonar for short range.” ([155], p. 6). The team technical paper contains a specification sheet for a “Developer's Kit” as an appendix, but reported no additional identifying information. The author concluded SensComp was the manufacturer of the Developer's Kit based on an Internet search using the key words “+'600 series' +'environmental transducer' +7000 +9000” as the search string. As confirmation, the picture embedded in the specification sheet included with the team technical paper ([155]) matches the picture from manufacturer product literature ([156]). The author considers this sensor known.

V.C.21.d. Unknown IR sensors

In response to 2004 GCE SQ 2.a (see Table XXII), Team 2004-21 stated: “The key components that have been tested so far include ... the various IR and Sonar sensors.” ([155], p. 9), but reported no additional identifying information. However, Team 2004-21 did not refer to IR sensors in response to 2004 SQ 1.e.i (see Table XXII). The author concluded IR sensors were not in use by Team 2004-21 during the 2004 QID.

V.C.22. Team 2004-22

- The Team 2004-22 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).
- No hyperlink to the Team 2004-22 website was hosted by DARPA via the Archived Grand Challenge 2004 website ([17]).
- Team 2004-22 did not participate in the 2004 QID or GCE.

V.C.22.a. Unknown SpaceAge Control string potentiometers

In response to 2004 GCE SQ 1.c.2 (see Table XXII), Team 2004-22 stated: “Shock monitoring System (SMS)—each shock is equipped with a string pot to determine the actual position of the shock (compressed or uncompressed).” ([157], p. 3) and “The shock suspension uses SpaceAge Controls, [*sic*] string pots...” ([157], p. 4), but did not report the model number of the string potentiometers in use by the team. The author estimated four SpaceAge Control string potentiometers were in use by Team 2004-22, but considers the model number of this sensor unknown.

V.C.22.b. Unknown temperature sensors

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-22 stated: “Temperature sensors – used to monitor engine, oil and outside temperatures.” ([157], p. 5), but reported no additional identifying information. The author concluded three temperature sensors were in use by Team 2004-22, but otherwise considers these sensors unknown.

V.C.22.c. Team 2004-22 Video System

In response to 2004 SQ 1.b (see Table XXII), Team 2004-22 stated: “Video Processing—See Proprietary Annex” ([157], p. 3). Although Team 2004-22 referred to a “video system” throughout the team technical paper ([157]), including their response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-22 reported very little additional identifying information for the components comprising their proprietary solution, and no additional identifying information for the cameras in use by the team.

The author considers the proprietary video system in use by Team 2004-22 known, but concluded the cost of this sensor cannot be independently determined.

V.C.22.d. Unknown Microstrain gyroscope

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-22 stated: "3-axis gyro (Microstrain) – used to determine heading of the vehicle, acceleration in any axis and the Eulers / Quaterion [*sic*] matrices to determine the 6-degrees of freedom equations[.]" ([157], p. 5), but reported no additional identifying information. The author concluded one Microstrain 3-axis gyroscope was in use by Team 2004-22, but considers the model number of this sensor unknown.

V.C.22.e. Unknown gyroscope

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-22 stated: "1-axis gyro – specifically used for the GPS for heading sensing in odometry mode." ([157], p. 5), but reported no additional identifying information. The author concluded one 1-axis gyroscope was in use by Team 2004-22, but otherwise considers this sensor unknown.

V.C.22.f. Unknown Honeywell pressure transducer

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-22 stated: "Altitude sensor (Honeywell, SSEC) – highly accurate pressure transducer is used to measure altitude of the vehicle." ([157], p. 5), but reported no additional identifying information. The author concluded one Honeywell pressure transducer was in use by Team 2004-22, but considers the model number of this sensor unknown.

V.C.22.g. Unknown u-blox GPS receiver

Team 2004-22 stated: "u-Blox GPS, with Wide Area Augmentation System (WAAS), is the secondary means for updating the vehicles position during the race." ([157], p. 2) and "the u-Blox GPS unit has a self-calibrating sensor feed for odometry. Hall-State proximity sensors are attached to each of the front wheels and two to the rear drive shaft. The GPS requires two more feeds for DR mode; a single-axis gyro and a logic high/low for forward or reverse motion. The Kalman filter on the GPS is self-calibrating." ([157], p. 3), but reported no additional identifying information.

U-blox manufactured multiple product families, e.g., "GPS modules", "GPS cards", and "GPS chips", each of which has multiple model numbers ([158]), and that at least three current GPS modules offer an integrated Kalman filter: LEA-4R, TIM-4R, and AEK-4R. The author considers it likely that multiple products with the capabilities reported by Team 2004-22 were available at the time of the 2004 QID, and concluded one u-blox GPS receiver was in use by Team 2004-22, but considers the model number of this sensor unknown.

V.C.22.h. Unknown Hall Effect sensors

Team 2004-22 stated: "Hall-State proximity sensors are attached to each of the front wheels and two to the rear drive shaft." ([157], p. 3). The author concluded four Hall Effect sensors were in use by Team 2004-22, but otherwise considers these sensors unknown.

V.C.23. Team 2004-23

- Team 2004-23 participated in the 2005 GCE as Team 2005-21. See paragraph V.C.45.
- The hyperlink hosted by DARPA via the Archived Grand Challenge 2004 website ([17]) to the Team 2004-23 website was actually a hyperlink to the Oshkosh Defense corporate website. This website hosted a hyperlink to the Team 2004-23 website, which was updated prior to the 2005 GCE, and which reported no additional identifying information for the sensors in use by Team 2004-23.
- Team 2004-23 partially completed the 2004 QID course on the second day of the 2004 QID ([84]), nearly completed the 2004 QID course on the third day of the 2004 QID ([85]), and completed the 2004 QID course on the last day of the 2004 QID ([79]).
- Team 2004-23 was selected to participate in the 2004 GCE ([80]).

V.C.23.a. Unknown state sensors

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-23 stated: "We will also have access to vehicle and actuator sensors to determine throttle, brakes, and engine condition." ([159], p. 9), but reported no additional identifying information. The author estimated the quantity of state sensors in use by Team 2004-23 in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.23.b. Unknown SICK LIDAR sensors

Team 2004-23 stated: "Four SICK LADARs (Model: LMS 221) are to be used. These are 2-D laser rangefinders (active sensors) with 180 degree scanning spectrum and have maximum scanning distance of 80 meters[.] The actual range, of course, depends on the reflectivity of the target, but our experience to date indicates that 40 meters is a reasonable minimum operational range." ([159], p. 8), but did not report the model numbers for the four SICK LIDAR sensors in use by the team.

Team 2005-21 used a combination of SICK LMS 291 and IBEO ALASCA LIDAR sensors ([160]).

The author concluded four SICK LIDAR sensors were in use by Team 2004-23, but considers the model number of these sensors unknown.

V.C.23.c. Unknown Eaton RADARs

Team 2004-23 stated: "2 Eaton-Vorad radars are mounted (front and rear) for providing 150 m range target tracking." ([159], p. 9), but reported no additional identifying information.

Team 2005-21 did not refer to RADAR in use by the team ([160] and [57]).

The author concluded two Eaton RADARs were in use by Team 2004-23, but considers the model number of these sensors unknown.

V.C.23.d. Unknown Massa ultrasonic sensors

Team 2004-23 stated: "12 ultrasonic sensors (Massa—8in to 14 ft) are mounted around the vehicle for short range sensing." ([159], p. 9), but reported no additional identifying information. Team 2005-21 did not refer to ultrasonic sensors in use by the team ([160] and [57]). The author concluded 12 Massa ultrasonic sensors were in use by Team 2004-23, but considers the model number of these sensors unknown.

V.C.23.e. Unknown cameras

Team 2004-23 stated: "The vision system consists of 6 CCD digital color cameras. Two pairs are used to provide stereovision information (both forward and rear looking). The two single cameras will sense the terrain in front and behind the truck and provide free-space estimation and path/road estimation." ([159], p. 8), but reported no additional identifying information.

Team 2005-21 stated: "The vision system is comprised of a forward-looking system and a backward looking one. Both systems share the same technology and processing: color cameras and stereoscopic vision." ([160], p. 10); "The forward-looking system consists of three identical cameras mounted on a rigid bar on top of the hood." ([160], p. 10); and "Pairs of stereo images are used for both obstacle detection and path detection." ([160], p. 11). Team 2005-21 did not report additional identifying information for the cameras in use by the team.

The author concluded six CCD digital color cameras were in use by Team 2004-23, but otherwise considers these sensors unknown.

V.C.23.f. Unknown IMU

Team 2004-23 stated: "One inertial measurement unit (IMU) will measure the total accelerations and angular velocity of the vehicle." ([159], p. 9) and "With options 1 and 2, the IMU will be either Honeywell HG1700 or the Litton LN200. Option 3 provides an integrated IMU. A magnetic compass and dead-reckoning information will also be included in the navigation solution. Our current plan is to implement Option 2 as soon as funding is available." ([159], p. 10).

Team 2004-23 did not refer to "options" again throughout the team technical paper ([159]). The author considers it likely this paragraph was copied-and-pasted from another document, such as a proposal, or was an artifact of the PDF conversion process.

Team 2005-21 stated: "Two Oxford Technical Solutions (OXTS) RT3100s supply GPS position information to the VMS system." ([160], p. 8) and "Two Oxford Technical Solutions RT3100's ... supply GPS position information to the iVMS system." ([57], p. 700).

The author concluded one IMU was in use by Team 2004-23, but otherwise considers this sensor unknown.

V.C.23.g. Unknown wheel speed sensors

Team 2004-23 stated: "Individual wheel speed is available off the J1939 bus." ([159], p. 9), but reported no additional identifying information. The author concluded six wheel speed sensors were in use by Team 2004-23, but otherwise considers these sensors unknown.

V.C.24. Team 2004-24

- No hyperlink to the Team 2004-24 website was hosted by DARPA via the Archived Grand Challenge 2004 website ([17]).
- Team 2004-24 partially completed the 2004 QID course on the second and third day of the 2004 QID ([84] and [85]).
- Team 2004-24 was selected to participate in the 2004 GCE ([80]).

V.C.24.a. Unknown pressure sensors

Team 2004-24 stated: "There are two pressure sensors per suspension cylinder and steering cylinder set (one on each side of the piston), two for the brake actuators and one for each storage tanks [*sic*]. There are a total of 19 sensors." ([161], p. 5), but reported no additional identifying information. The author concluded 19 pressure sensors were in use by Team 2004-24, but otherwise considers these sensors unknown.

V.C.24.b. Unknown power system sensors

Team 2004-24 stated: "The power system controller monitors the state of charge of the batteries through voltage and current sensors. The state of the generators is monitored through voltage sensors, speed sensors and water temperature sensors." ([161],

p. 6), but reported no additional identifying information. The author estimated the quantity of power system sensors in use by Team 2004-24 in accordance with paragraph V.B.3.a., but otherwise considers these sensors unknown.

V.C.24.c. Unknown cameras

Team 2004-24 alternately referred to a "road ID camera" and "road ID cameras" or "boundary ID camera" and "boundary ID cameras", and "binocular vision", and stated: "The Boundary ID cameras are low resolution video sensors primarily used to identify artificial boundaries installed by the DAPRA Grand Challenge staff."; "The road ID cameras use texture ID algorithms to identify roads/trails along with associated confidence levels."; and "The matched set of machine vision cameras are the first of three sensors used to construct a near real time solid model for low to moderate speed navigation." ([161], p. 5).

Figure 2 ("Processing System Layout") of the team technical paper ([161], p. 12) reported that there are two "Road Following" cameras and two "Vision Cameras", but no "boundary ID" cameras. Therefore, the author estimated two road ID cameras were in use by Team 2004-24; concluded the quantity of boundary ID cameras is unknown; and concluded one matched set of machine vision cameras were in use by the team as a stereo camera pair. The author considers the manufacturers and model numbers of the cameras in use by Team 2004-24 unknown.

V.C.24.d. Unknown LIDAR sensor

Team 2004-24 stated: "The Lidar sensor is the final sensor used for solid model construction. It is the primary obstacle avoidance sensor." ([161], p. 5), but reported no additional identifying information. The author concluded one LIDAR sensor was in use by Team 2004-24, but otherwise considers this sensor unknown.

V.C.24.e. Unknown Eaton RADAR

Team 2004-24 stated: "The Eaton VORAD radar provides tracking data on up to 20 objects. This data includes azimuth, distance and closing speed." ([161], p. 5), but reported no additional identifying information. The "CW tone" of 24.5 GHz and "max power" of 50 mW reported by the team technical paper ([161]) does not conform to the "frequency" of 24.725 GHz and "transmitted RF power" of 3.0 mW reported by Eaton for either the VBOX or EVT-300 ([106] and [162]).

Searching the Eaton website for manufacturer product literature for other models of the VORAD RADAR with capabilities matching those reported by Team 2004-24 was ultimately unproductive. On January 5, 2009, Eaton sold the VORAD system to Bendix ([163]). Although Eaton reported Eaton's "Roadranger" organization will continue to support the VORAD system ([163]), and the VORAD system is a featured product at the online Roadranger "store", attempts to "click through" for VORAD products or literature terminated in pages stating: “For more information please contact your Roadranger Representative” and attempts to search for “VORAD” terminated in a page stating: “No items were found matching your search criteria.”. Manufacturer product literature for the VORAD system was not available from Bendix.

The author concluded one Eaton RADAR was in use by Team 2004-24, but considers the model number of this sensor unknown.

V.C.24.f. Unknown magnetometers, gyroscopes, and accelerometers

Team 2004-24 stated: “The coarse heading sensor contains three magnetometers, three gyros and three accelerometers of moderate quality.” ([161], p. 4), but reported no additional identifying information. The author concluded three magnetometers, three gyroscopes, and three accelerometers were in use by Team 2004-24, but otherwise considers these sensors unknown.

V.C.24.g. Unknown NavCom GPS receiver

Team 2004-24 stated: “Geolocation of the sensor platform is accomplished with the Navcom GPS and LN-200 inertial reference unit.” ([161], p. 6), but reported no additional identifying information for the NavCom GPS receiver in use by the team. The author concluded one NavCom GPS receiver was in use by Team 2004-24, but considers the model number of this sensor unknown.

V.C.24.h. Team 2004-24 wheel speed sensors

Team 2004-24 stated: “For each motor and driver, a small custom board interfaces with the controlling PC 104 board and provides data on motor/wheel speed.” ([161], p. 6).

The author considers the wheel speed sensors in use by Team 2004-24 known, but concluded the cost of these sensors cannot be independently determined.

V.C.25. Team 2004-25

- Team 2004-25 participated in the 2005 GCE as Team 2005-22. See paragraph V.C.46.

- The Team 2004-25 technical paper was one of 19 technical papers described by DARPA as “completely acceptable” on November 13, 2003, approximately four months prior to the 2004 GCE ([83]).

- The Team 2004-25 website was updated prior to the 2005 GCE, but reported no additional identifying information for the sensors in use by the team.

- Team 2004-25 passed on their turn on the second day of the 2004 QID ([84]), completed the 2004 QID course on the third day of the 2004 QID ([85]), and partially completed the 2004 QID course on the last day of the 2004 QID ([79]).
- Team 2004-25 was selected to participate in the 2004 GCE ([80]).

V.C.25.a. Japan Servo DME 60B6HF, unknown linear potentiometer, and Bodine Electric 42A-5N

In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-25 stated: “The Challenge Vehicle uses optical encoders to determine the position and velocity of the brake, steering and throttle motors.” ([49], p. 11). Team 2004-25 also stated: “The throttle is actuated by a 24 volt Japan Servo Company model DME 60B6HF permanent magnet dc gear motor with an integral encoder. The encoder provides throttle position feedback...” ([49], p. 2); “A linear potentiometer attached to the actuator provides feedback for the braking system.” ([49], p. 3); and “Autonomous steering actuation is accomplished using a Bodine 24 volt permanent magnet right-angle gear motor (model 42A-5N) with an integral encoder (model 0941). ... As with the throttle and brake actuators, the encoder detects steering angle and feeds this information back to a motor controller.” ([49], p. 3).

As a result, the author concluded: the optical encoder determining the position and velocity of the throttle motor was the integral encoder of the Japan Servo DME 60B6HF motor, and considers this sensor known; a linear potentiometer, in lieu of an optical encoder, was in use by Team 2004-25 for determining the position and velocity of the braking system linear actuator, and otherwise considers this sensor unknown; and the optical encoder determining the position and velocity of the steering motor was the integral encoder of the Bodine Electric 42A-5N motor, and considers this sensor known.

V.C.25.b. Unknown state sensors

In response to 2004 SQ 1.c.1 (see Table XXII), Team 2004-25 stated: “We also monitor the temperature of the electronic enclosure and battery voltage.” ([49], p. 7). In response to 2004 GCE SQ 1.f.1 (see Table XXII), Team 2004-25 stated: “Status sensors are used to monitor the health of the overall vehicle and its subsystems. As a minimum, we expect to monitor battery voltage for each on-board battery and the temperature inside all electronic enclosures.” ([49], p. 11). Team 2004-25 also stated: “In addition, the vehicle carries a Yamaha 1600-watt gasoline powered AC generator that powers the AC computers and fans and indirectly charges two 12-volt lead acid batteries.” ([49], p. 3), but reported no additional identifying information. The author concluded two “battery voltage” sensors were in use by Team 2004-25, but otherwise considers the “battery voltage” sensors unknown, and considers the temperature sensors in use by the team unknown.

V.C.25.c. Unknown thermal camera

In response to 2004 GCE SQ 2.b (see Table XXII), Team 2004-25 stated: "These tests will help us refine and integrate the laser rangefinder, thermal camera and radar systems." ([49], p. 14), but reported no additional identifying information for the thermal camera in use by the team. Team 2004-25 does not make any other reference to a "thermal camera"; all other references to a camera are to a "visible light camera". The author concluded no thermal camera was in use by Team 2004-25.

V.C.25.d. Unknown camera

Team 2004-25 stated: "...the Challenge Vehicle uses radar, laser rangefinders, and a visible light camera to sense local obstacles and discontinuities." ([49], p. 8), but reported no additional identifying information for the visible light camera in use by the team. The author concluded one camera was in use by Team 2004-25, but otherwise considers this sensor unknown.

V.C.25.e. Unknown SICK LIDAR sensors

Figure 3 ("Computational Hardware Layout") of the team technical paper ([49], p. 5) reported "2 LRF" (two laser range finders) were in use by Team 2004-25. However, Team 2004-25 stated: "Two laser rangefinders are mounted vertically from the roll cage of the vehicle. These laser rangefinders are used to detect obstacles in front of the vehicle. *The third laser rangefinder* is mounted on the brush guard in front of the vehicle." ([49], pp. 9 - 10, *emphasis added*).

Team 2004-25 also stated: "Three Sick optic laser rangefinders, shown in Figures 10 and 11, actively scan the surroundings for obstacles. These units have a horizontal field of view of 90 degrees." ([49], p. 9). Review of Figures 10 and 11 revealed the LIDAR sensor depicted by Figure 10 is a SICK LMS 200-30106 ("200-30106") and the LIDAR sensor depicted by Figure 11 is either a LMS 211-30106 or -30206, or LMS 221-30106 or -30206. The SICK LMS 211-S14 ("211-S14") has a scanning angle of 90 degrees ([74]); other models used by teams participating in the 2004 QID and GCE, including sensors matching those depicted by Figures 10 and 11 above, have a scanning angle of 100 or 180 degrees.

Although Team 2004-25 stated that three SICK LIDAR sensors were in use by the team, Team 2004-25 did not report the quantity of each depicted sensor or the model number for the SICK LIDAR sensors depicted by Figure 11, and the Team 2004-25 reported scanning angle does not conform to the manufacturer reported scanning angle for the potential sensors depicted. The author concluded three SICK LIDAR sensors were in use by Team 2004-25, but considers the quantities of each sensor depicted by Figures 10 and 11 and model number of the sensor depicted by Figure 11 unknown.

V.C.25.f. Unknown Eaton RADARs

Team 2004-25 stated: “Two Eaton VORAD radar units are mounted to the front of the Challenge Vehicle, each with a horizontal field of view of approximately 14 degrees.” ([49], p. 10), but reported no additional identifying information. Although the “horizontal field of view” of “approximately 14 degrees” reported by Team 2004-25 does not conform to the radar beam width of 12 degrees reported by Eaton, the “output power” of “3 mW” and “operating [frequency]” of “24.7 GHz” reported by Team 2004-25 conform to the transmitted RF power of 3.0 mW and frequency of 24.725 GHz reported by Eaton ([162]).

Neither Team 2005-22 nor its co-participant Team 2005-23 referred to RADAR sensors in use by the team ([58], [164], and [59]).

The author considers it was likely the Eaton EVT-300 was in use by Team 2004-25. However, in the absence of an affirmative statement from Team 2004-25 that the Eaton EVT-300 was in use by the team, the author concluded two Eaton RADARs were in use by Team 2004-25, but considers the model number of these sensors unknown.

V.C.25.g. Unknown Honeywell INS

Team 2004-25 stated: “The Challenge Vehicle uses a TALIN integrated DGPS/INS system from Honeywell for positioning.” ([49], p. 12), but reported no additional identifying information.

TALIN is an acronym for the Tactical Advanced Land Inertial Navigator (TALIN) product family, and multiple model numbers exist ([165]). Neither Team 2005-22 nor its co-participant Team 2005-23 referred to a Honeywell TALIN INS in use by the team ([58], [164], and [59]).

The author concluded one Honeywell INS was in use by Team 2004-25, but considers the model number of this sensor unknown.

V.C.25.h. Unknown wheel encoder

Team 2004-25 stated: “Actual speed, as determined from the DGPS/INS unit and a wheel encoder...” ([49], p. 9) and “A fourth encoder provides wheel velocity...” ([49], p. 11), but reported no additional identifying information. The author concluded one wheel encoder was in use by Team 2004-25, but otherwise considers this sensor unknown.

V.C.26. Team 2005-01

- Team 2005-01 participated in the 2004 GCE as Team 2004-02. See paragraph V.C.2.

- The Team 2005-01 website was updated prior to the 2007 Urban Challenge, and reported little additional identifying information for the sensors in use by the team.

- Team 2005-01 did not publish its results via the Journal of Field Robotics.

V.C.26.a. FLIR A20M and unknown AVT camera

Team 2005-01 stated: "[The challenge vehicle's Artificial Intelligence software] is utilized by [the challenge vehicle's] stereo cameras, thermal *cameras*, and RADAR." ([10], p. 5, *emphasis added*), but reported no additional identifying information for the thermal cameras in use by the team. Via Table 1 ("Computing Hardware") of the team technical paper ([10], p. 4), Team 2005-01 reported one color camera was in use by the team, but alternately stated: "The RSE also uses wiper blades to keep mud and rain from blocking the stereo and color *cameras*." ([10], p. 9, *emphasis added*). Via Figure 4 ("Sensing & Stopping Distances") of the team technical paper ([10], p. 9), Team 2005-01 reported one FLIR camera and one color camera were in use by the team.

Via Figure 2 ("Computing Systems") of the team technical paper ([10], p. 5), Team 2005-01 reported two EMX Raytheon thermal cameras were in use by the team; Figure 2 did not report either the FLIR camera or color camera were in use by the team. Figure 2 of the Team 2005-01 technical paper ([10], p. 5) is virtually identical to Figure 2 of the Team 2004-02 technical paper ([9], p. 6).

Team 2005-01 alternately stated: "The RSE also uses wiper blades to keep mud and rain from blocking the stereo and color *cameras*." ([10], p. 9, *emphasis added*) and "Other software used in [the challenge vehicle] comes from established vendors with a long history of application success. This software is utilized by [the challenge vehicle's] stereo cameras, thermal *cameras*, and RADAR." ([10], p. 5, *emphasis added*). In addition, Team 2005-01 reported a FLIR camera was in use by the team, and stated: "High speed (400 Mbits/s) Red, Green, Blue (RGB) *cameras* are used mainly to enhance [the challenge vehicle's] ability to find road edges." ([86], *emphasis added*).

As a result, the author concluded Figure 2 of the Team 2005-01 technical paper ([10]) was in error, that one color camera and one thermal camera were in use by Team 2005-01 despite several references to "cameras", considers the FLIR camera in use by the team known based on the 2004 GCE published record and Figure 4 of the team technical paper ([10]), and considers the quantity and manufacturer of the color camera in use by the team known, but model number unknown, based on the 2004 GCE published record and Figure 4 of the team technical paper ([10]). See paragraph V.C.2.

V.C.26.b. Unknown Eaton RADAR, Amphitech OASys, and unknown RADARs

Team 2005-01 stated: "Other software used in [the challenge vehicle] comes from established vendors with a long history of application success. This software is utilized by [the challenge vehicle's] stereo cameras, thermal cameras, and RADAR." ([10], p. 5). Via Figure 4 ("Sensing & Stopping Distances") of the team technical paper ([10], p. 9), Team 2005-01 reported one "Eaton VORAD RADAR", one "Epsilon Lambda RADAR", and one "OASYS RADAR" were in use by the team. Team 2005-01 does not make any other reference to RADAR throughout the team technical paper ([10]) and reported no additional identifying information for the RADAR in use by the team.

In addition, Team 2005-01 reported RADAR in use by the team obliquely, via a page that could only be reached from the team website's site map. Team 2005-01 stated: "Eaton Vorad provides three of [the challenge vehicle's] seven RADAR units..." ([86]). A picture hosted by Team 2005-01 via the Team 2005-01 website denotes three sensors installed on the team challenge vehicle by red circles. The number on the hood of the challenge vehicle in the picture is "23", which was Team 2005-01's DARPA-assigned team number during the 2005 NQE. However, the resolution of this picture is limited, and the author was unable to identify the sensors in use by Team 2005-01. As a result, the author concluded one Eaton RADAR *system* utilizing three sensors, such as one antenna assembly and two side sensors, was in use by Team 2005-01 during the 2005 GCE, but considers the model number of this *system* unknown.

Team 2005-01 stated: "[The challenge vehicle's] RADAR range is from over 1 foot to 5 miles!" and "[The challenge vehicle] is using a Northrop Grumman LN-270 INS and an Amphitech OASYS 3D MWM RADAR..." ([86]). Team 2005-01 also stated: "[The Amphitech OASys] moves up and down and can see up to 5 miles in front of [the challenge vehicle]..." ([166]). The team website hosts a picture of the Amphitech OASys identical to the picture from the press release, but reported no additional information. As a result, the author concluded one Amphitech OASys was in use by Team 2005-01, and considers this sensor known.

Aside from Figure 4 of the team technical paper ([10], p. 9), Team 2005-01 did not refer to the Epsilon Lambda RADAR in use by the team, and a detailed search of the team website for additional detail was unsuccessful. Team 2005-01 stated seven RADAR units were in use by the team ([86]). The author considers it unlikely that three Epsilon Lambda RADARs were in use by Team 2005-01, although one Epsilon Lambda ELSC71-1A was in use by Team 2004-02 during the 2004 QID and GCE. As a result, the author considers additional RADARs in use by Team 2005-01 unknown.

V.C.26.c. SICK LMS 211-30206 and unknown SICK LIDAR sensors

Via Figure 4 of the team technical paper ([10], p. 9), Team 2005-01 reported three "SICK 291" LIDAR sensors and one "SICK 211" LIDAR sensor were in use by the team. Team 2005-01 stated: "If an obstacle is detected in the path, the vehicle detects this with either the four LADAR sensors or the five bumblebee cameras." ([10], p. 12), but reported no additional identifying information.

Team 2005-01 reported LIDAR sensors were in use by the team ([86]), but a detailed search of the team website for additional detail was unsuccessful.

The author considers the SICK LMS 211-30206 LIDAR sensor in use by Team 2005-01 known based on the 2004 GCE published record and Figure 4 of the team technical paper ([10], p. 9), and considers the quantity and manufacturer of the other SICK LIDAR sensors in use by Team 2005-01 known, but model numbers of these sensors unknown.

V.C.27. Team 2005-02

- Team 2005-02 participated in the 2004 GCE as Team 2004-04. See paragraph V.C.4.
- The Team 2005-02 website reported no additional identifying information for the sensors in use by the team.

Team 2005-02 stated: "An array of sensors including cameras, ladar, and radar are used for path modification due to obstacles and to acquire and track smooth terrain." ([167], p. 2).

V.C.27.a. SICK LMS 291-S05 LIDAR sensors

Team 2005-02 stated: "Also mounted on the sensor cage are two SICK ladars: one rotating ladar for 3D obstacle detection, the other fixed to scan the ground ahead of the vehicle for terrain slope estimation, tuned for negative obstacle detection." ([167], p. 8) and "Also, a third SICK ladar for planar obstacle detection ... [is] mounted on the front of the vehicle at bumper level." ([167], p. 8), but reported no additional identifying information.

Team 2005-02 later stated: "Also mounted on the sensor cage are two SICK LADARs that scan the ground ahead of the vehicle for terrain slope estimation; one tuned for negative obstacle detection and the other for smooth terrain detection. Also, an additional SICK LADAR aimed parallel to the ground plane is mounted on the front of the vehicle at bumper level for planar obstacle detection." ([50], p. 604) and "There are three Smart Sensors that rely on LADAR range data to produce their results: the Terrain Smart Sensor (TSS), the Negative Obstacle Smart Sensor (NOSS) and the Planar LADAR Smart Sensor (PLSS). All three components use the LMS291-S05 from Sick Inc. for range measurement." ([50], p. 607).

The author concluded three SICK LMS 291-S05 LIDAR sensors were in use by Team 2005-02, and considers these sensors known.

V.C.27.b. Unknown Eaton RADAR

Team 2005-02 stated: "...a long-range Eaton Vorad radar for free space detection [is] mounted on the front of the vehicle at bumper level." ([167], p. 8), but reported no additional identifying information. In addition, Figure 2 ("System Architecture") of the team technical paper ([167], p. 4) reported a "VORAD Radar" was in use by Team 2005-02.

Team 2005-02 did not refer to the Eaton RADAR via the Journal of Field Robotics ([50]). Team 2005-02 stated: "Additional sensors were mounted on the vehicle for experimental purposes, but were not activated for the Darpa Grand Challenge (DGC) event. Each sensor system is described in detail later in this paper." ([50], p. 604).

The author concluded the unknown Eaton RADAR was not in use by Team 2005-02 during the 2005 GCE.

V.C.27.c. Unknown camera

Team 2005-02 stated: "These sensors include five cameras equipped with automatic iris. Two of these cameras are used for obstacle detection by stereo vision. The remaining three detect the path in a scene." ([167], p. 8). However, Team 2005-02 later stated: "The Pathfinder Smart Sensor (PFSS) consists of a single color camera mounted in the sensor cage and aimed at the terrain in front of the vehicle." ([50], p. 609).

Team 2005-02 reported no additional identifying information for the camera in use by the team. The author concluded one camera, in lieu of five, was in use by Team 2005-02, but otherwise considers this sensor unknown.

V.C.27.d. Smiths Aerospace North Finding Module

Team 2005-02 stated: "The processing of all navigation data is done by a Smiths Industries Northfinding Module (NFM), which is an inertial navigation system. This module maintains Kalman Filter estimates of the vehicle's global position, orientation, as well as linear and angular velocites [*sic*]. It fuses internal accelerometer and gyroscope data, with data from an external NMEA GPS and external odometer." ([167], p. 6) and "In summary, the Smith's IMU fuses and filters information from the NavCom or Garmin GPS, as well as a vehicle odometer." ([167], p. 7).

The author was unable to locate a manufacturer named "Smiths Industries", but a manufacturer named "Smiths Aerospace" existed at the time of the 2004 QID and GCE, and has since been acquired by GE.

Team 2005-02 later stated: "The processing of all navigation data is done by a Smiths Aerospace North-finding Module (NFM), which is an inertial navigation system. This module maintains Kalman filter estimates of the vehicle's global position and orientation, as well as linear and angular velocities. It fuses internal accelerometer and gyroscope data, with data from an external NMEA GPS, and external odometer." ([50], p. 607).

Without GPS integration, the "north finding" module determines azimuth only. Although GE stated the North Finding Module adds "GPS/Inertial Kalman Filter Solution" and "Inertial or GPS backup" ([168]), the author does not consider a North Finding Module to be either an INS or an IMU. However, the author concluded one Smiths Aerospace North Finding Module was in use by Team 2005-02, and considers this sensor known.

V.C.27.e. Unknown NavCom GPS receiver

Team 2005-02 stated: "The GPS signal provided to the (NMF) [*sic*] comes from one of the two sensors onboard. These include a NavCom Technologies Starfire 2050..." ([167], p. 6), but reported no additional identifying information.

Team 2005-02 later stated: "The GPS signal provided to the NFM comes from one of the two onboard sensors. These include a NavCom Technologies Starfire 2050..."([50], p. 607), but reported no additional identifying information.

The NavCom StarFire SF-2050 GPS receiver and StarFire network were in use by 12 of 40 NQE semifinalists ([102]) and 6 of 23 GCE finalists ([103]). At least two different NavCom StarFire models existed at the time of the 2005 GCE, and they targeted different markets: "The SF-2050G is designed for backpack GIS and mapping applications while the SF-2050M is ideal for vehicle mounting to suit a wide variety of machine guidance and control applications." ([104]). NavCom launched both the SF-2050G and SF-2050M receivers in 2002 ([105]). The author concluded one NavCom GPS receiver was in use by Team 2005-02, but considers the model number of this sensor unknown.

V.C.28. Team 2005-03

- Team 2005-03 participated in the 2004 QID and GCE as Team 2004-06. See paragraph V.C.6.
- The Team 2005-03 website was no longer available.
- Team 2005-03 did not publish its results via the Journal of Field Robotics.

V.C.28.a. Proprietary LIDAR sensor

Team 2005-03 stated: "A unique LADAR terrain mapping and obstacle detection system is employed as the single sensor." ([33], p.7), but reported no additional identifying information.

The author considers the proprietary LIDAR sensor in use by Team 2005-03 known, but concluded the cost of this sensor cannot be independently determined.

V.C.28.b. NavCom SF-2050G and NovAtel ProPak-LBplus

Team 2005-03 stated: “Dual GPS receivers are used, both to establish direction at rest and to provide redundancy. The first is a Navcom 2050G using the Starfire subscription service and the second is a Novatel ProPak-LB receiver using the Omnistar subscription service.” ([33], p. 7).

The author concluded one NavCom SF-2050G and one NovAtel ProPak-LBplus[21] were in use by Team 2005-03, and considers these sensors known.

V.C.28.c. Unknown IMU

Team 2005-03 stated: “Also, there is a 6-axis inertial system mounted on the LADAR head (described below) that is used to correct the LADAR signal as well as provide pitch and roll information for correcting the FOG gyro signal. The third gyro in the 6-axis system is used as a redundant backup for the FOG gyro. ” ([33], p. 7), but reported no additional identifying information for the “6-axis inertial system” in use by the team. The author considers it likely Team 2005-03 was referring to 6DOF, in lieu of “6-axis”, and concluded one IMU was in use by Team 2005-03, but otherwise considers this sensor unknown.

V.C.28.d. Honeywell TALIN-4000

Team 2005-03 stated: “Additionally, there is a Honeywell TALON-4000 unit that might be installed by race time.” ([33], p. 7). Honeywell did not manufacture a model number “TALON-4000”. TALIN is an acronym for the Tactical Advanced Land Inertial Navigator (TALIN) product family, and the correct model number is “TALIN-4000” ([165]). The author concluded “TALON-4000” was an error and that Team 2005-03 was referring to the Honeywell TALIN-4000, and considers this sensor known. However, Team 2005-03 stated this sensor “might be installed by race time”. In the absence of an affirmative statement by Team 2005-03 that the Honeywell TALIN-4000 was in use during the 2005 GCE, the author concluded this sensor was not in use during the 2005 GCE.

V.C.29. Team 2005-04

- The Team 2005-04 website reported no additional identifying information for the sensors in use by the team.
- Team 2005-04 published its results via the Journal of Field Robotics, however Team 2005-04 reported no additional identifying information for the sensors in use by the team via the Journal of Field Robotics.

Team 2005-04 stated: "A set of sensors (LIDAR's, radars, cameras and ultrasonic transducers) and a GPS and IMU unit provide extensive sensing capability." ([169], p. 2) and "[The challenge vehicle] has LIDAR's, radars, cameras and ultrasonic sensors to sense its immediate surroundings." ([169], p. 8).

V.C.29.a. NovAtel ProPak-LBplus

Team 2005-04 stated: "The GPS used is a Novatel Propak LB-L1L2 with Omnistar HP differential correction." ([169], p. 7)[21]. The author concluded one NovAtel ProPak-LBplus was in use by Team 2005-04, and considers this sensor known.

V.C.29.b. Unknown RADAR

Team 2005-04 stated: "The second radar has a slewing dish antenna and is an in-house development." ([169], p. 8), but reported no additional identifying information. The author concluded one "second radar" was in use by Team 2005-04 and that Team 2005-04 was the manufacturer of this sensor, but considers the model number of this sensor unknown, and concluded the cost of this sensor cannot be independently determined.

V.C.29.c. Unknown stereo camera pair

Team 2005-04 stated: "The stereo camera system is mounted on the top and again pointed ahead." ([169], pp. 8 - 9), but reported no additional identifying information. The author concluded one stereo camera pair was in use by Team 2005-04, but otherwise considers this sensor unknown.

V.C.29.d. Unknown ultrasonic range finders

Team 2005-04 stated: "8 ultrasonic rangefinders are mounted around the vehicle and are for short distance sensing at low speeds, and in particular for sensing in confined areas when the vehicle is operating at low speeds and potentially without accurate position information." ([169], p. 9), but reported no additional identifying information. The author concluded eight ultrasonic range finders were in use by Team 2005-04, but otherwise considers these sensors unknown.

V.C.29.e. Wheel speed sensors

Team 2005-04 stated: "Localization, vehicle motion status, and internal state sensing is accomplished using ... wheel speed sensors that were added to the vehicle..." ([169], p. 11), but reported no additional identifying information. The author estimated the quantity of wheel speed sensors in use by Team 2005-04 in accordance with paragraph V.B.5.c., but otherwise considers these sensors unknown.

V.C.30. Team 2005-05

- Team 2005-05 participated in the 2004 QID and GCE as Team 2004-07. See paragraph V.C.7.

- The Team 2005-05 website reported limited additional identifying information for the sensors in use by the team.

The Team 2005-05 technical paper ([34]) described two vehicles. However, only one of the two vehicles participated in the 2005 GCE as the challenge vehicle. The discussion that follows is based on the Team 2005-05 challenge vehicle.

Team 2005-05 stated: “Our sensing strategy is to use Sick laser measurement systems ('ladars') to detect significant positive and negative obstacles (roughly defined as too-abrupt changes of apparent ground elevation), and a Mobileye Pathfinder vision system to detect the edges of the road or trail.” ([34], p. 5).

V.C.30.a. Unknown SICK LIDAR sensors

Team 2005-05 stated: “Each [challenge vehicle] has one or more Sick LMS-291 ladars...” ([34], p. 5). Via Figure 2 (“Arrangement of vertical-plane Sick LMS-291 ladars on the Golem vehicles”) of the team technical paper ([34], p. 6), Team 2005-05 reported the challenge vehicle had three “vertical-plane Sick LMS-291 ladars”. Team 2005-05 also stated: “We also use a Sick LMS-221 which sweeps its beam in a horizontal plane through a 180-degree arc of azimuth. It can be supplemented by a Sick LMS-291 which sweeps a 90-degree arc in a horizontal plane at a different height.” ([34], p. 6). Team 2005-05 did not report whether the horizontal plane LIDAR sensors were in use on one, the other, or both vehicles, or even if the supplemental horizontal plane LIDAR sensor was in use by the team.

Team 2005-05 later stated: “The sensors used for terrain perception included a Sick LMS-221 ladar... There were also four Sick LMS-291 ladars...” ([170], p. 529), but did not report the model number for the LIDAR sensors in use by the team. The team website reported no additional identifying information for the LIDAR sensors in use by the team.

As a result, the author concluded five SICK LIDAR sensors were in use by Team 2005-05, but considers the model numbers of these sensors unknown.

V.C.30.b. Mobileye ACP5

Team 2005-05 stated: “Our sensing strategy is to use ... a Mobileye Pathfinder vision system to detect the edges of the road or trail.” ([34], p. 5); “Mobileye's Pathfinder system is a vision system using images from a forward looking camera to detect paved road or unpaved trail boundaries using intensity contrast information and texture analysis.” ([34], p. 8); and “The prototype system developed by Mobileye uses a miniature lipstick analog CCD camera with a typical 45 degree horizontal field of view for acquiring video images." ([34], p. 8).

The "Pathfinder system" was an application designed to leverage an existing product, the Mobileye ACP5 On-Line Vision System ([171]). The Pathfinder system may no longer be in production and the ACP5 is not a current "Manufacturer Product". The author concluded one Mobileye ACP5 was in use by Team 2005-05, and considers this sensor known.

V.C.30.c. NovAtel ProPak-LBplus

Team 2005-05 stated: "[The challenge vehicles] each use a NovAtel Propak-LBPlus receiver for GPS positioning with Omnistar HP correction. During our development process we also had good results using a Trimble AgGPS 114 receiver with Omnistar VBS correction." ([34], p. 5).

Team 2005-05 later stated: "The sensors mounted on [the challenge vehicle] ... included a Novatel ProPak LB-Plus differential GPS receiver with nominal 14-cm accuracy using OmniStar HP correction..." ([170], p. 529).

The author concluded one NovAtel ProPak-LBplus[21], in lieu of a Trimble AgGPS 114, was in use by Team 2005-05, and considers this sensor known.

V.C.30.d. Systron Donner C-MIGITS III

Team 2005-05 stated: "A C-MIGITS III inertial navigation system from BEI Technologies is used to track changes in orientation." ([34], p. 5).

Team 2005-05 later stated: "The sensors mounted on [the challenge vehicle] ... included ... a BEI C-MIGITS inertial measurement unit (IMU)..." ([170], p. 529).

The C-MIGITS III IMU is a product of Systron Donner, which is a division of BEI. The author concluded one Systron Donner C-MIGITS III was in use by Team 2005-05, and considers this sensor known.

V.C.30.e. Unknown Hall Effect sensor

Team 2005-05 stated: "During GPS outages we continue to track position using the C-MIGITS III and measurements of wheel rotation and steering angle." ([34], p. 5) and "A Hall sensor and a ring of magnets attached to the rear differential form a high-accuracy odometer that measures revolutions of the rear axle." ([34], p. 11).

Team 2005-05 later stated: "The sensors mounted on [the challenge vehicle] ... included ... a custom Hall encoder on the differential for odometry with approximately 10-cm accuracy..." ([170], p. 529).

The author concluded one Hall Effect sensor was in use by Team 2005-05, but otherwise considers this sensor unknown.

V.C.31. Team 2005-06

- The hyperlink to the Team 2005-06 website hosted by DARPA via the Archived Grand Challenge 2005 website ([19]) redirected to another website, which was no longer available.

V.C.31.a. Oxford RT3000

Team 2005-06 stated: “[Team 2005-06] chose to use the RT3000 from Oxford Technical Solutions to provide vehicle localization.” ([172], p. 8) and “[Team 2005-06] has installed two Oxford RT3000 GPS units on its vehicle. Rather than try to integrate the data from both units at the same time, [Team 2005-06] instead chose to use the two units in a primary/secondary role. Both units are always active, but if one unit stops sending data for some reason, the other unit immediately takes over and becomes the primary unit. This configuration ensures that [Team 2005-06] will have accurate GPS information at all times.” ([172], p. 9).

Team 2005-06 later stated: “The position and pose of [the challenge vehicle] is reported by an Oxford Technical Solutions RT3000, an integrated GPS with two antennas and an Inertial Navigation System (INS).” ([28], p. 513).

The author concluded, although Team 2005-06 may have installed two Oxford RT3000 sensors for redundancy, only one at a time was in use during the 2005 GCE, and considers this sensor known.

V.C.31.b. Unknown stereo camera pair

Team 2005-06 stated: “Stereographic cameras capable of producing a three-dimensional point cloud are also mounted on the front of the vehicle behind the windshield. These cameras operate in a secondary mode to the LADAR units, and they are only used to help identify the road and to confirm the existence of obstacles.” ([172], p. 9), but reported no additional identifying information.

Team 2005-06 later stated: “While other sensors were considered for inclusion into the vision system, their contributions were not considered useful enough to warrant the complications they would have added to the sensor fusion algorithms.” ([28], p. 525). The author concluded the stereo camera pair was not in use by Team 2005-06 during the 2005 GCE.

V.C.31.c. Riegl LMS-Q120 and unknown SICK LIDAR sensors

Team 2005-06 stated: “[Team 2005-06] has mounted three Sick LMS 291 LADAR units and one RIEGL LMS-Q120 LADAR on the front of its vehicle.” ([172],

p. 9), but did not report the model number of the SICK LIDAR sensors in use by the team.

Team 2005-06 later stated: "Two Sick LMS 291 Laser Detecting and Ranging (LADAR) devices provided the autonomous vehicle with environmental sensing." ([28], p. 513), but did not report the model number of the SICK LIDAR sensors in use by the team or report the Riegl LMS-Q120 was in use during the 2005 GCE.

The author concluded the Riegl LMS-Q120 was not in use by Team 2005-06 during the 2005 GCE and that two SICK LIDAR sensors were in use by the team, but considers the model number of these sensors unknown.

V.C.31.d. Unknown wheel speed sensor

Team 2005-06 stated: "The RT3000 also accepts additional custom inputs to reduce drift in its estimate of vehicle position when GPS is not available. ... One of these custom inputs is a wheel speed sensor which provides TTL pulses based upon an encoder placed on a single wheel on the vehicle." and "The wheel speed sensor consisted of a digital sensor capable of detecting either ferrous metal or magnets that are in motion." ([28], p. 513). The author concluded one wheel speed sensor was in use by Team 2005-06, but otherwise considers this sensor unknown.

V.C.32. Team 2005-07

- Team 2005-07 participated in the 2004 QID as Team 2004-08. See paragraph V.C.8.
- The Team 2005-07 website reported no additional identifying information for the sensors in use by the team.
- The hyperlink to the Team 2005-07 technical paper hosted by DARPA via the Archived Grand Challenge 2005 website ([19]) was actually a hyperlink to the team website. The author was unable to locate a copy of the Team 2005-07 technical paper on the team website. As a result, the author concluded the technical paper was unavailable for review.
- Team 2005-07 did not publish its results via the Journal of Field Robotics.

V.C.32.a. Unknown SICK LIDAR sensors, unknown GPS receiver, and unknown cameras

Team 2005-07 published a description of their challenge vehicle via the team website ([118]), and the caption of a picture embedded in this reference reported SICK LIDAR sensors, cameras, and a GPS receiver were in use by the team. Team 2005-07 stated: "Commercial camcorders that provide image stabilization collect video from inside the vehicle allowing both 2 dimensional and stereo scene analysis." and "We use two SICK Lidar units to monitor the terrain in front of the moving vehicle." ([118]). Team 2005-07 did not report the model number of the SICK LIDAR sensors in use by the team, or the quantity, manufacturer, or model number of the cameras or GPS receiver.

As a result, the author concluded two SICK LIDAR sensors were in use by Team 2005-07, but considers the model number of these sensors unknown; estimated one GPS receiver was in use by Team 2005-07, but otherwise considers this sensor unknown; and considers the cameras in use by Team 2005-07 unknown.

V.C.33. Team 2005-08

- The Team 2005-08 website was no longer available.
- Team 2005-08 did not publish its results via the Journal of Field Robotics.

V.C.33.a. SICK LMS 291-S14 and SICK LMS 211-30106

Via Figure 1 ("F250 Platform") of the team technical paper ([173], p. 4), Team 2005-08 reported a "Vertical SICK" and a "Profile SICK" were in use by the team. However, via Figure 2 ("Hardware Configuration") of the team technical paper ([173], p. 7), Team 2005-08 reported three SICK sensors were in use by the team. Figure 6 ("Sensor position and envelopes") of the team technical paper ([173], p. 12) reported "sensor position and envelope" for the profile SICK referred to by Figure 1.

Team 2005-08 stated: "A combination of SICK LMS line scan ladar units are used for close range terrain sensing on [the challenge vehicle]. The LMS 290-S14 (90 deg at 0.5 deg/pixel with 75Hz scan rate) mounted in the roof sensor suite is used to provide a vertical slice of the terrain in front of the vehicle for assessment of the support surface, especially in undulating terrain. The LMS 211-30106 (180 deg at 1 deg/pixel with 75Hz scan rate) mounted on the front sensor rack is used both for profile following and hazard detection." ([173], p. 9).

Three SICK LIDAR sensors had model numbers ending in "-S14" at the time of the 2005 GCE ([75]): LMS 211-S14, 221-S14, and 291-S14. Based on its use by other teams, the author concluded "LMS 290-S14" was an error, and that the sensor in use by Team 2005-08 was a SICK LMS 291-S14, and considers this sensor known.

In addition, the author concluded two SICK LIDAR sensors were in use by Team 2005-08, in lieu of three reported via Figure 2 of the team technical paper, and that a SICK LMS 211-30106 was the second SICK LIDAR sensor, and considers this sensor known.

V.C.33.b. Unknown ultrasonic sensors

Team 2005-08 stated: “Ultrasonic sensors are present at the four corners of the vehicle covering the left and right sides at close range for tunnel following.” ([173], p. 11), but reported no additional identifying information.

The author concluded four ultrasonic sensors were in use by Team 2005-08, but otherwise considers these sensors unknown.

V.C.33.c. Unknown Vansco RADAR

Team 2005-08 reported a “Vansco Doppler radar sensor” was in use by the team ([173], p. 8). Vansco manufactured a “740 Radar” product ([174]).

However, the author was unable to confirm this model number was current at the time of the 2005 GCE, and concluded one Vansco RADAR was in use by Team 2005-08, but considers the model number of this sensor unknown.

V.C.33.d. Sony DFW-VL500 and unknown cameras

Via Figure 1 (“F250 Platform”) of the team technical paper ([173], p. 4), Team 2005-08 reported “Road Following Color Cameras” were in use by the team. Via Figure 2 (“Hardware Configuration”) of the team technical paper ([173], p. 7), Team 2005-08 reported four cameras were in use by the team, two as a stereo camera pair. Figure 6 (“Sensor position and envelopes”) of the team technical paper ([173], p. 12) reported “sensor position and envelope” for the road-following cameras referred to by Figure 1.

Team 2005-08 stated: “A fixed baseline stereo pair of firewire color cameras (Sony DFW-VL500) is located on the front sensor rack to provide dense local range data.” ([173], p. 11). Team 2005-08 reported no additional identifying information for the two road-following cameras in use by the team.

The author concluded two Sony DFW-VL500 cameras were in use by Team 2005-08 as a stereo camera pair, and considers these sensors known. The author concluded two “road-following” cameras were in use by Team 2005-08, but otherwise considers these sensors unknown.

V.C.33.e. Unknown active bumper

Team 2005-08 stated: “An active bumper is integrated into the front sensor rack to provide a last line of response for protection of vehicle hardware and a means to recover from sensing and planning errors that could place the vehicle in contact with obstacles.” ([173], p. 11), but reported no additional identifying information.

The author concluded one active bumper was in use by Team 2005-08, but otherwise considers this sensor unknown.

V.C.34. Team 2005-09

- The hyperlink to the Team 2005-09 website hosted by DARPA via the Archived Grand Challenge 2005 website ([19]) redirected to a URL which resulted in a "404 File Not Found" error. However, a search of that domain revealed the Team 2005-09 website was relocated to an alternate URL on the same domain. The Team 2005-09 website reported no additional identifying information for the sensors in use by the team.

V.C.34.a. Unknown SICK LIDAR sensors

Team 2005-09 stated: "Eight SICK laser range finders provide a two-dimensional range/distance map up to 40 meters with a 100 degree field of view. Two vertically mounted lasers provide ground plane information. Three lasers are mounted horizontally at different angles allowing for both short and long range detection of road obstacles. A fourth laser is mounted on a gimbal that allows for dynamic pointing in order to compensate for vehicle pitch and terrain variations. Finally, two downward looking lasers are mounted on the roof to derive road characteristics." ([175], p. 7), but reported no additional identifying information.

Team 2005-09 later stated: "The sensing centers around eight laser sensors were [*sic*] oriented in different directions and mounted on the top and front of the vehicle..." and "Two vertically mounted lasers provide information about the ground plane. Three lasers, mounted horizontally at different angles, provide both short- and long-range detection of road obstacles. A sixth horizontal laser is mounted on gimbals, and points dynamically to compensate for vehicle pitch and terrain variations. Finally, two downward-looking lasers are mounted on the roof to detect road characteristics." ([52], p. 813), but reported no additional identifying information.

The author concluded eight SICK LIDAR sensors were in use by Team 2005-09, but otherwise considers these sensors unknown.

V.C.34.b. Unknown Eaton RADAR

Team 2005-09 stated: "Additional sensors include an Eaton Vorad doppler range rate radar developed for the trucking industry." ([175], p. 8), but reported no additional identifying information.

Team 2005-09 later stated, in a series of goals prior to the 2005 GCE: "May. Prepare for a DARPA site visit. Testing had moved from obstacle avoidance to finding a balance between speed, planning, and reaction time. At this point, sensing strategies were unresolved with stereo vision, radar, and machine vision for road detection under consideration." ([52], p. 831). Team 2005-09 did not refer to the Eaton RADAR elsewhere throughout the Journal of Field Robotics ([52]), or report RADAR was in use by the team during the 2005 GCE.

The author concluded the unknown Eaton RADAR was not in use by Team 2005-09 during the 2005 GCE.

V.C.34.c. Unknown stereo camera pair and unknown machine vision system

Team 2005-09 stated: “In addition to the obstacle detection sensors, [the challenge vehicle] has a vision system to detect the edges of and center of the road.” ([175], p. 8), but reported no additional identifying information.

Team 2005-09 later stated, in a series of goals prior to the 2005 GCE: “May. Prepare for a DARPA site visit. Testing had moved from obstacle avoidance to finding a balance between speed, planning, and reaction time. At this point, sensing strategies were unresolved with stereo vision, radar, and machine vision for road detection under consideration.” ([52], p. 831). Team 2005-09 did not refer to “stereo vision” or “machine vision” system elsewhere throughout the Journal of Field Robotics ([52]), or report a stereo camera pair or machine vision system were in use by the team during the 2005 GCE.

The author concluded the unknown stereo camera pair and unknown machine vision system were not in use by Team 2005-09 during the 2005 GCE.

V.C.34.d. Trimble AgGPS 132 DGPS receivers

Team 2005-09 stated: “Two Trimble GPS systems provide submeter accuracy through an Omnistar subscription.” ([175], p. 7), but reported no additional identifying information.

Team 2005-09 later stated: “The primary GPS receivers are two Trimble AgGPS132 differential GPS units, with differential corrections from the Omnistar subscription service.” ([52], p. 817).

The author concluded two Trimble AgGPS 132 DGPS receivers were in use by Team 2005-09, and considers these sensors known.

V.C.34.e. Microbotics MIDG-II

Team 2005-09 stated: “A third GPS is provided by a MIDG-2 inertial navigation system that comes from the remote controlled plane community.” ([175], p. 7), but reported no additional identifying information.

Team 2005-09 later stated: “A third GPS is a MIDG-2 INS.” ([52], p. 819), but reported no additional identifying information.

An Internet search using the key words “+'MIDG-2' +ins +gps” as the search string revealed the MIDG-II INS/GPS is a Microbotics product. The author concluded one Microbotics MIDG-II was in use by Team 2005-09, and considers this sensor known.

V.C.34.f. <u>Unknown Honeywell compass</u>

Team 2005-09 stated: "...a Honeywell magnetic compass is used as an alternative source of heading." ([175], p. 7), but reported no additional identifying information.

Team 2005-09 later stated: "Two sensor racks were built to mount the sensors to the outside of the vehicle. The largest sensor rack is mounted on top of the vehicle. It provides the platform for mounting the global positioning system (GPS) receivers, inertial navigation system (INS), and magnetic compass." ([52], p. 813); "Positioning is by three GPS units, an INS unit and a compass on the roof." ([52], p. 814); and "Initially, a Honeywell magnetic compass provided an alternative source of heading. However, it was abandoned because it required calibration in different locations (Nevada and California), had high latency (degrees per minute), and drifted as much as 10º with the vehicle stopped." ([52], p. 819). Team 2005-09 did not refer to a compass in use by the team elsewhere throughout the Journal of Field Robotics ([52]).

The author concluded the unknown Honeywell compass was not in use by Team 2005-09 during the 2005 GCE.

V.C.34.g. <u>Unknown encoders</u>

Team 2005-09 stated: "Additionally, shaft encoders provide odometry at very slow speeds providing information that is needed for dead reckoning." ([175], p. 7), but reported no additional identifying information.

Team 2005-09 later stated: "Vehicle displacement is measured via a multielement quadrature shaft encoder, mounted directly to the vehicle drive shaft. We assume no differential slip or tire slip. A similar encoder is mounted to the steering column, and provides steering wheel angle." ([52], p. 819), but reported no additional identifying information.

The author concluded one "quadrature shaft encoder" was in use by Team 2005-09 to measure "vehicle displacement" and one "encoder" was in use by Team 2005-09 to measure "steering wheel angle", but otherwise considers these sensors unknown.

V.C.35. Team 2005-10

- The Team 2005-10 website was no longer available.

- Team 2005-10 did not publish its results via the Journal of Field Robotics.

V.C.35.a. <u>Unknown SICK LIDAR sensors</u>

Team 2005-10 stated: "Two SICK LMS-291 2 dimensional laser range finders." ([176], p. 3), but did not report the model number of these sensors.

The author concluded two SICK LIDAR sensors were in use by Team 2005-10, but considers the model number of these sensors unknown.

V.C.35.b. Cognex DVT 542C cameras

Team 2005-10 stated two “DVT 542C color cameras” were in use by the team ([176], p. 3). Cognex acquired DVT in May, 2005 ([177] and [178]). DVT 542C is not a current Cognex model number ([179]), but a model number DVT 542C was offered by Cognex through 2006 ([180]).

The author concluded two Cognex DVT 542C cameras were in use by Team 2005-10, and considers these sensors known.

V.C.35.c. Unknown stereo camera pair

Team 2005-10 reported one stereo camera pair was in use by the team ([176], p. 3), and stated: “Stereo vision was the most difficult data analysis challenge, but in the end, has become a very useful sensor. Using a unique and proprietary algorithm, we are able to use the fast, 30 frames per second, update rate from the stereo vision camera and detect most obstacles easily.” ([176], p. 7).

The author concluded one stereo camera pair was in use by Team 2005-10, but otherwise considers this sensor unknown.

V.C.35.d. NavCom SF-2050G

Team 2005-10 stated a “Navcom Starfire™ 2050G” was in use by the team ([176], p. 3).

NavCom manufactured a model number SF-2050G. The author concluded “2050G” was an incomplete model number and that Team 2005-10 was referring to a NavCom SF-2050G, and considers this sensor known.

V.C.35.e. Unknown Kearfott INS

Team 2005-10 reported one “Kearfott MIL-NAV inertial navigation unit” was in use by the team ([176], p. 4), but reported no additional identifying information.

“MILNAV” is an acronym for “Miniature Integrated Land Navigation System” ([181]). The MILNAV has a manufacturer product family of KN-4050, however multiple model numbers within this product family existed.

The author concluded one Kearfott INS was in use by Team 2005-10, but considers the model number of this sensor unknown.

V.C.35.f. Unknown Crossbow accelerometer

Team 2005-10 stated: “One Crossbow 3 axis accelerometer measures G forces in the X, Y and Z direction.” ([176], p. 3), but reported no additional identifying information.

The author concluded one Crossbow accelerometer was in use by Team 2005-10, but considers the model number of this sensor unknown.

V.C.36. Team 2005-11

- Team 2005-11 did not publish its results via the Journal of Field Robotics.
- The hyperlink to the Team 2005-11 website hosted by DARPA via the Archived Grand Challenge 2005 website ([19]) redirected to a URL which resulted in a “HTTP 404 - File not found” error. However, a search of that domain revealed the Team 2005-11 website was relocated to an alternate URL on the same domain. The Team 2005-11 website reported no additional identifying information for the sensors in use by the team.

V.C.36.a. Unknown SICK LIDAR sensors

Team 2005-11 stated: “Three to four SICK LMS 291 LIDAR units are deployed at various fixed locations and orientations on [the challenge vehicle].” ([182], p. 7), but reported no additional identifying information.

The author concluded the manufacturer of the SICK LIDAR sensors in use by Team 2005-11 was known, but otherwise considers these sensors unknown.

V.C.36.b. Unknown Crossbow INS

Team 2005-11 stated: “A Crossbow Navigation Attitude Heading Reference System (NAHRS) module is the main navigation and guidance application.” ([182], p. 7), but reported no additional identifying information.

The Team 2005-11 description matches multiple product series with multiple model numbers ([96]). The author concluded one Crossbow INS was in use by Team 2005-11, but otherwise considers this sensor unknown.

V.C.36.c. Unknown NovAtel GPS receiver

Team 2005-11 stated: “This system augments the Crossbow navigation solution with input from a decimeter accurate Novatel GPS receiver with Omnistar capability.” ([182], p. 7), but reported no additional identifying information.

The author concluded one NovAtel GPS receiver was in use by Team 2005-11, but otherwise considers this sensor unknown.

V.C.36.d. Unknown wheel speed sensors

Team 2005-11 stated: "The master navigation filter under certain situations also employs odometry data from the wheels." ([182], p. 7) and "Wheel speed sensors are used to control [the challenge vehicle's] antilock brakes." ([182], p. 8), but reported no additional identifying information.

The author did not estimate the quantity of wheel speed sensors in accordance with paragraph V.B.5.c., and considers these sensors unknown.

V.C.37. Team 2005-12

- Team 2005-12 published its 2005 GCE results via the Journal of Field Robotics ([183]).
- No hyperlink to the Team 2005-12 website was hosted by DARPA via the Archived Grand Challenge 2005 website ([19]). However, an Internet search using the key words "+'princeton' +darpa +'grand challenge'" as the search string revealed a team website existed ([184]). The Team 2005-12 website reported no additional identifying information for the sensors in use by the team.

V.C.37.a. Unknown Trimble DGPS receiver

Team 2005-12 stated: "A Trimble DGPS unit (using WAAS) provides position data..." ([185], p. 5), but reported no additional identifying information.

Team 2005-12 referred to "GPS" throughout the Journal of Field Robotics ([183]), but reported no additional identifying information for the Trimble DGPS receiver in use by the team.

The author concluded one Trimble DGPS receiver was in use by Team 2005-12, but otherwise considers this sensor unknown.

V.C.37.b. Unknown CoPilot GPS receiver

Team 2005-12 stated: "A CoPilot GPS unit is used as a backup receiver." ([185], p. 5), but reported no additional identifying information.

Team 2005-12 referred to "GPS" throughout the Journal of Field Robotics ([183]), but reported no additional identifying information for the CoPilot GPS receiver in use by the team.

ALK reported "CoPilot GPS" is the name of a family of software products developed by ALK ([186]). The author did not record the ALK CoPilot GPS software in Table XXVIII because it is a software product, not a navigation sensor.

The CoPilot GPS software requires the use of a GPS receiver, such as the "CoPilot USB GPS Receiver" ([186]). However, in the absence of a definitive statement from the team, the author concluded neither the ALK CoPilot GPS software nor accompanying GPS receiver was in use by Team 2005-12 during the 2005 GCE.

V.C.37.c. Unknown encoder

Via an un-numbered and un-titled figure ([185], p. 4), Team 2005-12 reported one "Steering Wheel Position Encoder" and "ABS Wheel Encoders" were in use by the team. Team 2005-12 stated: "An optical digital position encoder is used for precise position feedback." ([185], p. 3).

Team 2005-12 later stated: "An optical rotary encoder, also attached to the steering wheel, provides precise position feedback." ([183], p. 746). Team 2005-12 did not refer to "wheel encoder" or "ABS" throughout the Journal of Field Robotics ([183]).

The author concluded one "optical rotary encoder" was in use by Team 2005-12 to provide "precise position feedback" during the 2005 GCE, but otherwise considers this sensor unknown. Due to the difficulty other teams reported adapting existing OEM sensors to other uses (e.g., OBD-II), and in the absence of a definitive statement from the team, the author concluded the "ABS Wheel Encoders" were not in use by Team 2005-12 during the 2005 GCE.

V.C.37.d. Unknown compass

Via an un-numbered and un-titled figure ([185], p. 4), Team 2005-12 reported one "Compass" was in use by the team. Team 2005-12 did not refer to "compass" throughout the Journal of Field Robotics ([183]).

The author concluded the compass was not in use by Team 2005-12 during the 2005 GCE.

V.C.38. Teams 2005-13 and 2005-14

- Team 2005-13 participated in the 2004 QID and GCE as Team 2004-10. See paragraph V.C.10.
- Teams 2005-13 and 2005-14 were co-participants during the 2005 GCE, and published their results jointly via the Journal of Field Robotics ([24]).
- The Teams 2005-13 and 2005-14 website reported no additional identifying information for the sensors in use by the team.

V.C.38.a. Riegl LMS-Q140i and unknown SICK LIDAR sensors

Throughout the team technical papers ([11] and [12]), Teams 2005-13 and 2005-14 referred to “LIDAR”, “LIDAR line scanner”, “short range LIDAR”, “short range LIDAR line scanner”, “long range LIDAR”, “long Range LIDAR line scanner”, and “long range single line LIDAR”.

Via Table 2 of the team technical papers ([11], p. 9 and [12], p. 9), Teams 2005-13 and 2005-14 reported one long-range LIDAR sensor and six short-range LIDAR sensors were in use by the teams.

Teams 2005-13 and 2005-14 stated: “Four (4) short range LIDAR line scanners ... are mounted on ... the vehicle. ... Two (2) short range LIDARs are mounted on the shock isolated electronics bay.” ([11], p. 8) and “Four (4) short range LIDAR line scanners ... are mounted on ... the vehicle. ... Two short range LIDARs are mounted ... on the superstructure of the roof.” ([12], p. 8).

Teams 2005-13 and 2005-14 later stated: “A Riegl Q140i scanning laser range finder is used as the primary terrain perception sensor for both robots...” ([24], p. 476) and “...four SICK LMS 291 laser scanners are used to provide short-range supplemental sensing.” ([24], p. 477), but did not report the model number of the SICK LMS 291 LIDAR sensors in use by the team.

The author concluded one Riegl LMS-Q140i was in use by Teams 2005-13 and 2005-14, and considers this sensor known; and, because the Journal of Field Robotics ([24]) represents the final written report of Teams 2005-13 and 2005-14, concluded four SICK LIDAR sensors, in lieu of six, were in use by Teams 2005-13 and 2005-14, but considers the model number of these sensors unknown.

V.C.38.b. Navtech DS2000

Throughout the team technical papers ([11] and [12]), Teams 2005-13 and 2005-14 referred to “RADAR”, “360 degree RADAR”, and “360º RADAR”.

Teams 2005-13 and 2005-14 later stated: “...the NavTech DS2000 continuous-wave frequency modulated (CWFM) radar was used as a complimentary [*sic*] sensor to the LIDAR devices.” ([24], p. 478).

As a result, the author concluded one Navtech DS2000 was in use by Teams 2005-13 and 2005-14, and considers this sensor known.

V.C.38.c. Unknown other sensors

Teams 2005-13 and 2005-14 stated: “In selecting sensors, the team evaluated monocular cameras, stereo cameras, LIDAR, and RADAR systems to find modalities amenable to generating terrain evaluations under the difficult conditions of the Grand

Challenge. Table I outlines the sensing modalities considered and the advantages and disadvantages for this problem." ([24], p. 476). Via Table 1 ("A qualitative comparison of sensors considered for inclusion in the navigation system.") of the Journal of Field Robotics ([24], p. 476), Teams 2005-13 and 2005-14 reported considering "conventional camera", "stereo camera", and "automotive RADAR" sensors in addition to LIDAR and "navigation RADAR".

However, Teams 2005-13 and 2005-14 also stated: "These considerations led to a perception strategy based on a set of five LIDAR and a navigation RADAR." ([24], p. 476).

The author concluded conventional camera, stereo camera, and automotive RADAR sensors were not in use by Teams 2005-13 and 2005-14.

V.C.38.d. Unknown Applanix INS

Teams 2005-13 and 2005-14 stated: "The INS/GPS (Applanix POS LV) is a strapdown inertial navigation platform..." ([11], p. 7 and [12], p. 7), but reported no additional identifying information.

Teams 2005-13 and 2005-14 later stated: "The Applanix M-POS provides position estimates..." ([24], p. 478). A search of the manufacturer website ([187]) for a product with model number "m-pos" did not produce any results. An Internet search using the key words "+applanix +'m-pos'" as the search string produced three results, two of which were references to the Journal of Field Robotics ([24]), and the third so similarly-worded as to suggest its source was the Journal of Field Robotics ([24]).

Several model numbers of the POS LV exist: 200, 220, 420, and 610 ([120]). At least two of these model numbers were available at the time of the 2005 GCE: 220 and 420 ([124]), and the author concluded 320 was an existing model number at the time of the 2004 GCE based on review of manufacturer product literature. See paragraph V.C.8.d.

Alternate sources variously stated: "Around the same time as vehicle designs were being drafted and redesigned..., a meeting between [Team 2005-13] and Applanix over the capabilities of POS LV technology quickly developed into a strong partnership." ([188], p. 71) and "[Team 2005-13] engineers immediately recognized the value of having data from the GPS, IMU and DMI blended together in real time and began working to include the POS LV system on both Red Team vehicles." ([188], p. 72); and "Risk adverse [*sic*] [Team 2005-13] engineers adopted a system approach with redundancy and back-ups for both [Team 2005-13] vehicles. ... Applanix POS LV technology with inertial/GPS and distance measurement hardware generated position and orientation data throughout the course." ([189], p. 43) and "[Team 2005-13] engineers adopted the Applanix POS LV system." ([189], p. 44).

The author concluded one Applanix INS was in use by Teams 2005-13 and 2005-14, but considers the model number of this sensor unknown.

V.C.38.e. Trimble AgGPS 252

Team 2005-13 stated: "A differential GPS receiver (Trimble AG132 with Omnistar VBS corrections) augments the INS/GPS's two antennas to enhance position estimation." ([11], p. 7). Team 2005-14 stated: "A differential GPS receiver (Trimble AG252 with Omnistar VBS corrections) augments the INS/GPS's two antennas to enhance position estimation." ([12], p. 7).

Teams 2005-13 and 2005-14 did not refer to "Trimble" throughout the Journal of Field Robotics ([24]), and references to "GPS" reported no additional identifying information.

Alternate sources stated: "The only addition to this system setup for [Team 2005-13] at the 2005 DARPA Grand Challenge was a Trimble Ag 252 receiver which provided OmniSTAR VBS corrections for position information." ([190], p. 1237) and "The only addition to this system setup for [Team 2005-13] was a Trimble Ag 252 receiver which provided RTCM corrections for position information." ([191], p. 373). Although only the Team 2005-13 name is used by both alternate sources ([190] and [191]), it is used to describe both Team 2005-13 and 2005-14 challenge vehicles.

Trimble does not manufacture an "Ag 252" DGPS receiver ([192]); the corresponding model number is "AgGPS 252". The author concluded it was likely this was an error and that one Trimble AgGPS 252 was in use by Teams 2005-13 and 2005-14, and considers this sensor known.

V.C.39. Team 2005-15

- Team 2005-15 participated in the 2004 QID and GCE as Team 2004-13. See paragraph V.C.13.
- The Team 2005-15 website was no longer available.

V.C.39.a. Unknown SICK LIDAR sensors

Team 2005-15 stated: "The main obstacle sensing is based on SICK LIDAR sensors. Two of these sensors are used to scan horizontally, to detect objects that are in the path to be driven. Two other LIDAR sensors scan vertically, to detect surface continuity and discontinuity (negative obstacles)." ([53], p. 9), but reported no additional identifying information.

Team 2005-15 later stated: "Five sensors were used to search for obstacles within the corridor: The stereo vision system (SVS) from Seibersdorf Research and four SICK

LMS-221 light detection and ranging device (LIDAR) units...” ([133], p. 586), but did not report the model number of the SICK LIDAR sensors in use by the team.

The author concluded four SICK LIDAR sensors were in use by Team 2005-15, but considers the model number of these sensors unknown.

V.C.39.b. Team 2005-15 stereo camera pair

Team 2005-15 stated: “As a mid-range (10 m < R <20m) obstacle sensing system, a stereo vision system jointly developed by Seibersdorf research and [Advanced Computer Vision], is used.” ([53], p. 9). Team 2005-15 later referred to this sensor as a “novel stereo vision system” ([133], p. 579).

Although the Team 2005-15 description of this sensor was detailed, the author was unable to determine if this was a proprietary stereo camera pair or a commercially-available product similar to other commercially-available stereo camera pairs in use by teams participating in the 2005 GCE. Considering its description as “novel”, the author concluded it was unlikely the stereo camera pair was a commercially-available product at the time of the 2005 GCE.

The author considers the stereo camera pair in use by Team 2005-15 known, but concluded the cost of this sensor cannot be independently determined.

V.C.39.c. Unknown ultrasonic sensors and unknown contact sensors

Team 2005-15 stated: “Other sensors include a suite of ultrasound sensors...” ([53], p. 9), but reported no additional identifying information.

Team 2005-15 later stated: “Further work was planned to integrate ultrasonic and contact sensors to discriminate between false and real obstacles, but was not implemented.” ([133], p. 591). Team 2005-15 did not refer to “contact” sensors throughout the team technical paper ([53]).

The author concluded the unknown ultrasonic sensors and unknown contact sensors were not in use by Team 2005-15.

V.C.39.d. Unknown NavCom DGPS receiver

Team 2005-15 stated: “The primary sensor used in estimating vehicle state is a Navcom Starfire GPS system...” ([53], p. 9), but reported no additional identifying information.

Team 2005-15 later stated: “The cornerstone of vehicle localization was a single antenna Navcom differential global positioning system (DGPS) receiver with Starfire corrections broadcast by Navcom.” ([133], p. 582), but reported no additional identifying information.

The NavCom StarFire SF-2050 GPS receiver and StarFire network were in use by 12 of 40 NQE semifinalists ([102]) and 6 of 23 GCE finalists ([103]). At least two different model numbers of NavCom StarFire GPS receiver existed at the time of the 2005 GCE, and they targeted different markets: "The SF-2050G is designed for backpack GIS and mapping applications while the SF-2050M is ideal for vehicle mounting to suit a wide variety of machine guidance and control applications." ([104]). NavCom launched both the SF-2050G or SF-2050M receivers in 2002 ([105]). Although the SF-2050M was specifically designed to be vehicle-mounted, review of technical papers revealed both sensors were in use by teams participating in the 2004 and 2005 GCE, and that the SF-2050G was more popular[22].

The author concluded one NavCom DGPS receiver was in use by Team 2005-15, but considers the model number of this sensor unknown.

V.C.39.e. Unknown Rockwell Collins IMU

Team 2005-15 stated: "A Rockwell Collins GNP-10 provides inertial updates of acceleration and angular rate at 50 Hz through accelerometers and gyros." ([53], p. 9).

Team 2005-15 later stated: "An inertial measurement unit (IMU) was used to obtain high update rate measurements. A Rockwell Collins GIC-100 tactical-grade six degrees of freedom IMU measured translational accelerations and angular rates at 50 Hz." ([133], p. 582).

The author was unable to confirm that "GIC-100" was an existing product at the time of the 2005 GCE. A search of the Rockwell Collins Product Catalog ([193]) and Technical Publications Index ([194]) for "gic", "gic-100", and the potential variant "g1c" did not produce any results. An Internet search using the key words "+'rockwell collins' +'gic-100'" as the search string produced 16 results, several of which were so similarly-worded as to suggest their source was the Journal of Field Robotics ([133]).

Based on a review of the published record, the author concluded it was possible that Rockwell Collins produced a model number GIC-100 IMU at the time of the 2005 GCE that may not have been commercially available, or that it has since been discontinued. In the absence of evidence that a GIC-100 IMU was in use by Team 2005-15 during the 2005 GCE, the author concluded one Rockwell Collins IMU was in use by Team 2005-15, but considers the model number of this sensor unknown.

V.C.39.f. PNI TCM2 magnetometer

Team 2005-15 stated: "A TCM2 magnetometer provides roll, pitch, and yaw data at 16 Hz." ([53], p. 9), but did not identify the manufacturer of this sensor.

Team 2005-15 later stated: “A TCM2 magnetometer provided 16 Hz measurements that contained high noise, but a slow bias drift rate.” ([133], p. 582), but did not identify the manufacturer of this sensor.

The TCM2 magnetometer is a product of PNI. The author concluded one PNI TCM2 magnetometer was in use by Team 2005-15, and considers this sensor known.

V.C.39.g. OEM speedometer encoder

Team 2005-15 stated: “A speedometer encoder provides speed data at a variable rate, depending on the speed of the vehicle.” ([53], p. 9), but reported no additional information.

Team 2005-15 later stated: “[The challenge vehicle's] onboard speedometer was used as an additional speed sensor.” ([133], p. 582).

The author concluded the challenge vehicle's OEM speedometer was in use by Team 2005-15 as a “speedometer encoder”, and considers this sensor known.

V.C.40. Team 2005-16

- The Team 2005-16 website reported no additional identifying information for the sensors in use by the team.

V.C.40.a. Unknown GPS receiver and unknown GPS compass

Team 2005-16 stated: “A number of antenna are also attached to the roof rack, specifically one antenna for the GPS positioning system, two additional GPS antennae for the GPS compass... Three additional GPS antenna [*sic*] for the DARPA E-Stop are directly attached to the roof.” ([195], p. 4), but reported no additional identifying information.

Although Team 2005-16 specifically referred to six GPS antennas throughout the team technical paper ([195]), three are of particular interest because they are used by the “GPS positioning system” and “GPS compass”. Team 2005-16 later stated: “The GPS positioning unit is a L1/L2/Omnistar HP receiver.” ([25], p. 665). “L1”, “L2”, and “Omnistar HP” are references to the specific types of GPS signals which are common to many commercially-available DGPS receivers.

As a result, the author concluded one GPS receiver and one GPS compass were in use by Team 2005-16, but otherwise considers these sensors unknown.

V.C.40.b. Unknown IMU

Team 2005-16 stated: "A 6 degree of freedom (DOF) inertial measurement unit (IMU) is rigidly attached to the vehicle frame underneath the computing rack in the trunk." ([195], p. 5), but reported no additional identifying information.

Team 2005-16 later stated: "A six degree-of-freedom IMU is rigidly attached to the vehicle frame underneath the computing rack in the trunk." ([25], p. 665), but reported no additional identifying information.

The author concluded one IMU was in use by Team 2005-16, but otherwise considers this sensor unknown.

V.C.40.c. Unknown SICK LIDAR sensors

Team 2005-16 stated: "For environment perception, the roof rack holds five SICK laser range finders..." ([195], p. 4), but reported no additional identifying information.

Team 2005-16 later stated: "For environment perception, the roof rack houses five SICK laser range finders." ([25], p. 664), but reported no additional identifying information.

Team 2005-16 published a picture of the challenge vehicle's roof rack with sensors via the Journal of Field Robotics ([25]). The LIDAR sensors in use by Team 2005-16 appear to be SICK LMS 291 product family LIDAR sensors. However, in the absence of an affirmative statement by Team 2005-16 specifically identifying the model number of the SICK LIDAR sensors in use by the team, the author concluded five SICK LIDAR sensors were in use by Team 2005-16, but considers the model number of these sensors unknown.

V.C.40.d. Unknown camera

Team 2005-16 stated: "For environment perception, the roof rack holds ... a color camera..." ([195], p. 4), but reported no additional identifying information.

Team 2005-16 later stated: "The roof rack also holds a color camera for long-range road perception..." ([25], p. 664), but reported no additional identifying information. As noted above, the team published a picture of the challenge vehicle's roof rack with sensors via the Journal of Field Robotics ([25]). However, the author was unable to identify the camera, or determine the manufacturer and model number from the picture alone, and concluded one camera was in use by Team 2005-16, but otherwise considers this sensor unknown.

V.C.40.e. Unknown Smart Microwave RADARs

Team 2005-16 stated: "For environment perception, the roof rack holds ... two antennae of a forward-pointed RADAR system." ([195], p. 4), but reported no additional identifying information.

Team 2005-16 later alternately stated: "[The challenge vehicle's] roof rack also holds two 24 GHz RADAR sensors, supplied by Smart Microwave Sensors." ([25], p. 664), but reported no additional identifying information; and "The second sensor that was not used in the race was the 24 GHz RADAR system." ([25], p. 686). The author concluded the Smart Microwave RADARs were not in use by Team 2005-16 during the 2005 GCE.

V.C.41. Team 2005-17

- Team 2005-17 participated in the 2004 QID and GCE as Team 2004-16. See paragraph V.C.16.
- The Team 2005-17 website reported no additional identifying information for the sensors in use by the team.

V.C.41.a. Unknown SICK LIDAR sensors

Team 2005-17 stated: "The single (functional) SICK LMS 221 is augmented by four SICK LMS 291s." ([140], p. 2), "Four SICK LMS 291 LIDARs and one SICK LMS 221 constitute [the challenge vehicle's] obstacle sensors." ([140], p. 5), and "The five SICK LMS configuration is the maximal configuration." ([140], p. 5), but reported no additional identifying information.

Team 2005-17 later stated: "[The challenge vehicle] uses … two lidar scanners (SICK LMS 291) for autonomous operation." ([196], p. 559). Team 2005-17 also stated: "...a SICK LMS 291 lidar operates at 75 Hz, producing scans separated by 13 ms intervals." ([196], p. 567). These capabilities match the description of both the SICK LMS 291-S05 and 291-S15. Team 2005-17 did not report sufficient identifying information to determine which model was in use by the team.

The author concluded two SICK LIDAR sensors were in use by Team 2005-17 during the 2005 GCE, but considers the model number of these sensors unknown.

V.C.41.b. Oxford RT3102

Team 2005-17 stated: "An Oxford Technical Solutions RT3000 inertial navigation system (INS) is the primary navigation sensor." ([140], p. 5).

Team 2005-17 later stated: "[The challenge vehicle] uses an inertial navigation system (INS) (Oxford Technology Solutions RT3102) ... for autonomous operation." ([196], p. 559).

Because the Journal of Field Robotics ([196]) represents the final technical report of Team 2005-17, the author concluded one Oxford RT3102 was in use by Team 2005-17, and considers this sensor known.

V.C.41.c. Unknown C&C Technologies C-Nav DGPS receiver

Team 2005-17 stated: "The accuracy of the INS is enhanced by Starfire differential GPS correction signals provided by a C&C Technologies C-Nav receiver." ([140], p. 5).

Several model numbers existed for the C&C Technologies C-Nav at the time of the 2005 GCE ([141]). The author concluded one C&C Technologies C-Nav DGPS receiver was in use by Team 2005-17, but considers the model number of this sensor unknown.

V.C.42. Team 2005-18

- Team 2005-18 participated in the 2004 QID and GCE as Team 2004-17. See paragraph V.C.17.
- The Team 2005-18 website was updated prior to the 2007 Urban Challenge, and reported no additional identifying information for the sensors in use by the team.

V.C.42.a. SICK LMS 221-30206, SICK LMS 291-S14, and SICK LMS 291-S05 LIDAR sensors

Team 2005-18 stated: "We currently have 2 SICK LMS-221-30206 LADARs mounted on [the challenge vehicle]." and "An additional SICK LMS 291-S14 LADAR has been mounted on the roof." ([197], p. 10).

Team 2005-18 later stated: "Obstacle detection is performed using a combination of several SICK and Riegl LADAR units, as well as two pairs of stereovision cameras." ([54], p. 789). Via Table II ("Sensors used on [the challenge vehicle].") of the Journal of Field Robotics ([54], p. 790), Team 2005-18 reported that a SICK LMS 291-S05 LIDAR sensor was in use by the team, in addition to the three LIDAR sensors referred to previously.

The author concluded two SICK LMS 221-30206 LIDAR sensors, one SICK LMS 291-S14, and one SICK LMS 291-S05 were in use by Team 2005-18 and considers these sensors known.

V.C.42.b. <u>Point Grey Dragonfly stereo camera pairs</u>

Team 2005-18 stated: “A pair of Point Grey Dragonfly cameras mounted on the roof are used in combination with SRI’s Small Vision System to generate 3D pointclouds.” ([197], p. 10).

Team 2005-18 later stated: “Obstacle detection is performed using a combination of several SICK and Riegl LADAR units, as well as two pairs of stereovision cameras.” ([54], p. 789). Via Table II (“Sensors used on [the challenge vehicle].”) of the Journal of Field Robotics ([54], p. 790), Team 2005-18 reported two Point Grey Dragonfly “Stereovision” pairs were in use by the team.

Point Grey Research has product lines named “Bumblebee”, “Dragonfly”, “Flea”, etc. ([108]). Each product line has multiple model numbers. For example, the current model number for the Dragonfly product line is “Dragonfly 2” ([143]). The Dragonfly 2 was introduced January 20, 2005 ([144]). The Dragonfly is not available as a stereo camera pair ([146]).

The author concluded “Dragonfly” was the model number at the time of the 2005 GCE and that each stereo camera pair was comprised of two Point Grey Dragonfly cameras, and considers these sensors known.

V.C.42.c. <u>Point Grey Dragonfly camera</u>

Team 2005-18 stated: “An additional single camera mounted on the vehicle also feeds a road-finding algorithm.” ([197], p. 10).

Team 2005-18 later stated: “[The challenge vehicle's] road-following algorithm ... uses a single calibrated grayscale camera and a bumper-mounted SICK LADAR.” ([54], p. 793). Via Table II (“Sensors used on [the challenge vehicle].”) of the Journal of Field Robotics ([54], p. 790), Team 2005-18 reported one Point Grey Dragonfly “Road-finding camera” was in use by the team.

The author concluded the “additional single camera” referred to by the team technical paper ([197]) was the Point Grey Dragonfly in use by Team 2005-18 as a “Road-finding camera” during the 2005 GCE and considers this sensor known.

V.C.42.d. <u>NovAtel DL-4plus and NavCom SF-2050G</u>

Team 2005-18 stated: “State estimation is accomplished through the combination of Navcom SF2050G and Novatel ProPak-LBplus differential GPS units to measure absolute position...” ([197], p. 9). Via Table II (“Sensors used on [the challenge vehicle].”) of the Journal of Field Robotics ([54], p. 790), Team 2005-18 later reported that a “Navcom SF-2050” and “NovAtel DL-4plus” were in use by the team.

The author concluded one NovAtel DL-4plus, in lieu of the NovAtel ProPak-LBplus reported by the team technical paper ([197]), was in use by Team 2005-18 during the 2005 GCE, and considers this sensor known. In the absence of conflicting evidence that an alternate model number NavCom GPS receiver was in use by Team 2005-18, the author concluded one NavCom SF-2050G was in use by Team 2005-18, and considers this sensor known.

V.C.43. Team 2005-19

V.C.43.a. Unknown SICK LIDAR sensors

Team 2005-19 reported "two rigidly-mounted SICK LMS-291 LIDAR" and a "third LIDAR unit" were in use by the team ([55], p. 5), but did not report the model number of the SICK LIDAR sensors in use by the team. Figure 2 of the team technical paper ([55], p. 5) reported the third LIDAR sensor was also a SICK LIDAR sensor.

Team 2005-19 later stated: "Sensed terrain data for the terrain estimator is provided by three SICK LMS 291 laser rangefinders (LIDARs)." ([198], p. 636), but did not report the model number of the SICK LMS 291 LIDAR sensors in use by the team.

The author concluded three SICK LIDAR sensors were in use by Team 2005-19, but considers the model number of these sensors unknown.

V.C.43.b. Basler A311FC stereo camera pair

Team 2005-19 stated: "...[Team 2005-19] also uses a pair of cameras to create a depth map of the surrounding world using stereo vision. The [Team 2005-19] stereo vision camera pair is a pair of Basler A311FC cameras..." ([55], p. 6).

However, Team 2005-19 did not refer to "stereo", "vision", "camera", or "Basler" throughout the Journal of Field Robotics ([198]). Because the Journal of Field Robotics ([198]) represents the final technical report of Team 2005-19, the author concluded the Basler A311FC stereo camera pair was not in use by Team 2005-19 during the 2005 GCE.

V.C.43.c. Northrop Grumman LN-200

Team 2005-19 reported a "a Litton LN-200 Inertial Measurement Unit (IMU)" was in use by the team ([55], p. 4).

Team 2005-19 later stated: "[The challenge vehicle's] fused position and orientation estimates are provided by three sensors: a Litton LN-200 IMU, a Trimble Ag252 GPS receiver, and a vehicle speed sensor." ([198], p. 629).

Litton was acquired by Northrop Grumman in 2001 ([199]). The LN-200 is a product of Northrop Grumman ([200]). The author concluded one Northrop Grumman LN-200 was in use by Team 2005-19, and considers this sensor known.

V.C.43.d. Trimble AgGPS 252

Team 2005-19 reported a "Trimble Ag252 GPS unit" was in use by the team ([55], p. 4).

Team 2005-19 later stated: "[The challenge vehicle's] fused position and orientation estimates are provided by three sensors: a Litton LN-200 IMU, a Trimble Ag252 GPS receiver, and a vehicle speed sensor." and "The second sensor, a Trimble AgGPS 252 GPS receiver..." ([198], p. 629).

Trimble does not manufacture an "Ag 252" GPS receiver ([192]); the corresponding model number is "AgGPS 252". The author concluded this was an error and that one Trimble AgGPS 252 was in use by Team 2005-19, and considers this sensor known.

V.C.43.e. Unknown speed brake sensor

Team 2005-19 reported a "speed brake sensor (SBS)" was in use by the team ([55], p. 4). Team 2005-19 later stated: "[The challenge vehicle's] fused position and orientation estimates are provided by three sensors: a Litton LN-200 IMU, a Trimble Ag252 GPS receiver, and a vehicle speed sensor." and "The final sensor, a speed sensor (SBS), is mounted directly to [the challenge vehicle's] transmission." ([198], p. 629), but reported no additional identifying information.

The author concluded one "speed brake sensor" was in use by Team 2005-19, but otherwise considers this sensor unknown.

V.C.44. Team 2005-20

- Team 2005-20 participated in the 2004 QID and GCE as Team 2004-18. See paragraph V.C.18.
- Team 2005-20 did not publish its results via the Journal of Field Robotics.
- The hyperlink to the Team 2005-20 website hosted by DARPA via the Archived Grand Challenge 2005 website ([19]) redirected to another website, which was updated prior to the 2007 Urban Challenge, but reported no additional identifying information for the sensors in use by Team 2005-20.

Team 2005-20 stated: "Obstacle avoidance is achieved using LIDAR, Millimeter Wave Radar, and Stereo Vision Camera systems." ([56], p. 2).

V.C.44.a. Unknown LIDAR sensor(s)

Team 2005-20 did not report any identifying information for the "LIDAR ... systems" in use by the team. The author considers these sensors unknown.

V.C.44.b. Unknown RADAR(s)

Team 2005-20 did not report any identifying information for the "Millimeter Wave Radar ... systems" in use by the team. The author considers these sensors unknown.

V.C.44.c. Unknown stereo camera pair(s)

Team 2005-20 did not report any identifying information for the "Stereo Vision Camera ... systems" in use by the team. The author considers these sensors unknown.

V.C.44.d. NovAtel ProPak-LBplus and NovAtel HG1700 SPAN

Team 2005-20 stated: "[Team 2005-20] has developed a system that combines two Novatel Pro-Pack LB dual frequency (L1/L2) GPS receivers and NovAtel's SPAN™ (Synchronized Position Attitude Navigation) Technology." ([56], pp. 8 - 9). NovAtel's SPAN is available for several different IMUs ([201]). Team 2005-20 also stated: "...the SPAN system provides location information at a 20-Hz rate by combining DGPS and inertial data from an internal Honeywell HG-1700 tactical-grade IMU." ([56], p. 9).

The author concluded two NovAtel ProPak-LBplus[21] and one NovAtel HG1700 SPAN were in use by Team 2005-20, and considers these sensors known.

V.C.45. Team 2005-21

- Team 2005-21 participated in the 2004 QID and GCE as Team 2004-23. See paragraph V.C.23.
- The Team 2005-21 website reported no additional identifying information for the sensors in use by the team.

V.C.45.a. Unknown SICK LIDAR sensors

Team 2005-21 stated: "LIDAR and vision sensors are used to detect obstacles in front and behind the vehicle." ([160], p. 7) and "There are three SICK LMS-291 LIDARs used for positive and negative obstacle detection. The two forward facing SICK LIDARs are mounted on the outermost edges of the front rollbar. … The rear facing LIDAR is mounted near the cargo bed height in the middle of the truck..." ([160], p. 10), but did not report the model number of the SICK LMS 291 LIDAR sensors in use by the team.

Team 2005-21 later stated: “There are two SICK LMS-291 LIDARs used for positive and negative obstacle detection...” ([57], p. 701), but did not report the model number of the SICK LMS 291 LIDAR sensors in use by the team.

Although Team 2005-21 stated: “Obstacle detected behind the vehicle while backing up: Another behavior will stop the vehicle and command it back into normal operation to try to find a valid path ahead.” ([57], p. 700), it is unclear what sensors were in use to detect obstacles behind the vehicle. The rear-facing SICK LIDAR sensor described by the team technical paper ([160]) was not reported to have been in use by the team via the Journal of Field Robotics ([57]).

As a result, the author concluded no rear-facing SICK LIDAR sensor was in use by Team 2005-21 during the 2005 GCE and that two SICK LIDAR sensors were in use by Team 2005-21, but considers the model number of these sensors unknown.

V.C.45.b. <u>Unknown Ibeo LIDAR sensor</u>

Team 2005-21 stated: “The IBEO ALASCA LIDAR is a 4-plane scanner that is used for positive obstacle detection.” ([160], p. 10). However, Team 2005-21 did not report the model number of the IBEO LIDAR sensor in use by the team. The Journal of Field Robotics ([57]) confirms this sensor was in use by Team 2005-21 during the 2005 GCE.

The current version of the Ibeo ALASCA LIDAR is model number XT, and that it is offered in two different product lines: “Single”, which includes one ALASCA XT sensor and “Fusion”, which includes two ALASCA XT sensors ([202]). However, Ibeo stated: “In the form of Alasca XT, [Ibeo] has been presenting the first Multi-Application Sensor with high-resolution laser technology since October 2005.” ([203]). The 2005 GCE took place on October 8, 2005. See Appendix C, paragraph I.B.11. As a result, the ALASCA XT could not have been the sensor in use by Team 2005-21 during the 2005 GCE.

An Ibeo “Case Study” stated: “...[Team 2005-21] opted for an innovative laser technology from Germany, the laser scanner developed and produced by [Ibeo].” ([204], p. 1). Throughout this “Case Study”, Ibeo referred to “innovative”, “historic”, or “multi-application” LIDAR sensors ([204]), and also stated: “Ibeo developed the multi-application sensor ibeo XS especially for use in trucks and buses.” without stating the “ibeo XS” sensor was in use by Team 2005-21 during the 2005 GCE. In addition, neither a search of the Ibeo website ([202]) for a sensor with model number “XS” nor an Internet search using the key words “"ibeo XS"” or “+ibeo +lidar +xs” as the search string produced any results for an Ibeo model number “XS” LIDAR sensor.

Team 2005-21 also participated in the 2007 Urban Challenge. The team website was updated to reflect the challenge vehicle configuration in use during that event, and stated: "Ibeo Automobile Sensor GmbH is providing a customized LIDAR system utilizing Ibeo's Alasca XT™ sensors." ([205]).

As a result, the author concluded one Ibeo LIDAR sensor was in use by Team 2005-21, but considers the model number of this sensor unknown.

V.C.45.c. Unknown cameras

Team 2005-21 stated: "The vision system is comprised of a forward-looking system and a backward looking one. Both systems share the same technology and processing: color cameras and stereoscopic vision.", and "The forward-looking system consists of three identical cameras mounted on a rigid bar on top of the hood." ([160], p. 10). Team 2005-21 did not report any technical detail for the backward-looking vision system, or additional identifying information for the cameras in use by the team.

Team 2005-21 published its 2005 GCE results via the Journal of Field Robotics ([57]). The description of the challenge vehicle generally conforms to the description reported by the team technical paper ([160]), although Team 2005-21 referred to the "Parma Vision System" via the team technical paper ([160]) and the "forward-looking vision and [*sic*] system" via the Journal of Field Robotics ([57], p. 701). Team 2005-21 reported no additional identifying information for the cameras in use by the team.

Although Team 2005-21 stated: "Obstacle detected behind the vehicle while backing up: Another behavior will stop the vehicle and command it back into normal operation to try to find a valid path ahead." ([57], p. 700), it is unclear what sensors were in use to detect obstacles behind the vehicle. The backward-looking vision system described by the team technical paper ([160]) was not described by the Journal of Field Robotics ([57]).

The trinocular camera system described by Team 2005-21 uses three identical cameras to form three stereo camera pairs with three different field-of-view depths: large, medium, and short.

As a result, the author concluded the backward-looking vision system was not in use by Team 2005-21 during the 2005 GCE and that three cameras were in use by Team 2005-21 in the forward-looking system, but otherwise considers these sensors unknown.

V.C.45.d. Unknown wheel speed sensor and wheel angle sensor

Team 2005-21 stated: "In order to aid the INS solution in dead reckoning mode, a wheel speed sensor on the vehicle provides input to the RT3100." and "In the case of a failure or short-term loss of the RT3100's, a second dead reckoner is implemented using sensed wheel speed and wheel angle." ([160], p. 8), but reported no additional identifying information.

Team 2005-21 later stated: “The servomotor has an integrated high-resolution encoder that allows precise control of wheel angle.” ([57], p. 695) and “In the case of a failure or short-term loss of the RT3100’s, a second dead reckoner is implemented using sensed wheel speed and wheel angle.” ([57], p. 701), but reported no additional identifying information.

The author concluded one wheel speed sensor and one wheel angle sensor were in use by Team 2005-21, but otherwise considers these sensors unknown.

V.C.46. Teams 2005-22 and 2005-23

- Team 2005-22 participated in the 2004 QID and GCE as Team 2004-25. See paragraph V.C.25.
- Teams 2005-22 and 2005-23 were co-participants during the 2005 GCE, and published their results jointly via the Journal of Field Robotics ([59]).
- The Teams 2005-22 and 2005-23 website reported no additional identifying information for the sensors in use by the team.

V.C.46.a. Unknown SICK LIDAR sensors

Team 2005-22 stated: “The horizontally mounted scanning LIDAR scans a 180 degree arc in front of the vehicle and is hard-mounted in position. This sensor is used for primary obstacle detection. The advertised range of the LMS-291 is 80m, but [the challenge vehicle's] software only uses LIDAR data at a maximum range of 40m.” ([58], p. 6). Team 2005-22 did not report the model number of the SICK LMS 291 sensor in use by the team.

Team 2005-23 stated: “[The challenge vehicle] uses three scanning LIDAR...”, “Two Sick single plane scanning LIDAR are mounted to the top left and right front corners of the vehicle...”, and “The third LIDAR is an IBEO ALASCA...” ([164], p. 7).

Team 2005-23 did not report the model number of the SICK LIDAR sensors in use by the team. Although the Journal of Field Robotics ([59]) confirmed the quantity of SICK LIDAR sensors in use by Teams 2005-22 and 2005-23, it contradicted the Team 2005-23 technical paper ([164]) by stating that a third SICK LIDAR sensor was in use by Team 2005-23 in lieu of an IBEO LIDAR sensor, and reported no additional identifying information for the LIDAR sensors in use by Teams 2005-22 and 2005-23.

The author concluded one SICK LIDAR sensor was in use by Team 2005-22 during the 2005 GCE, but considers the model number of this sensor unknown. The author concluded the IBEO LIDAR sensor was not in use by Team 2005-23 and that three SICK LIDAR sensors were in use by Team 2005-23 during the 2005 GCE, but considers the model number of these sensors unknown.

V.C.46.b. NovAtel ProPak-LBplus and NovAtel HG1700 SPAN

Team 2005-22 stated: "[The challenge vehicle] uses a Honeywell TALIN inertial navigation system coupled with a Rockwell-Collins PLGR GPS to determine position, velocity and attitude." ([58], p. 6).

Teams 2005-22 and 2005-23 later stated: "Both vehicles used Novatel Propak LBplus positioning systems ... in the Grand Challenge... The system consists of a Novatel Propak LBplus GPS receiver and a Novatel IMUG2 enclosure housing a Honeywell HG1700 inertial measurement unit (IMU)." ([59], p. 711).

NovAtel stated: "The ProPak-LB plus features NovAtel's SPAN™ Technology to provide support for an external inertial measurement unit (IMU)." ([206]). The author concluded it was likely the Honeywell HG1700 IMU referred to by the Journal of Field Robotics ([59]) was actually a NovAtel HG1700 SPAN (see also paragraph V.C.44.d.).

The author concluded one NovAtel ProPak-LBplus[21] and one NovAtel HG1700 SPAN were in use by Team 2005-22 during the 2005 GCE, in lieu of the Honeywell TALIN INS and Rockwell-Collins PLGR GPS reported by the Team 2005-22 technical paper ([58]), and considers these sensors known.

The author concluded one NovAtel ProPak-LBplus[21] and one NovAtel HG1700 SPAN were in use by Team 2005-23 during the 2005 GCE, and considers these sensors known.

V.C.46.c. Point Grey Bumblebee stereo camera pair

Via Figure 1 of the team technical papers ([58], p. 4 and [164], p. 4), Teams 2005-22 and 2005-23 reported one Point Grey Bumblebee stereo camera pair was in use by the teams. Team 2005-22 stated: "If a road is detected by the stereo vision cameras..." ([58], p. 8), but otherwise referred to a "stereo vision camera" or "camera" throughout the Team 2005-22 technical paper ([58]). Team 2005-23 referred to a "stereo vision camera" or "camera" throughout the Team 2005-23 technical paper ([164]).

Teams 2005-22 and 2005-23 later stated: "A Point Grey Bumblebee stereovision camera, mounted to the top center of the vehicle's roll cage, is used to observe the area in front of the vehicle." ([59], p. 712). The author concluded it was likely the Team 2005-22 reference to "cameras" was an error, and that one stereo camera pair was in use by the team.

In addition, Teams 2005-22 and 2005-23 later stated: "The monocular/stereovision system allows [the challenge vehicles] to perceive roads ahead of the vehicle and mark them as preferred areas of travel." ([59], p. 712), but later reported the "monocular system" described referred to the use of stereo vision camera images for road detection: "After simplifying the image, the software searches for the basic geometric characteristics that define a road. This search is done using only one of the 2D images provided by the stereocameras." ([59], p. 712). The author concluded no additional camera was in use by either Team 2005-22 or 2005-23 during the 2005 GCE.

The author concluded one Point Grey Bumblebee stereo camera pair was in use by Teams 2005-22 and 2005-23, and considers this sensor known.

V.C.46.d. Unknown encoders

Via Figure 1 of the team technical papers ([58], p. 4 and [164], p. 4), Teams 2005-22 and 2005-23 reported "Encoders" were in use by the teams, but reported no additional identifying information.

Teams 2005-22 and 2005-23 later stated: "Both vehicles actuate the throttle using a dc gear motor with integrated encoder feedback." and "Both vehicles use right-angle gear motors fitted with quadrature encoders to actuate the steering." ([59], p. 710), but reported no additional identifying information.

The author concluded one "throttle" encoder and one "steering" encoder were in use by Teams 2005-22 and 2005-23, but otherwise considers these sensors unknown.

V.D. Results

Results for 2004 technical papers are presented in Tables XXIX, XXX, and XXXI, and summarized in paragraph V.D.1. below. Results for 2005 technical papers are presented in Table XXXII, XXXIII, and XXXIV, and summarized in paragraph V.D.2. below. The columns "K", "U", and "E" represent "known", "unknown", and "estimated", respectively.

V.D.1. 2004

V.D.1.a. Known sensors by quantity (2004 QID and GCE participants)

See Table XXIX.

V.D.1.a.i. State sensors

The 25 2004 technical papers described 90 state sensors in use by teams which participated in both the 2004 QID and GCE, some of which were common to more than one challenge vehicle. Of the 90 state sensors, 47 were in use by teams which participated in the 2004 GCE.

V.D.1.a.i.a. Known

- The quantity of 31 of 90 (34.4 percent) state sensors in use by teams which participated in both the 2004 QID and GCE were known.

- The quantity of 16 of 47 (34.0 percent) state sensors in use by teams which participated in the 2004 GCE were known.

V.D.1.a.i.b. Unknown

- The quantity of 16 of 90 (17.8 percent) state sensors in use by teams which participated in both the 2004 QID and GCE were unknown.

- The quantity of nine of 47 (19.1 percent) state sensors in use by teams which participated in the 2004 GCE were unknown.

V.D.1.a.i.c. Estimated

- The quantity of 43 of 90 (47.8 percent) state sensors in use by teams which participated in both the 2004 QID and GCE were were estimated by the author in accordance with paragraph V.B.3.a.

- The quantity of 22 of 47 (46.8 percent) state sensors in use by teams which participated in the 2004 GCE were estimated by the author in accordance with paragraph V.B.3.a.

V.D.1.a.ii. Environment sensors

The 25 2004 technical papers describe 96 environment sensors in use by teams which participated in both the 2004 QID and GCE, some of which were common to more than one challenge vehicle. Of the 96 environment sensors, 61 were in use by teams which participated in the 2004 GCE.

V.D.1.a.ii.a. Known

- The quantity of 81 of 96 (84.4 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE were known.

- The quantity of 50 of 61 (82.0 percent) environment sensors in use by teams which participated in the 2004 GCE were known.

V.D.1.a.ii.b. Unknown

- The quantity of 11 of 96 (11.5 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE were unknown.

- The quantity of seven of 61 (11.5 percent) environment sensors in use by teams which participated in the 2004 GCE were unknown.

V.D.1.a.ii.c. Estimated

- The quantity of four of 96 (4.2 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE were estimated by the author as described in paragraph V.C.

- The quantity of four of 61 (6.6 percent) environment sensors in use by teams which participated in the 2004 GCE were estimated by the author as described in paragraph V.C.

V.D.1.a.iii. Navigation sensors

The 25 2004 technical papers describe 103 navigation sensors in use by teams which participated in both the 2004 QID and GCE, some of which were common to more than one challenge vehicle. Of the 103 navigation sensors, 62 were in use by teams which participated in the 2004 GCE.

V.D.1.a.iii.a. Known

- The quantity of 89 of 103 (86.4 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE were known.

- The quantity of 52 of 62 (83.9 percent) navigation sensors in use by teams which participated in the 2004 GCE were known.

V.D.1.a.iii.b. Unknown

- The quantity of four of 103 (3.9 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE were unknown.

- The quantity of one of 62 (1.6 percent) navigation sensors in use by teams which participated in the 2004 GCE was unknown.

V.D.1.a.iii.c. Estimated

- The quantity of ten of 103 (9.7 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE were estimated by the author in accordance with paragraph V.B.5.c.

- The quantity of nine of 62 (14.5 percent) navigation sensors in use by teams which participated in the 2004 GCE were estimated by the author in accordance with paragraph V.B.5.c.

V.D.1.b. Known sensors by manufacturer (2004 QID and GCE participants)

See Table XXX.

V.D.1.b.i. <u>State sensors</u>

The 25 2004 technical papers describe 90 state sensors in use by teams which participated in both the 2004 QID and GCE, some of which were common to more than one challenge vehicle. Of the 90 state sensors, 47 were in use by teams which participated in the 2004 GCE.

V.D.1.b.i.a. <u>Known</u>

- The manufacturers of 13 of 90 (14.4 percent) state sensors in use by teams which participated in both the 2004 QID and GCE were known.

- The manufacturers of nine of 47 (19.1 percent) state sensors in use by teams which participated in the 2004 GCE were known.

V.D.1.b.i.b. <u>Unknown</u>

- The manufacturers of 77 of 90 (85.6 percent) state sensors in use by teams which participated in both the 2004 QID and GCE were unknown.

- The manufacturers of 38 of 47 (80.9 percent) state sensors in use by teams which participated in the 2004 GCE were unknown.

V.D.1.b.ii. <u>Environment sensors</u>

The 25 2004 technical papers describe 96 environment sensors in use by teams which participated in both the 2004 QID and GCE, some of which were common to more than one challenge vehicle. Of the 96 environment sensors, 61 were in use by teams which participated in the 2004 GCE.

V.D.1.b.ii.a. <u>Known</u>

- The manufacturers of 57 of 96 (59.4 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE were known.

- The manufacturers of 37 of 61 (60.7 percent) environment sensors in use by teams which participated in the 2004 GCE were known.

V.D.1.b.ii.b. <u>Unknown</u>

- The manufacturers of 39 of 96 (40.6 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE were unknown.

- The manufacturers of 24 of 61 (39.3 percent) environment sensors in use by teams which participated in the 2004 GCE were unknown.

V.D.1.b.iii. Navigation sensors

The 25 2004 technical papers describe 103 navigation sensors in use by teams which participated in both the 2004 QID and GCE, some of which were common to more than one challenge vehicle. Of the 103 navigation sensors, 62 were in use by teams which participated in the 2004 GCE.

V.D.1.b.iii.a. Known

- The manufacturers of 58 of 103 (56.3 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE were known.

- The manufacturers of 36 of 62 (58.1 percent) navigation sensors in use by teams which participated in the 2004 GCE were known.

V.D.1.b.iii.b. Unknown

- The manufacturers of 45 of 103 (43.7 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE were unknown.

- The manufacturers of 26 of 62 (41.9 percent) navigation sensors in use by teams which participated in the 2004 GCE were unknown.

V.D.1.c. Known sensors by manufacturer and model number (2004 QID and GCE participants)

See Table XXXI.

V.D.1.c.i. State sensors

The 25 2004 technical papers describe 13 state sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers, some of which were common to more than one challenge vehicle. Of the 13 state sensors with known manufacturers, nine were in use by teams which participated in the 2004 GCE.

V.D.1.c.i.a. Known

- The model numbers of 12 of 13 (92.3 percent) state sensors with known manufacturers in use by teams which participated in both the 2004 QID and GCE were known.

- The model numbers of nine of nine (100.0 percent) state sensors with known manufacturers in use by teams which participated in the 2004 GCE were known.

V.D.1.c.i.b. Unknown

- The model numbers of one of 13 (7.7 percent) state sensors with known manufacturers in use by teams which participated in both the 2004 QID and GCE were unknown.

- No state sensors with known manufacturers in use by teams which participated in the 2004 GCE were unknown.

V.D.1.c.ii. Environment sensors

The 25 2004 technical papers describe 57 environment sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers, some of which were common to more than one challenge vehicle. Of the 57 environment sensors with known manufacturers, 37 were in use by teams which participated in the 2004 GCE.

V.D.1.c.ii.a. Known

- The model numbers of 33 of 57 (57.9 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers were known.

- The model numbers of 17 of 37 (45.9 percent) environment sensors in use by teams which participated in the 2004 GCE with known manufacturers were known.

V.D.1.c.ii.b. Unknown

- The model numbers of 24 of 57 (42.1 percent) environment sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers were unknown.

- The model numbers of 20 of 37 (54.1 percent) environment sensors in use by teams which participated in the 2004 GCE with known manufacturers were unknown.

V.D.1.c.iii. Navigation sensors

The 25 2004 technical papers describe 58 navigation sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers, some of which were common to more than one challenge vehicle. Of the 58 navigation sensors with known manufacturers, 36 were in use by teams which participated in the 2004 GCE.

V.D.1.c.iii.a. Known

- The model numbers of 38 of 58 (65.5 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers were known.

- The model numbers of 24 of 36 (66.7 percent) navigation sensors in use by teams which participated in the 2004 GCE with known manufacturers were known.

V.D.1.c.iii.b. Unknown

- The model numbers of 20 of 58 (34.5 percent) navigation sensors in use by teams which participated in both the 2004 QID and GCE with known manufacturers were unknown.

- The model numbers of 12 of 36 (33.3 percent) navigation sensors in use by teams which participated in the 2004 GCE with known manufacturers were unknown.

V.D.2. 2005

V.D.2.a. Known sensors by quantity (2005 GCE participants)

See Table XXXII.

V.D.2.a.i. Environment sensors

The 23 2005 technical papers describe 66 environment sensors in use by teams which participated in the 2005 GCE, some of which were common to more than one challenge vehicle.

V.D.2.a.i.a. Known

The quantity of 60 of 66 (90.9 percent) were known.

V.D.2.a.i.b. Unknown

The quantity of six of 66 (9.1 percent) were unknown.

V.D.2.a.ii. Navigation sensors

The 23 2005 technical papers describe 70 navigation sensors in use by teams which participated in the 2005 GCE, some of which were common to more than one challenge vehicle.

V.D.2.a.ii.a. Known

The quantity of 67 of 70 (95.7 percent) were known.

V.D.2.a.ii.b. Unknown

The quantity of one of 70 (1.4 percent) was unknown.

V.D.2.a.ii.c. Estimated

The quantity of two of 70 (2.9 percent) were estimated by the author in accordance with paragraph V.B.5.c.

V.D.2.b. Known sensors by manufacturer (2005 GCE participants)

See Table XXXIII.

V.D.2.b.i. Environment sensors

The 23 2005 technical papers describe 66 environment sensors in use by teams which participated in the 2005 GCE, some of which were common to more than one challenge vehicle.

V.D.2.b.i.a. Known

The manufacturers of 52 of 66 (78.8 percent) were known.

V.D.2.b.i.b. Unknown

The manufacturers of 14 of 66 (21.2 percent) were unknown.

V.D.2.b.ii. Navigation sensors

The 23 2005 technical papers describe 70 navigation sensors in use by teams which participated in the 2005 GCE, some of which were common to more than one challenge vehicle.

V.D.2.b.ii.a. Known

The manufacturers of 51 of 70 (72.9 percent) were known.

V.D.2.b.ii.b. Unknown

The manufacturers of 19 of 70 (27.1 percent) were unknown.

V.D.2.c. Known sensors by manufacturer and model number (2005 GCE participants)

See Table XXXIV.

V.D.2.c.i. Environment sensors

The 23 2005 technical papers describe 52 environment sensors in use by teams which participated in the 2005 GCE with known manufacturers, some of which were common to more than one challenge vehicle.

V.D.2.c.i.a. Known

The model numbers of 31 of 52 (59.6 percent) were known.

V.D.2.c.i.b. Unknown

The model numbers of 21 of 52 (40.4 percent) were unknown.

V.D.2.c.ii. Navigation sensors

The 23 2005 technical papers describe 51 navigation sensors in use by teams which participated in the 2005 GCE with known manufacturers, some of which were common to more than one challenge vehicle.

V.D.2.c.ii.a. Known

The model numbers of 39 of 51 (76.5 percent) were known.

V.D.2.c.ii.b. Unknown

The model numbers of 12 of 51 (23.5 percent) were unknown.

V.D.3. Summary of results

The results of the comprehensive review of technical papers for teams which participated in both the 2004 QID and GCE and selected review of technical papers for teams which participated in the 2005 GCE are summarized by Table I. For each category reported by paragraph V.D., the known, unknown, and estimated sensors are represented as a percentage of the total quantity of sensors in use by the teams.

Table I. Results of the review of 2004 and 2005 technical papers.										
		Percentage of all sensors								
		2004 QID/GCE			2004 GCE			2005 GCE		
		K	U	E	K	U	E	K	U	E
State	Quantity	34.4	17.8	47.8	34.0	19.1	46.8			
	Manufacturer	14.4	85.6		19.1	80.9				
	Model No.	92.3	7.7		100					
Environment	Quantity	84.4	11.5	4.2	82.0	11.5	6.6	90.9	9.1	
	Manufacturer	59.4	40.6		60.7	39.3		78.8	21.2	
	Model No.	57.9	42.1		45.9	54.1		59.6	40.4	
Navigation	Quantity	86.4	3.9	9.7	83.9	1.6	14.5	95.7	1.4	2.9
	Manufacturer	56.3	43.7		58.1	41.9		72.9	27.1	
	Model No.	65.5	34.5		66.7	33.3		76.5	23.5	

V.D.3.a. Differences between 2004 QID and GCE results

The inclusion of teams which participated in the 2004 QID in the totals reported by Table I had no significant impact. The quantity of state sensors for which the manufacturer was unknown decreased from 85.6 to 80.9 percent (a decrease of 4.7 percent) when teams which participated in the 2004 QID were excluded, while the quantity of environment sensors for which both the manufacturer and model number was unknown increased from 42.1 to 54.1 (an increase of 12.0 percent). For the other 2004 totals reported, the difference was not considered significant.

V.D.3.b. Differences between 2004 and 2005 GCE results

The differences between 2004 and 2005 GCE results in each category reported by paragraph V.D. were significant. Not only was there an increase in the quantity of known sensors in each category, but there was an increase of 13.7 percent in the quantity of environment sensors with known manufacturers and model numbers, and 9.8 percent in the quantity of navigation sensors with known manufacturers and model numbers.

However, although 90.9 and 95.7 percent of the quantity of environment and navigation sensors, respectively, in use by the teams which participated in the 2005 GCE were known, the author was only able to determine the manufacturer and model number of 59.6 and 76.5 percent of the sensors, respectively.

V.E. Conclusion

Two of 48 teams reported sufficient technical detail via their 2004 or 2005 technical papers to determine the quantity, manufacturer, and model number for described state, environment, and navigation sensors: Teams 2004-17 and 2005-18. Team 2004-17 participated in the 2005 GCE as Team 2005-18.

As a result, the author concluded it would not be possible to reliably estimate the total cost of the sensor technology in use by each team using published records. Overall, attempting to determine the quantity, manufacturer, and model number for the various challenge vehicles' state, environment, and navigation sensors proved to be a time-consuming, tedious task requiring the author to very carefully review 2004 and 2005 technical papers for any information which might in any way provide some insight into the vehicles' sensor load, team websites for additional identifying information where possible, and other published records to determine if the vehicle described by the technical papers was actually the vehicle which participated in the 2004 and 2005 GCE.

V.E.1. Primary sources of uncertainty

V.E.1.a. <u>Technical paper requirements</u>

- 2004

DARPA established a requirement that teams participating in the 2004 QID or GCE submit a technical paper describing their challenge vehicle ([1]):

> A technical paper describing the Challenge Vehicle must be received at DARPA on or before the application deadline. A description of the mandatory subjects to be addressed in this paper is on the DARPA Grand Challenge web site (www.darpa.mil/grandchallenge).
>
> The technical paper will be reviewed by DARPA to ensure that the Challenge Vehicle design complies with the Rules. The panel also will judge the technical competence of the design and may not accept incomplete or ineffectual proposals.

The "description of the mandatory subjects to be addressed in this paper" was not available from the Archived Grand Challenge 2004 website ([17]).

DARPA also established a requirement that teams participating in the 2004 QID or GCE submit addenda to their technical papers if necessary ([1]):

> DARPA must be informed as soon as possible of any deviation in the technical approach described in a

current technical paper. These technical paper addenda may be submitted to DARPA without penalty prior to the application deadline or any time after the initial technical paper has been approved as long as they are submitted at least 14 calendar days prior to the QID in order that DARPA will have time to review and approve the deviation.

The technical paper addenda are intended for minor modifications and refinement of the Challenge Vehicle design. The addition or improvement of code, sensors, suspension, or actuators on basically the same vehicle, for example, are appropriate for a technical paper addendum.

DARPA later amended this requirement, and stated: “Addendums must be submitted as complete technical papers with the changes from the current technical paper marked. Alternately, these changes can be delineated in a separate document.” ([6]).

DARPA also established a requirement that technical papers and addenda submitted by teams participating in the 2004 GCE be reasonably accurate:

DARPA stated: “Challenge Vehicles presented for the Qualification Inspections and Demonstration (QID) that deviate substantially from the description in the approved technical paper (including approved addenda) will be disqualified.” ([1]). DARPA did not later amend this requirement.

DARPA later stated: “[The technical paper] is an integral part of the rules enforcement process that will help ensure this event is a fair and safe competition for all involved. Judges performing the technical inspection on the day prior to the main event will use the paper to validate the vehicles. Therefore, the paper should contain sufficient detail that a person could compare the vehicle to the paper and verify all the hardware that is present. As an example, 'the vehicle will use lidar' is not sufficiently detailed. If a commercial system is used, a reference to its specifications should be provided, as well as the planed [*sic*] location on the vehicle. If the system is completely home built, the components should be described in detail.” ([207]).

- 2005

DARPA established a similar requirement that teams participating in the 2005 GCE submit a technical paper describing their challenge vehicle ([2], p. 18):

A technical paper describing the vehicle of each semifinalist must be received at DARPA by August 15, 2005. A description of the subjects that must be addressed in the technical paper will be available on the Grand Challenge website.

Neither the 2005 GCE rules ([2]) nor the 2005 GCE Technical Paper Guidelines ([208]) require the submission of technical paper addenda if necessary.

V.E.1.b. Errors, omissions, and inconsistencies

During the review, it quickly became apparent that the technical papers submitted to DARPA were of indifferent quality, containing a large number of technical mistakes, and having generally poor presentation, such as figures which were missing or were shifted to later pages due to pagination problems or off of the page entirely, lack of whitespace, and errors of punctuation and pluralization which rendered meanings unclear, and that it would not be possible to reliably estimate the total cost of the sensor technology in use by each team based on their descriptions. The use of the words “the”, “a”, “an”, “was”, and “were” in combination with pluralization was often the only clue to the quantity of sensors in use. Examples have been noted throughout this technical report.

In addition, later published records directly contradict some technical papers, resulting in a difference between the proposed sensor load and reported sensor load. For this reason, and because of other differences between team technical papers and later published records, the phrase “technical proposal” is used in lieu of “technical paper” in all later chapters of this technical report. Although the author did not tabulate the proposed sensor load for each vehicle, it is of interest because a comparison between the proposed sensor load and the reported sensor load might identify sensors which were, in practice, more difficult to integrate than anticipated, or identify sensors the use of which was abandoned because they provided information of little utility.

V.E.1.c. Insufficient technical detail

Insufficient technical detail was the most significant contributing factor to an overall inability to determine the quantity, manufacturer, and model number of state, environment, and navigation sensors in use by the teams. Most commonly, a team failed to report the complete model number for the environment sensors in use by the team.

DARPA identified this as a weakness in correspondence with teams participating in the 2004 QID or GCE approximately six weeks before the teams were required to submit their technical paper. DARPA stated: “Common weak areas in technical paper submissions are a lack of completeness and a lack of detail.” ([207]). However, despite having established a requirement that teams participating in the 2004 QID or GCE describe their challenge vehicle in “sufficient detail” and identifying lack of detail as a problem, teams did not report sufficient technical detail to determine what sensors were in use by the team.

Several teams attempted to answer the questions DARPA asked in the format they were asked. For example, Team 2004-15 stated: "The following [Team 2004-15] technical information is presented in the same format as the Required Contents in the Technical Paper Requirements." ([137], p. 1). The author was unable to locate a copy of the 2004 GCE "Technical Paper Requirements" for review, although a copy of the 2005 Technical Paper Guidelines ([208]) was hosted by DARPA via the Archived Grand Challenge 2005 website ([19]).

To a certain extent, the standard questions to which DARPA requested teams respond in their technical papers may have predetermined the content of some team's responses and had a negative impact on the overall quality of team technical papers.

Several of the standard questions were ambiguous. When the intent of the standard question was unclear, the question was variously interpreted by the teams, often resulting in redundancy which is evident from the large number of technical mistakes which are repeated throughout some technical proposals.

In addition, several of the standard questions were very general and the order in which they were asked may have been interpreted as redundant requests for information, which may have contributed to an overall lack of specificity in their responses. For example, in response to 2004 SQ 1.e.1 (see Table XXII), Team 2004-09 stated: "[The challenge vehicle] will be using a laser range finding system, a video camera, a gyroscope, GPS, and a vibration sensor to determine the location of the path being taken, location of the vehicle, obstacles in the path, and the condition of the road/path surface." ([38], p. 7). Team 2004-09 did not describe how the controlling intelligence uses this information except in the most general terms, although DARPA requested the teams "Describe the methodology for the interpretation of sensor data..." via a previous question, 2004 SQ 1.c.2 (see Table XXII), which also addressed vehicle state and navigation sensors.

DARPA exhibited concern with some team responses. For example:

- Team 2004-10

Team 2004-10 stated: "GC Review comments are in Attachment C." ([77], p. 1), however the Team 2004-10 technical paper did not include Attachment C.

- Team 2004-20

Team 2004-20 stated: "The Government's questions from revisions 1 and 2, along with our replies, appear at the end of this document. In addition, per the Government's request, the replies have been incorporated into the text, in bold italic." ([107], p. 1). Team 2004-20 maintained an extensive online repository which contained several revisions of their technical paper prior to the final version accepted by DARPA ([107]), including DARPA responses to their first and second revisions indicating that DARPA requested “technical specs (and/or manufacturer and model name if a commercial product)” for several sensors as well as other technical detail not reported by Team 2004-20 ([209]).

- Team 2004-21

Team 2004-21 responded to two sections labeled “DGC concerns” via their technical paper ([155]).

However, the author was unable to determine the extent of DARPA's involvement in a review of technical papers prior to the 2004 and 2005 GCE. There is no evidence this effort was comprehensive. The large number of technical mistakes in papers deemed “completely acceptable” by DARPA, and the failure of some teams to report “sufficient detail”, supports a conclusion the review, however extensive, was inadequate. Although DARPA established a penalty of disqualification for team challenge vehicles which “deviate substantially” from their description, no teams were disqualified for failure to report sufficient technical detail.

When the author concluded insufficient technical detail was reported to determine the total cost of team challenge vehicles, the author contacted DARPA to ask if DARPA had access to additional information not available from the technical papers. The author asked ([210]):

> I'm collecting pricing information for sensor technologies that were used in the 2004 and 2005 DARPA Grand Challenge, and I was wondering if DARPA collected this information, e.g., if the proposals from the teams, not the technical papers, included a cost breakdown that is public information or may be requested through a FOIA request.

DARPA responded:

> DARPA did not collect information from the teams that is publicly available.
>
> A good way to get the information you are looking for would be to start with the description in the technical papers and on the website, then to check with the manufacturers.

The author considers this validates the author's approach, and the results presented in this section refute the assertion that team technical papers reported sufficient technical detail to identify all sensors in use, let alone produce a reliable estimate of the total cost of challenge vehicles. In addition, the results presented in this section support a conclusion that DARPA was itself aware of the deficiencies in team technical papers but did not act to ensure the technical papers would be “the primary mechanism from which knowledge gained from this event is utilized in future research and development” ([207]).

V.E.1.d. Poor revision control

Several 2004 technical papers contained marks used to annotate revision such as colored or italicized text, highlighting, or comments, for example: Teams 2004-04, 2004-11, 2004-14, 2004-20, 2004-21, and 2004-25. DARPA required teams participating in the 2004 GCE to annotate revisions or include changes in a separate document. See paragraph V.E.1.a. Although DARPA did not establish a similar requirement prior to the 2005 GCE, the Team 2005-22 technical paper contained many annotated revisions.

As a result of these annotations, it is unclear if the technical paper represents the final published record of the teams prior to the 2004 QID or GCE or 2005 GCE or if the technical paper was incomplete, or a work in progress, when it was submitted to DARPA.

V.E.2. Additional sources of uncertainty

Several teams reported a cost for their challenge vehicles, either directly via team technical papers or the Journal of Field Robotics, or indirectly via another source. For example, teams participating in the 2005 GCE reported the following total costs and team sizes (source is [211] unless otherwise noted):

Table II. Reported cost and team size of selected team challenge vehicles.		
Team	Reported cost, dollars	Reported team size
2004-07	35,000[a]	N/A
2004-10	approximately $3 million[b]	N/A
2004-16	175,000[c]	N/A
2005-01	450,000[d]	N/A
2005-03	[e]	7
2005-06	650,000	12
2005-08	[f]	20
2005-12	125,000	14
2005-13	in excess of 3,000,000[g]	100+
2005-16	500,000	60
2005-18	120,000[h]	50
2005-20	500,000	18
2005-21	[f]	32
2005-22	60,000[i]	57+
2005-23	60,000[i]	

Notes:

[a] Team 2005-05 participated in the 2004 GCE as Team 2004-07. Team 2005-05 stated: "[The challenge vehicle] traveled 5.1 miles in the 2004 Challenge ... before stopping on a steep slope because of an excessively conservative safety limit on the throttle control. This was the fourth-greatest distance traveled in the 2004 DGC; a good performance considering [the challenge vehicle's] small total budget of $35,000." ([170], p. 528).

[b] Team 2004-10 reported a cost of "approximately $3 million" ([212]).

[c] Team 2004-16 stated: "Estimated Cost: $15,000 vehicle, $90,000 electronics, and $70,000 in-kind loaner equipment. Total hardware: $175,000. Not including thousands of hours of custom programming." ([139]).

[d] Team 2005-01 stated: "[Team 2005-01] will have spent roughly $450,000 on its 2005 DARPA Grand Challenge entry. This would have increased to $625,000, if the team had been charged for its MMW RADAR loaner unit." ([213]).

[e] Team 2005-03 did not report the cost of their challenge vehicle, but stated their

challenge vehicle cost "A lot!".

[f] Teams 2005-08 and 2005-21 did not report the cost of their challenge vehicle.

[g] Team 2005-13 did not report the cost of their challenge vehicle, but stated their challenge vehicle was "Priceless". However, Team 2004-10 reported a cost of "approximately $3 million" ([212]). Team 2004-10 participated in the 2005 GCE as Team 2005-13. The author concluded the cost of Team 2005-13's challenge vehicle exceeded the figure of "approximately $3 million" reported by Team 2004-10 due to continuing development. In addition, Teams 2005-13 and 2005-14 were co-participants during the 2005 GCE. As a result, the combined cost of the Team 2005-13 and 2005-14 challenge vehicles was in excess of $3 million.

[h] Team 2005-18 stated: "$120K total equipment budget (excl. donations); CS/EE/ME 75abc + 24 SURFs." ([197], p. 5).

[i] Teams 2005-22 and 2005-23 were co-participants during the 2005 GCE and stated the cost of their challenge vehicles was: "<$20,000 cash, with equipment donations worth ~$100,000". The author evenly divided the $120,000 combined cost between the two teams.

However, without context, the costs reported by the teams are meaningless. It was immediately apparent that different accounting methods were used and that reported costs misrepresented the total cost of team challenge vehicles. In general, available objective evidence supports a conclusion that the published record did not report enough information with which to estimate the total cost of team challenge vehicles, although the author was able to identify additional sources of uncertainty during the review:

V.E.2.a. The cost of labor was not reported

From review of the published record, it is evident most teams did not report the cost of labor. Only one team which participated in the 2005 GCE, arguably, included the cost of student labor in reported cost: Team 2005-12.

Team 2005-12 stated the cost of their challenge vehicle was: "$125,000, including all travel expenses, hardware, and summer stipends for students", and that their team was composed of: "1 professor and 1 grad student (supervisors) and 12 undergrads (who did all the work) over 18 months" ([211]). Team 2005-12 alternately stated: "[Team 2005-12] consists of a dedicated team of enrolled full-time undergraduate students, one graduate research assistant and several advising faculty." ([185], p. 2), and identified more than 14 team members and "advisors". In either case, the cost reported by Team 2005-12 ostensibly included the cost of undergraduate student labor during the summer as "summer stipends for students".

In addition, Team 2005-12 stated: "The one Graduate Assistant contributed as part oh [*sic*] his graduate research requirement." ([185], p. 2). As a result, the author concluded the "Graduate Assistant" was not compensated.

Team 2005-12 did not account for the cost of "advising faculty".

The author considers it likely other teams accounted for the cost of labor, and that the cost of labor is included in the reported cost for some teams. However, there is no evidence this practice was widespread, or comprehensive. The author considers it more likely the cost of labor for student members of teams with limited Academic sponsorship or other teams on which students participated was not accounted for.

V.E.2.b. <u>Labor cost estimation</u>

Several teams reported general team composition, but not the cost of labor, and reported team composition indicated a large number of individuals worked on the team challenge vehicle. For example:

- Teams 2005-13 and 2005-14

Teams 2005-13 and 2005-14 stated: "[The team] is a collaborative enterprise of students, volunteers, professionals and corporations..." ([11], p. 2 and [12], p. 2).

- Team 2005-15

Team 2005-15 stated: "Our team was formed in March 2003, in response to the announcement of the DARPA Grand Challenge 2004. Initially it comprised a team of scientists and engineers from Rockwell Scientific (RSC) of Thousand Oaks, CA, although many volunteers from other companies have joined the team." ([53], p. 2) and via a footnote on the same page: "Our volunteers are employed at numerous companies including Amgen and Teradyne in the Thousand Oaks area and a number of our volunteers are Rockwell Scientific retirees.".

- Team 2005-16

Team 2005-16 stated: "[Team 2005-16] brings together leading automotive engineers, artificial intelligence researchers, and experienced program managers..." ([195], pp. 1 - 2) and "The team consists of approximately 50 individuals that include... students, faculty, and alumni, and employees of [Team 2005-16] primary supporters and other nearby research labs. ([195], p. 3).

- Team 2005-17

Team 2005-17 stated: "[Team 2005-17] consists of faculty and students of the University of Louisiana at Lafayette and professionals from the Lafayette and Louisiana communities." ([140], p. 2).

- Team 2005-18

Team 2005-18 stated: "[Team 2005-18] consists of over 50 undergraduates who have worked to conceive, design, build and optimize [the challenge vehicle]..." ([197], p. 1) and "As part of the plan to gain a competitive advantage, [Team 2005-18] invites industry experts to review the progress of the team at the end of each spiral of development and milestone (once per term). This review committee includes people from JPL, Northrop Grumman, STI and other companies. As part of the review, the industry experts submit requests for action (RFA's) on any component of the architecture that they feel needs work." ([197], p. 13).

As a result, the author considered using the reported number of team members to estimate the cost of labor, but concluded it would not be possible due to varying levels of experience or qualification. For example, as Team 2005-12 above, Teams 2005-22 and 2005-23 reported the composition of their teams: "40+ undergraduate students, 10 grad students, 2 faculty, 5+ volunteers" ([211]). There is a difference between the value of student labor, graduate student labor, and professional faculty labor. The same or similar differences exist between the value of engineer labor, project management labor, etc.

There is no evidence the cost of labor was differentiated based on experience or qualifications, but review of team descriptions available from the Archived Grand Challenge 2005 website ([19]) revealed individuals with varying levels of expertise and diverse backgrounds participated in the Grand Challenge.

In addition, the author concluded attempting to estimate the cost of labor by dividing the reported cost by the number of team members would not be possible, even after reducing the total cost by a fixed hardware cost. Dividing the reported cost by number of team members yielded annual salaries in the range of $2,000 to $54,000, which is a range so wide as to be meaningless.

The author likewise concluded attempting to estimate the cost of labor by multiplying an hourly rate by the number of hours reported would not be possible. Most teams did not report the number of team members, let alone the number of hours required to complete their challenge vehicles. Some teams reported thousands of hours of labor. For example, Team 2004-16 stated: "Estimated Cost: $15,000 vehicle, $90,000 electronics, and $70,000 in-kind loaner equipment. Total hardware: $175,000. Not including thousands of hours of custom programming." ([139]). Anecdotal evidence supports an assertion that most teams spent thousands of hours preparing for the 2004 and 2005 GCE.

To help establish perspective:

- The cost of labor for a team with 50 members working for one year (52 weeks with two weeks of unpaid vacation) 40 hours per week on average at an hourly rate of $10/hr would be $1 million.

- The cost of labor for a team with 50 members working for one year (52 weeks with two weeks of unpaid vacation) 60 hours per week on average, and being paid overtime, at an hourly rate of $10/hr would be $1.75 million.

- The cost of labor if the number of hours is limited to 2000 hours as the least possible number representative of "thousands of hours", at an hourly rate of $10/hr would be $200,000. This exceeds the reported cost of six of 13 challenge vehicles. See Table II.

V.E.2.c. Estimation of comparative costs

An alternate strategy considered by the author was estimation of comparative costs. Several teams reported comparative costs which could ostensibly be used to determine total cost. For example:

- Team 2005-01

Team 2005-01 stated: "There were Defense funded teams that could not be 'Completely Accepted' for the 2004 DARPA Grand Challenge, while we spent 5 cents to every dollar spent by other Defense teams." ([213]).

- Teams 2005-22 and 2005-23

Teams 2005-22 and 2005-23 stated: "By miles traveled at the Grand Challenge per dollars invested, the VT vehicles lead the field." ([214]).

However, it is unclear which teams Team 2005-01 identified as "Defense teams", or how Team 2005-01 arrived at an estimate of "5 cents to every dollar spent by other Defense teams"; and it is unclear how Teams 2005-22 and 2005-23 were able to determine "dollars invested" for all the teams which participated in the 2005 GCE.

As a result, the author concluded published comparative costs were unreliable, and that attempting to determine total cost by estimation of comparative costs would not be possible.

V.E.2.d. The cost of sensors was not reported

Although two estimates are publicly available which reported pricing information for some sensors in use by teams participating in the 2004 and 2005 GCE ([215] and [216]), the source of the pricing information reported by these documents is not available, and no team participating in the 2004 or 2005 GCE published a similar detailed cost breakdown, specifically listing the cost per sensor in use by the team. The author concluded these estimates are unreliable in the absence of corroborating evidence.

In addition, the author notes the price of sensors in use by the teams may depend on distributor, date procured, and reputation of the organization or institution procuring the sensor. Although the author has no direct evidence supporting variable pricing by manufacturers for sensors in use by teams participating during the 2004 and 2005 GCE, it is not an uncommon practice for manufacturers or distributors to variably price goods. As a result, teams with prior experience in autonomous vehicle development such as Teams 2005-13, 2005-14, and 2005-16 might have paid less for the same sensor in use by other teams based on reputation alone, or been able to negotiate more favorable prices based on prior experience.

V.E.2.d.i. Pricing information for most high-quality sensors is not available from published records

Pricing information for most sensors is not available from published records. The author does not consider manufacturer product literature, including pricing information, to which access is directly controlled by the manufacturer or indirectly controlled by an agent of the manufacturer to be published records. See Chapter XVI.

For example:

- SICK LIDAR sensors

SICK manufactured several models of Laser Measurement System (LMS) in use by teams which participated in the 2004 and 2005 GCE. However, pricing information for these sensors was not available from the manufacturer (e.g., [74] and [73]), and hyperlinks to distributors on the manufacturer website ([217]) led to a search dialogue for "local" distributors.

Realistically, there may be more of a difference in cost between SICK LMS 211-30106 and LMS 211-30206 LIDAR sensors than there is between LMS 211-30106 and LMS 220-30106 LIDAR sensors. Published estimates ([215] and [216]) reported pricing information for SICK LMS 211-30206 and SICK LMS 221-30206, but the reliability of either estimate could not be independently confirmed because SICK does not publicly disclose pricing information.

- Trimble DGPS receivers

Trimble manufactured several DGPS receivers in use by teams which participated in the 2004 and 2005 GCE. However, as with SICK, hyperlinks to distributors on the manufacturer website led to a search dialogue for "local" distributors ([192]).

The author noted the manufacturers most likely to publicly disclose pricing information were manufacturers of low-cost sensors such as state sensors, ultrasonic sensors, or cameras, e.g., SpaceAge Control, SensComp, and Unibrain. The author considers the greater competition in the market for such sensors may provide an incentive to the manufacturers of low-cost sensors to publicly disclose pricing information, and the greater cost of high-quality sensors may provide a disincentive to the manufacturers of such sensors to publicly disclose pricing information.

V.E.2.d.ii. Insufficient technical detail was reported to determine the total cost of reported sensors

The total cost of reported sensors includes the cost of accessories such as cabling and mounts, the individual cost of which is not significant but which collectively represent a cost that must be considered part of the total cost of the vehicle; the cost of optional accessories for alternate configurations which may not be included in the cost of the individual sensor, but which may have been in use by the teams, albeit not reported; and software. For example:

- Trimble DGPS receivers

The Trimble AgGPS 114 is a centerpiece surrounded by many other potential components, including the “AgGPS 70 RDL”, “AgGPS PSO Plus”, “AgGPS 170 Field Computer with Guidance”, “10 Hz positioning upgrade for AgGPS114”, “Everest Multi-path reduction for AgGPS 114”, and “OTHER AgGPS COMPONENTS/SYSTEMS” ([82]).

In addition, DGPS receivers typically receive free differential correction signals such as WAAS and USCG, but also differential correction signals from subscription services such as OmniSTAR or StarFire. Review of team technical papers revealed many teams used subscription services which provide differential correction signals. In general, the total cost of DGPS receivers should include the cost of subscription services such as OmniSTAR or StarFire.

- Image processing software

Team 2004-04 stated that a “Videre Design stereo vision system” was in use by the team. The author concluded this was a reference to an unknown Videre Design stereo camera pair. See paragraph V.C.4.b. However, like most STEREO sensors, Videre Design stereo camera pairs require the use of specific image processing algorithms to produce information useful to the controlling intelligence. It is for this reason that the author considers a stereo camera pair to be a high-quality sensor only if proven software for image processing was also in use by the team. See paragraph VI.B.1.a.i.

SRI's Small Vision System (SVS) has support for the stereo camera pairs manufactured by Videre Design ([97]). The cost of the “stereo vision system” in use by

Team 2004-04 therefore must include the cost of SRI's SVS, and, in general, the total cost of any sensor must also include the cost of software required to provide the controlling intelligence with useful information.

V.E.2.d.iii. Some teams referred to sensors to describe "systems" or reported the "system" as the sensor

Some teams reported the sensors comprising a "system" individually, or reported the "system" as the sensor. This was most prevalent for RADAR sensors. For example, Eaton and PRECO Preview RADARs have multiple emitters, which some teams reported as individual sensors. See paragraphs V.C.4.d., V.C.20.b., V.C.21.b., V.C.23.c., V.C.26.b., V.C.27.b., and V.C.40.e. for specific examples. Several VISION or STEREO sensors with multiple cameras were also described as "systems". See paragraphs V.C.34.c., V.C.39.b., and V.C.45.c. for specific examples.

When the author determined the intent of the team was unambiguous and required no additional evaluation, he did not document occurrences of this discrepancy via paragraph V.C. For example:

- Team 2004-15

Team 2004-15 stated: "An active 24.725 GHz Doppler radar system (Eaton VORAD EVT-300) with a sensing horizon of 100 meters and 12 degree field of view will also be utilized for obstacle detection/avoidance as well as enhanced road following capability. The radar *system* will include a forward-looking antenna as well as range-gated side sensors." ([137], p. 3, *emphasis added*). Because Team 2004-15 clearly described the Eaton EVT-300 as a system which included one "forward-looking antenna" and two "side sensors", the author concluded one Eaton EVT-300 *system* was in use by the team.

- Team 2005-08

Team 2005-08 stated: "The SCC radars have a 15 degree field of view. For [the challenge vehicle], three SCC radars are configured across the front of the vehicle in a manner to provide a 45 degree field of view." ([173], p. 9). The author concluded three Delphi Forewarn ACC3 RADAR *sensors* were in use by Team 2005-08 based on the collective field-of-view reported by Team 2005-08.

V.E.2.e. The cost of equipment donated or loaned to the teams was not reported

Several teams directly or indirectly reported the cost of equipment donated or loaned to the teams. For example:

- Team 2004-16

Team 2004-16 stated: “Estimated Cost: $15,000 vehicle, $90,000 electronics, and $70,000 in-kind loaner equipment. Total hardware: $175,000.” ([139]).

- Team 2005-01

Team 2005-01 stated: “[Team 2005-01] will have spent roughly $450,000 on its 2005 DARPA Grand Challenge entry. This would have increased to $625,000, if the team had been charged for its MMW RADAR loaner unit.” ([213]).

- Team 2005-10

Team 2005-10 stated: “In the end, most of the cost of the project was covered by corporate donations of equipment.” ([176], p. 8).

- Team 2005-18

Team 2005-18 reported a “$120K total equipment budget (excl. donations)” ([197], p. 5).

- Teams 2005-22 and 2005-23

Teams 2005-22 and 2005-23 reported “equipment donations worth ~$100,000” ([211]).

However, most teams which participated in the 2004 and 2005 GCE did not report the cost of equipment donated or loaned to the teams.

V.E.2.e.i. <u>The cost of computing resources was not reported</u>

In general, the cost of sensors does not include the cost of computer or networking hardware required to integrate sensor data, unless a COTS product was in use by the team for this purpose, yet the total cost includes the cost of computing resources which provide useful information to the controlling intelligence.

V.E.2.f. <u>Confidential and proprietary appendixes conceal technical detail</u>

Via paragraph 4.3.3 of revision “April 1.2” of the 2004 GCE rules ([1]) DARPA stated: “DARPA will treat the technical papers as team proprietary information in their entirety until the conclusion of the 2004 Challenge, at which time the papers will be available to the public. Technical papers containing an attachment of information that is designated by the Team as proprietary information will not be made available with the proprietary attachment.”

Several teams which participated in the 2004 GCE included confidential or proprietary appendixes in their technical papers. The confidential or proprietary appendixes conceal technical detail. For example:

- Team 2004-03

Team 2004-03 referred to three "confidential" appendixes: "1A1-0", "1A1-1", and "1A2" ([92], p. 3) which provided information about challenge vehicle "mobility", and one non-confidential appendix "3D2", which provided information about the placement of E-stop switches on the challenge vehicle. Team 2004-03 was the only team to select a motorcycle as the platform for their challenge vehicle for either the 2004 or 2005 GCE (see Tables XIV, XV, and XVI).

DARPA published neither the Team 2004-03 confidential appendixes nor the non-confidential appendix. However, DARPA later noted: "The independent technical evaluation team identified the following technology from Grand Challenge 2004 noteworthy": "Dynamically balancing motorcycles" ([3], p. 10). As a result, the author considers this supports a conclusion that there was perceived value in the Team 2004-03 intellectual property.

- Team 2004-06

Team 2004-06 stated: "The entire contents of this paper are considered proprietary and confidential to DARPA." ([114], p. 7). This statement appears on the first page of the Team 2004-06 "Addendum to Technical Paper", however DARPA published the paper in its entirety, including the addendum.

- Team 2004-10

Team 2004-10 stated: "Four Attachments describe the vehicle design. The original GC questions are in Attachment B. GC Review comments are in Attachment C." ([77], p. 1). Team 2004-10 did not report the information Attachments A or D provided, and the technical paper did not include any of the attachments to which Team 2004-10 referred.

- Team 2004-22

Team 2004-22 twice referred to a "proprietary annex": "Video Processing—See Proprietary Annex" ([157], p. 3), and "Actual speeds in tight turns is addressed in the proprietary annex." ([157], p. 7); and once to an "attached annex": "Novatel ProPac-LB-HB satellite-based Differential GPS... Specifications are in attached annex" ([157], p. 2). Team 2004-22 also referred to a "presentation": "Attached PowerPoint presentation depicts the area of coverage for the new imagery." ([157], p. 4). DARPA did not publish either the Team 2004-22 proprietary annex, attached annex, or presentation.

- Team 2004-23

Team 2004-23 stated: “The vision system consists of 6 CCD digital color cameras. Two pairs are used to provide stereovision information (both forward and rear looking). The two single cameras will sense the terrain in front and behind the truck and provide free-space estimation and path/road estimation.” and “The vision system is a work in progress with the system being developed and tested initially in Italy by Prof. Alberto Broggi’s group.” ([159], p. 8).

Although Team 2004-23 did not refer to a confidential or proprietary appendix or annex, the team technical paper ([159]) essentially describes a vision processing system and, as DARPA later noted: “The independent technical evaluation team identified the following technology from Grand Challenge 2004 noteworthy”: “Custom hardware solution for low-cost, real-time stereo algorithm with reflexive planning” ([3], p. 10). Teams 2004-06, 2004-22, and 2004-23 each developed a custom vision processing system for use as a path and obstacle detection sensor. The author considers this supports a conclusion that there was perceived value in Team 2004-23 intellectual property, as well as the intellectual property of Teams 2004-06 and 2004-22.

In addition, some teams specifically referred to the value of intellectual property in their team technical papers or other published records. For example, Team 2005-15 stated: “A limited liability company ... was created as the legal entity for ownership of the vehicle and accessories and for participation in the event. [The LLC] ... will own the team intellectual property and is positioned to transition into a company that will exploit its autonomous vehicle technology after the Grand Challenge series is complete.” ([53], p. 2), and Team 2005-17 twice stated: “The algorithm is being evaluated by the University for its IP value. Hence, its details are not being disclosed in this public document.” ([140], p. 9).

As a result, the author concluded some teams were not motivated to disclose relevant technical information due to the perceived value of intellectual property that would be generated as a result of the 2004 and 2005 GCE.

Six teams which participated in the 2005 GCE referred to proprietary technologies via their technical papers. However, no teams which participated in the 2005 GCE included confidential or proprietary appendixes in their technical papers. DARPA did not refer to confidential or proprietary appendixes prior to the 2005 GCE, but stated ([2], p. 18):

> Other than the required technical paper and information already in the public domain, DARPA will not publicly release information regarding a team’s

technical approach without permission from the team leader.

DARPA claims no intellectual property (IP) rights from entrants, semifinalists, finalists, or the winner... All trade secrets, copyrights, patent rights, and software rights will remain with each respective team.

V.E.2.g. Anecdotal evidence

The author observed a difference in the amount of technical information disclosed by technical proposals submitted by teams with significant corporate sponsorship and other technical proposals during the comprehensive review of technical papers. Some teams with significant corporate sponsorship (e.g., Teams 2004-10, 2004-13, 2004-14, and 2004-18) seemed to disclose more relevant technical information than other teams.

A comment by the Team 2004-05 team leader may provide some insight into this observation. The Team 2004-05 team leader asserted that teams such as Team 2004-10 “largely pulled together a range of existing, expensive components that companies were keen to give away in order to attract the government's attention.” ([218]). As a result, the author proposes the decision to disclose relevant technical information may have been influenced by corporate sponsorship, in particular, a “quid pro quo” relationship in which equipment was donated or loaned to some teams in exchange for publicity or other exposure resulting from team use of the equipment. The many press releases detailing the use of a manufacturer's technology, equipment, or components by teams participating in the 2004 QID or GCE or 2005 GCE, some of which are referenced herein, support this assertion.

However, the author also concluded the use of COTS components and high-quality sensors were key factors contributing to success. As a result, although the author considers publicity or other exposure a reasonable explanation for the difference in the amount of technical information disclosed by teams with significant corporate sponsorship, the author also considers the incidental publicity or other exposure resulting from corporate sponsorship an unfortunate but unavoidable consequence of an event such as the Grand Challenge, which encouraged existing defense contractors to provide corporate sponsorship, but not participate directly.

Team sponsorship was not considered when evaluating the amount of technical information disclosed by teams.

Evidence such as teams referring specifically to the formation of business structures such as a Limited Liability Company and the existence of confidential or proprietary appendixes revealed the focus of many teams was on monetizing their intellectual property, not on sharing technical detail. See paragraph V.E.2.f. Anecdotal evidence such as the distribution of "shares" revealed the focus of many teams was on prize distribution.

Although Team 2005-10 stated: "We are especially grateful to those fellow Grand Challenge competitors who have been willing to share their knowledge directly and on the DARPA GC discussion forum. [The Team 2004-05 team leader] in particular has distinguished himself for his spirit of cooperation and willingness to share information." ([176], p. 7), the Team 2004-05 team leader's attitude was not prevalent. More teams referred to the non-disclosure of information than the sharing of information.

In addition, the author noted a difference in the approach of teams with moderate or extensive academic sponsorship as "compete to teach" and "compete to win". Some teams with a primary group identity as "Academic", such as Teams 2004-25, 2005-04 and 2005-12, referred specifically to participation in the Grand Challenge as a teaching opportunity, e.g., as part of an existing course or independent research. For example:

- Team 2004-25

Team 2004-25 stated: "[Team 2004-25] is using this Challenge as a senior design experience for undergraduate Mechanical Engineering students." ([49], p. 13).

- Team 2005-04

Team 2005-04 stated: "A two Quarter 'Capstone Design Course' sequence was initiated and helped investigate new ideas, apart from inspiring students." ([169], p. 7).

- Team 2005-12

Team 2005-12 stated: "Underclassmen have participated as either summer interns and/or on an extra-curricular basis, while upperclassmen have received independent research or senior thesis credit for their research contribution to the project. The one Graduate Assistant contributed as part oh [*sic*] his graduate research requirement." ([185], p. 2).

- Team 2005-18

Team 2005-18 stated: "Through a new course in multi-disciplinary project design, we have had over 50 students participate in conceiving, designing, implementing and testing our new vehicle..." ([197], p. 2).

Other teams with a primary group identity as "Academic", such as Teams 2005-13, 2005-14, and 2005-16, all of which successfully completed the 2005 GCE did not appear to have the same focus on the Grand Challenge as a teaching opportunity. For this reason, the author chose to focus on participation, in lieu of competition. See Chapter XVI.

CHAPTER VI. HIGH-QUALITY OBSTACLE AND PATH DETECTION SENSORS

VI.A. Discussion

During the review of 2004 and 2005 technical proposals, the author noted an increase in the number of major (i.e., not discounted) obstacle and path detection sensors in use by teams which participated in the 2004 and 2005 GCE, and a corresponding decrease in discounted obstacle and path detection sensors and state sensors.

VI.B. Analysis

The author reviewed the published record in an attempt to quantify the number of major obstacle and path detection sensors in use by the teams, in particular sensors which were considered high-quality. Environment sensors were first classified by type: “VISION”, “STEREO”, “RADAR”, or “LIDAR”. Environment sensors were then classified by quality. Discounted sensors were eliminated from consideration as described in paragraph V.B.4. Sensors of each type were classified as high-quality sensors in accordance with paragraphs VI.B.1., VI.B.2., and VI.B.3. In general, high-quality sensors were considered to be those sensors which provided discrete information about the environment, such as a point-map (using depth-to-LIDAR return) or point-cloud (using depth-to-pixel) or obstacle location relative to the challenge vehicle, at a speed at which the challenge vehicle's controlling intelligence was able to reliably interpret.

VI.B.1. VISION sensors

The author divided vision sensors in use by the teams into two categories: “Stereo Camera Pair” and “Other Cameras”.

VI.B.1.a. Stereo camera pair

The author considered a combination of two or more cameras to be a stereo camera pair if clearly described as a stereo camera pair by the team or manufacturer. The author considers a stereo camera pair to be a high-quality sensor if proven software for image processing was also in use by the team.

VI.B.1.a.i. High-quality stereo camera pairs

High-quality stereo camera pairs included the following known STEREO sensors:

- Point Grey Bumblebee.
- Videre Design Stereo Vision System (SVS).
- Team 2004-17 stereo camera pairs. Four Point Grey Dragonfly cameras were in use by Team 2004-17 as two stereo camera pairs during the 2004 QID and GCE.

See paragraph V.C.17.c. Team 2004-17 stated: “One short range and one long range pair of black and white stereovision cameras will produce point clouds at 30 Hz that we will process into local terrain maps at the same rate. This computation will be done with the Small Vision System purchased from Videre Systems.” ([142], p. 5).

- Team 2005-08 Sony DFW-VL500 stereo camera pair. Two Sony DFW-VL500 cameras were in use by Team 2005-08 during the 2005 GCE as a stereo camera pair. See paragraph V.C.33.d. Team 2005-08 stated: “The low level stereo processing is performed using the Small Vision System (SVS) software from Videre Design.” ([173], p. 11).

- Team 2005-15 stereo camera pair. One stereo camera pair was in use by Team 2005-15 during the 2005 GCE. See paragraph V.C.39.b. Team 2005-15 stated: “ARC Seibersdorf ... provided their stereovision system for feature detection.” ([53], p. 3) and “...a stereo vision system jointly developed by Seibersdorf research and ACV, is used.” ([53], p. 9). Although Team 2005-15 described this sensor as “novel”, the author concluded it was likely proven software for image processing was also in use by the team.

- Team 2005-18 stereo camera pairs. Four Point Grey Dragonfly cameras were in use by Team 2005-18 during the 2005 GCE as two stereo camera pairs. See paragraph V.C.42.b. Team 2005-18 stated: “A pair of Point Grey Dragonfly cameras mounted on the roof are used in combination with SRI’s Small Vision System to generate 3D pointclouds.” ([197], p. 10).

High-quality stereo camera pairs included the following unknown STEREO sensors, as described by team technical proposals:

- Team 2004-18 unknown stereo camera pair. One unknown stereo camera pair was in use by Team 2004-18 during the 2004 QID and GCE. See paragraph V.C.18.g. Team 2004-18 stated: “The Team will purchase and use an implementation of SRI’s Small Vision System (SVS) software that comes standard with certain brands of stereo vision hardware.”, “...the SVS includes SRI’s patent pending Stereo Engine algorithm...”, and “...a cloud of 3D surface points in front of the vehicle is produced and becomes accessible by [Team 2004-18's] custom software.” ([48], p. 5).

- Team 2004-23 unknown stereo camera pairs. Four unknown CCD digital color cameras were in use by Team 2004-23 as two stereo camera pairs. See paragraph V.C.23.e. Via the team technical proposal ([159]), Team 2004-23 described the image processing software and also how the image processing software was proven.

- Team 2005-04 unknown stereo camera pair. One unknown stereo camera pair was in use by Team 2005-04 during the 2005 GCE. See paragraph V.C.29.c. Team 2005-04 stated: "[The challenge vehicle] was developed in partnership with the University of Karlsruhe, which developed the vision system." ([169], p. 2) and "The Vision system was developed entirely separately by the University of Karlsruhe team in Germany, and then integrated with the Sensor Fusion set-up... The cross-Atlantic cooperative development was similar in nature to the one we initiated with an Italian team in 2004, while developing [the Team 2004-23 challenge vehicle]." ([169], p. 7). Based on the description of the Team 2004-23 challenge vehicle unknown stereo camera pairs, the author considers it likely a similar effort was made by Team 2005-04 to prove the image processing software.

- Team 2005-21 unknown trinocular camera system. An unknown trinocular camera system was in use by Team 2005-21 during the 2005 GCE. See paragraph V.C.45.c. Via the team technical paper ([160]), Team 2005-21 described the image processing software and also how the image processing software was proven.

VI.B.1.a.ii. Other stereo camera pairs

Stereo camera pairs which were not considered to be high-quality sensors included:

- Team 2004-03 unknown Cognex cameras. Two unknown Cognex cameras were in use by Team 2004-03 during the 2004 QID and GCE. See paragraph V.C.3.b. Team 2004-03 reported "a pair of high resolution 1600x1200 ethernet cameras manufactured by Cognex used for creating realtime 3D scene of the obstacles in front of the vehicle." were in use by the team ([94]). Because these cameras were used to create a "3D scene of the obstacles in front of the vehicle", the author concluded these cameras were in use as a stereo camera pair. Team 2004-03 reported no additional identifying information for the software in use by the team.

- Team 2004-06 Digital Auto Drive. A proprietary stereo camera pair was in use by Team 2004-06 during the 2004 QID and GCE. See paragraph V.C.6.a. Team 2004-06 participated in the 2005 GCE as Team 2005-03. A proprietary LIDAR sensor was in use by Team 2005-03. See paragraph V.C.28.a. Team 2005-03 stated: "Lessons learned from GC I drove the requirements for the LADAR terrain mapping and obstacle detection system..." ([33], p. 6). Although Team 2004-06 stated: "We are unaware of any other high quality vision systems in existence..." ([114], p. 7), the author concluded the proprietary stereo camera pair in use by Team 2004-06 was not a high-quality stereo camera pair because Team 2004-06 reported no additional identifying information for the software in use by the team and the proprietary stereo camera pair was not in use by Team 2005-03 during the 2005 GCE.

- Team 2004-19 unknown stereo camera pair. An unknown stereo camera pair was in use by Team 2004-19 during the 2004 QID. See paragraph V.C.19.a. Team 2004-19 stated: “We are still working on our stereo vision system, and have not yet interfaced it with the vehicles [*sic*] computing system.” ([151], p. 4). Team 2004-19 reported no additional identifying information for the software in use by the team.

- Team 2004-24 unknown stereo camera pair. An unknown stereo camera pair was in use by Team 2004-24 during the 2004 QID and GCE. See paragraph V.C.24.c. Team 2004-24 reported no additional identifying information for the software in use by the team.

- Team 2005-07 unknown stereo camera pair. An unknown stereo camera pair was in use by Team 2005-07 during the 2005 GCE. See paragraph V.C.32. Team 2005-07 reported no additional identifying information for the software in use by the team.

- Team 2005-10 unknown stereo camera pair. An unknown stereo camera pair was in use by Team 2005-10 during the 2005 GCE. See paragraph V.C.35.c. Team 2005-10 stated: “Using a unique and proprietary algorithm, we are able to use the fast, 30 frames per second, update rate from the stereo vision camera and detect most obstacles easily.” ([176], p. 7). Based on the results of other teams which independently implemented image processing algorithms during the 2004 and 2005 GCE, the author considers it likely the software implementing the algorithm described by Team 2005-10 was unproven.

- Team 2005-20 unknown stereo camera pair(s). Unknown stereo camera pair(s) were in use by Team 2005-20 during the 2005 GCE. See paragraph V.C.44.c. Team 2005-20 reported no additional identifying information for the software in use by the team.

VI.B.1.b. Other cameras

All other cameras are considered to be VISION sensors. The author does not consider VISION sensors to be high-quality sensors.

VI.B.2. RADAR sensors

The author divided RADAR sensors in use by the teams into two categories: “Navigation RADAR” and “Other RADAR”.

VI.B.2.a. Navigation RADAR

The author considered any RADAR sensor which provided the range, relative velocity, and azimuth to target for multiple targets to be navigation RADAR. The author considers navigation RADAR a high-quality sensor. Navigation RADAR included the following known RADAR sensors:

- Epsilon Lambda ELSC71-1A. The Team 2004-21 technical proposal incorporated a specification sheet for the Epsilon Lambda ELSC71-1A as an appendix. The appendix stated: "Obstacle data reported includes range; [*sic*] azimuth angle, elevation angle, relative velocity, and signal return amplitude." ([155], p. 14).

- Eaton EVT-300 when interfaced with the Eaton VBOX. Although Eaton stated the Eaton EVT-300 provides: "Accurate range, velocity and azimuth on up to 20 vehicles or objects within a range of 350 feet." ([162]), the Eaton EVT-300 "Driver Display Unit" does not provide the range, relative velocity, and azimuth to target. However, Eaton reported the Eaton VBOX provides "Target range, speed, [and] angle relative to host radar" ([106]) as output via an RS-232 port.

- Navtech DS2000. Navtech stated: "With the scanner and raydome [*sic*] the unit provides a full 360 degrees scan at 2.5 Hz with target ranges up to 200m and range accuracy down to +/- 0.03m." and "As standard the system will provide range and bearing information to the nearest target that is above a predefined size." ([219]).

Examples of navigation RADAR included the following unknown RADAR sensors, as described by team technical proposals:

- Team 2004-05 unknown Eaton RADAR. One unknown Eaton RADAR was in use by Team 2004-05 during the 2004 QID. See paragraph V.C.5.g. The author considers is likely the Team 2004-05 unknown Eaton RADAR would have had capabilities characteristic of the Eaton EVT-300 when interfaced with the "Eaton Vorad VBOX 83001-001" in use by the team.

- Teams 2004-13 and 2004-14 unknown Epsilon Lambda RADAR. One unknown Epsilon Lambda RADAR sensor was in use by Teams 2004-13 and 2004-14 during the 2004 QID and GCE. See paragraph V.C.13.f. and V.C.14.f. The author considers it likely the unknown Epsilon Lambda RADAR would have had capabilities characteristic of the Epsilon Lambda ELSC71-1A.

- Team 2004-16 unknown RADARs. Unknown RADARs were in use by Team 2004-16 during the 2004 QID and GCE. See paragraph V.C.16.d. Team 2004-16 stated: "Radar/sonar subsystem identifies large or small objects and radar can estimate velocity for distinguishing moving vehicles from stationary objects..." and "Differential signals from sonar and radar help to estimate location of object [*sic*]." ([138], pp. 3 - 4). The author concluded the Team 2004-16 unknown RADARs had capabilities characteristic of navigation RADAR.

- Team 2004-23 unknown Eaton RADARs. Two unknown Eaton RADARs were in use by Team 2004-23 during the 2004 QID and GCE. See paragraph V.C.23.c. Team 2004-23 stated: “2 Eaton-Vorad radars are mounted (front and rear) for providing 150 m range target tracking.” ([159], p. 9). The author considers it likely the Team 2004-23 unknown Eaton RADARs would have had capabilities characteristic of the Eaton EVT-300 when interfaced with the Eaton VBOX.

- Team 2004-24 unknown Eaton RADAR. One unknown Eaton RADAR was in use by Team 2004-24 during the 2004 QID and GCE. See paragraph V.C.24.e. Team 2004-24 stated: “The Eaton VORAD radar provides tracking data on up to 20 objects. This data includes azimuth, distance and closing speed.” ([161], p. 5). The author considers is likely the Team 2004-24 unknown Eaton RADAR would have had capabilities characteristic of the Eaton EVT-300 when interfaced with the Eaton VBOX.

- Team 2004-25 unknown Eaton RADARs. Two unknown Eaton RADARs were in use by Team 2004-25 during the 2004 QID and GCE. See paragraph V.C.25.f. Team 2004-25 stated: “The radar system actively distinguishes obstacles moving relative to the vehicle from the surroundings. The radar system and laser rangefinders are used to determine the direction, size, and speed of obstacles.” ([49], p. 10). The author considers is likely the Team 2004-25 unknown Eaton RADARs would have had capabilities characteristic of the Eaton EVT-300 when interfaced with the Eaton VBOX.

- Team 2005-20 unknown RADAR(s). Unknown RADAR(s) were in use by Team 2005-20 during the 2005 GCE. See paragraph V.C.44.b. Team 2005-20 stated: “The RADAR system, for example, preprocesses the data to locate obstacles in the vehicle path. It receives broadcast messages from the vehicle location navigation computer to determine a global position of the obstacle. Based on a confidence of the obstacle, the RADAR computer broadcasts the obstacle parameters including position in both local and global coordinates along with obstacle size to the path planner map.” ([56], p. 7). Based on the Team 2005-20 description of the “RADAR system”, the author considers it likely the Team 2005-20 unknown RADAR(s) provided the range, relative velocity, and azimuth to target for multiple targets.

VI.B.2.b. Other RADAR

All other RADAR sensors are considered to be “Other RADAR”. The author does not consider other RADAR sensors to be high-quality sensors. Other RADAR sensors include:

- All vehicle anti-collision or obstacle avoidance RADAR, including the Eaton EVT-300 when not interfaced with the Eaton VBOX, Amphitech OASys, Preco Preview, and Delphi Forewarn ACC3.

- All “short-range” RADAR sensors.

- All Doppler RADAR sensors.

- Team 2004-04 unknown long-range RADAR. One unknown long-range RADAR was in use by Team 2004-04 during the 2004 QID and GCE. See paragraph V.C.4.d. Team 2004-04 participated in the 2005 GCE as Team 2005-02. Team 2005-02 alternately stated an unknown Eaton RADAR sensor was in use by the team via the team technical proposal ([167]), and not in use by the team via the Journal of Field Robotics ([50]). See paragraph V.C.27.b. Team 2004-04 stated: “Because of the wide field of view of the RADAR system and the limited range resolution, the RADAR system will be used as a 'free space' detector.” ([44], p. 6). Team 2004-04 did not report sufficient technical detail to conclude the unknown long-range RADAR provided the range, relative velocity, and azimuth to target for multiple targets, and was not in use as a vehicle anti-collision RADAR.

- Team 2004-15 Eaton EVT-300. One Eaton EVT-300 was in use by Team 2004-15. Team 2004-15 stated: “An active 24.725 GHz Doppler radar system (Eaton VORAD EVT-300) with a sensing horizon of 100 meters and 12 degree field of view will also be utilized for obstacle detection/avoidance as well as enhanced road following capability. The radar system will include a forward-looking antenna as well as range-gated side sensors.” ([137], p. 3). The author concluded this sensor was in use as a vehicle anti-collision RADAR.

- Team 2005-01 unknown Eaton RADAR. One unknown Eaton RADAR was in use by Team 2005-01. See paragraph V.C.26.b. Team 2005-01 did not report sufficient technical detail to conclude the unknown Eaton RADAR would have had capabilities characteristic of the Eaton EVT-300 when interfaced with the Eaton VBOX.

- Team 2005-04 Eaton EVT-300. One Eaton EVT-300 was in use by Team 2005-04 during the 2005 GCE. Team 2005-04 stated: “One radar (the Eaton-Vorad 300 EVT) is pointed straight ahead and is mainly for long distance obstacle detection at high speed.” ([169], p. 8). The author concluded this sensor was in use as a vehicle anti-collision RADAR, not navigation RADAR.

- Team 2005-04 unknown RADAR. One unknown RADAR was in use by Team 2005-04 during the 2005 GCE. See paragraph V.C.29.b. Team 2005-04 did not report sufficient technical detail to conclude the unknown RADAR provided the range, relative velocity, and azimuth to target for multiple targets.

VI.B.3. LIDAR sensors

The author divided LIDAR sensors in use by the teams into two categories: scanning laser range finders and other LIDAR sensors.

VI.B.3.a. Scanning laser range finders

The author considers scanning laser range finders to be high-quality sensors. Examples of scanning laser range finders included the following known LIDAR sensors:

- All SICK LMS LIDAR sensors. SICK LMS LIDAR sensors were the most popular sensors in use by teams which participated in either the 2004 or 2005 GCE. Based on their popularity, the author considers all unknown SICK LIDAR sensors to be SICK LMS LIDAR sensors, unless otherwise noted.

- All Riegl LIDAR sensors.

- The Optech ILRIS-3D.

Examples of scanning laser range finders included the following unknown LIDAR sensors, as described by team technical proposals:

- Team 2004-11 unknown scanning laser range finder. One unknown scanning laser range finder was in use by Team 2004-11. See paragraph V.C.11.b.

- Team 2004-24 unknown LIDAR sensor. One unknown LIDAR sensor was in use by Team 2004-24 during the 2004 QID and GCE. See paragraph V.C.24.d. Team 2004-24 stated: “The Lidar sensor is the final sensor used for solid model construction. It is the primary obstacle avoidance sensor.” ([161], p. 5). Based on the use of the unknown LIDAR sensor for “solid model construction”, the author concluded this sensor was a scanning laser range finder capable of providing a point-map.

- Team 2005-03 Digital Auto Drive. A proprietary LIDAR sensor was in use by Team 2005-03 during the 2005 GCE. See paragraph V.C.28.a. The proprietary LIDAR sensor described by Team 2005-03 is a scanning LIDAR sensor with a 360-degree field-of-view similar to scanning LIDAR sensors with a more limited field-of-view in use by teams which participated in the 2005 GCE.

- Team 2005-20 unknown LIDAR sensor(s). Unknown LIDAR sensor(s) were in use by Team 2005-20 during the 2005 GCE. See paragraph V.C.44.a. No other team which participated in the 2005 GCE used non-scanning, or simple, laser range finders. As a result, the author considers it likely the unknown LIDAR sensor(s) in use by Team 2005-20 were scanning laser range finders.

- Team 2005-21 unknown Ibeo LIDAR sensors. One unknown Ibeo LIDAR sensor was in use by Team 2005-21 during the 2005 GCE. See paragraph V.C.45.b. An Ibeo “Case Study” described the Ibeo LIDAR sensor in use by Team 2005-21 as a “laser scanner” ([204]).

VI.B.3.b. <u>Other LIDAR</u>

All other LIDAR sensors are considered to be "Other LIDAR". The author does not consider other LIDAR sensors to be high-quality sensors. Examples of other LIDAR sensors include:

- Laseroptronix LDM 800-RS232. Laseroptronix stated the Laseroptronix LDM 800-RS232 is a "pulsed laser distance meter / laser range finder" ([220]), not a scanning laser range finder.

- Laseroptronix Sea-Lynx. Laseroptronix stated that, although the "passive" and "active" modes of the Laseroptronix Sea-Lynx function as an image-intensified camera the difference between which is the use of the built-in "laser illumination lamp" to provide a source of light for image intensification, the camera also has a "combined" mode in which "the camera is scanned all over the distance depth in gated mode and all is viewed in one image" ([221]). As a result, the author considers the Laseroptronix Sea-Lynx to be a combined VISION/LIDAR sensor, which uses LIDAR to function as a ranged VISION sensor. Because the Laseroptronix Sea-Lynx outputs what is essentially a television signal (PAL), and does not function primarily as a scanning laser range finder, the author does not consider it to be a high-quality LIDAR sensor.

- Team 2004-11 unknown long-range laser ranger. One unknown long-range laser ranger was in use by Team 2004-11. See paragraph V.C.11.b. Team 2004-11 did not report sufficient technical detail to determine if the long-range laser ranger described by the team was a scanning laser range finder.

- SICK DME 2000. SICK stated the SICK DME 2000 is a "distance measuring device", not a scanning laser range finder ([222]).

VI.C. Results

Results are presented in Tables XXXVI, XXXVII, XXXVIII, and XXXIX, and summarized in Tables XL, XLI, XLII, and XLIII.

VI.C.1. Differences in the number of teams using high-quality sensors from 2004 to 2005

As a percentage of the total number of teams which participated in the 2004 or 2005 GCE:

- There was an increase in the number of teams using high-quality STEREO sensors from 33 percent to 39 percent, a difference of 6 percent.

- There was an increase in the number of teams using high-quality LIDAR sensors from 87 percent to 96 percent, a difference of 9 percent.

- There was a decrease in the number of teams using high-quality RADAR sensors from 60 percent to 13 percent, a difference of 47 percent.

VI.C.2. Differences in the number of high-quality sensors in use

As an average of the number of high-quality sensors of each type in use divided by the total number of teams using sensors of that type during the 2004 and 2005 GCE:

- There was no net change in the number of STEREO sensors in use.

- There was an increase in the number of LIDAR sensors in use per team from 2.3 sensors per team to 3.6 sensors per team.

- There was a decrease in the number of RADAR sensors in use per team from 1.2 sensors per team to 1.0 sensors per team.

VI.D. Conclusions

Teams which participated in the 2004 GCE completed 1.95 miles of the 2004 GCE course, on average, or approximately 1.4 percent of the reported course length of 142 miles. Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average, or approximately 36.7 percent of the reported course length of 131.6 miles.

Based on the analysis, two teams which participated in the 2005 GCE stand out: Teams 2005-06 and 2005-12. Team 2005-06 implemented obstacle and path detection using two vertically-aligned LIDAR sensors on an oscillating mount, and, although Team 2005-12 completed only 9.5 miles of the 2005 GCE course, their later performance supports a conclusion they implemented an obstacle and path detection strategy using one Point Grey Bumblebee stereo camera pair. Both teams equaled or exceeded the performance of teams using a greater number and variety of sensors.

Based on the increase as a percentage of the total course length completed from 2004 to 2005, the author concluded there was a correlation between the following key factors and the average number of miles of the 2004 and 2005 GCE courses the teams completed. The author is not attempting to imply causation. However, the following key factors were common to teams which participated in both the 2004 and 2005 GCE, in general.

VI.D.1. Reduce the number of obstacle and path detection sensors in use by eliminating other sensors

Not only was there a decrease in the number of teams using other cameras, other LIDAR, and other RADAR from 2004 to 2005, but there was a decrease in the number of sensors, i.e., other cameras, other LIDAR, and other RADAR sensors, in use by teams which participated in the 2004 and 2005 GCE.

Overall, the author concluded reduction in complexity was a key factor, and considers the reduction in the number of obstacle and path detection sensors in use by eliminating other sensors an example of reducing complexity. See paragraph XIV.B.

VI.D.2. Use high-quality sensors which provide a point-map of the environment

High-quality STEREO and LIDAR sensors provide a point-map of the environment. Overall, there was an increase in the number of teams using high-quality STEREO and LIDAR sensors, and an increase in the number of sensors of each type in use by each team. The evidence supports a conclusion high-quality LIDAR sensors were easier to integrate, which may explain why high-quality LIDAR sensors were in use by approximately 87 or 96 percent of teams which participated in the 2004 or 2005 GCE, respectively. The number of high-quality LIDAR sensors in use by teams increased from 2.3 to 3.6 sensors, an average increase of approximately one LIDAR sensor per team.

Several teams cited this capability in their technical proposals. For example, an unknown Videre Design stereo vision system was in use by Team 2004-04. See Table XXV. Team 2004-04 stated: “The stereo vision system will be the three dimensional sensor used on [the challenge vehicle]. Its primary purpose will be to provide a dense, albeit noisy, cloud of three dimensional sensor data to our fusion algorithms at a high rate. While the data may in fact be noisy, it will provide valuable information about the presence of objects of interest at distances and elevations outside the field of view of the LADAR system.” ([44], p. 8).

By comparison, high-quality RADAR does not provide a point-map of the environment. Several teams which reported navigation RADAR was in use stated the information it provided was of limited utility or the sensor was difficult to integrate, or later reported navigation RADAR was not in use during the 2004 or 2005 GCE. For example:

- Team 2004-07

One Epsilon Lambda ELSC71-1A was in use by Team 2004-07 during the 2004 GCE. See Table XXV. Team 2004-07 stated: “The radar has been shown to give a minimal level of functionality but it is not clear if it will deliver the expected level of performance.” ([46], p. 9).

- Team 2004-10

Team 2004-10 reported a Navtech DS2000 was in use by the team, but later stated: “The RADAR was not integrated with the primary navigation system due to difficulties extracting noise free data.” ([39], p. 14). The author concluded the Navtech DS2000 was not in use by Team 2004-10 during the 2004 GCE. See paragraph V.C.10.c. The author concluded the Navtech DS2000 was not in use by Team 2004-10 because it was difficult to integrate.

- Team 2004-16

Unknown RADARs were in use by Team 2004-16. See Table XXV. Team 2004-16 participated in the 2005 GCE as Team 2005-17. Team 2005-17 stated: "The radar and sonar sensors are removed." ([140], p. 2). See paragraph V.C.16.d. The author considers it likely the unknown RADARs were removed because the information they provided was of limited utility or the RADARs were difficult to integrate.

- Team 2004-25

Two unknown Eaton RADARs were in use by Team 2004-25. See Table XXV. Team 2004-25 participated in the 2005 GCE as Team 2005-22. Neither Team 2005-22 nor its co-participant Team 2005-23 referred to RADAR sensors in use by the team. See paragraph V.C.25.f. The author considers it likely the unknown Eaton RADARs were not in use by either Team 2005-22 or 2005-23 because the information they provided was of limited utility or the RADARs were difficult to integrate.

- Team 2005-02

Team 2005-02 reported an unknown Eaton RADAR was in use by the team, but did not report the unknown Eaton RADAR was in use during the 2005 GCE, and later stated: "Additional sensors were mounted on the vehicle for experimental purposes, but were not activated for the Darpa Grand Challenge (DGC) event. Each sensor system is described in detail later in this paper." ([50], p. 604). The author concluded the unknown Eaton RADAR was not in use by Team 2005-02 during the 2005 GCE. See paragraph V.C.27.b. The author considers it likely the unknown Eaton RADAR was not in use by Team 2005-02 because the information it provided was of limited utility or the RADAR was difficult to integrate.

- Team 2005-09

Team 2005-09 reported an unknown Eaton RADAR was in use by the team, but did not report the unknown Eaton RADAR was in use during the 2005 GCE ([52]), and later stated: "May. Prepare for a DARPA site visit. Testing had moved from obstacle avoidance to finding a balance between speed, planning, and reaction time. At this point, sensing strategies were unresolved with stereo vision, radar, and machine vision for road detection under consideration." ([52], p. 831). The author concluded the unknown Eaton RADAR was not in use by Team 2005-09 during the 2005 GCE. See paragraph V.C.34.b. The author considers it likely the unknown Eaton RADAR was not in use by Team 2005-09 because the information it provided was of limited utility or the RADAR was difficult to integrate.

VI.D.3. Use LIDAR sensors with capabilities similar to the SICK LMS 291 product family

There was a significant increase in the number of SICK LMS 291 product family LIDAR sensors in use by teams which participated in the 2004 or 2005 GCE from zero to 36[23]. See Table XLIII. The SICK LMS 291 product family has a feature the manufacturer referred to as "fog correction" ([75]). Although fog correction is a capability of other SICK LIDAR sensors in use by teams participating in the 2004 QID or GCE or 2005 GCE, such as the SICK LMS 211-30206 or 221-30206, the author proposes some combination of features, such as fog correction and price[24], of the SICK LMS 291 product family provides an explanation for the significant increase in the number of this specific sensor in use by teams participating in the 2005 GCE.

CHAPTER VII. NAVIGATION SENSOR INTEGRATION

VII.A. Discussion

During the comprehensive review of technical proposals for 2004 QID and GCE participants and review of technical proposals for 2005 GCE participants, the author noted an increase in the number of references to Kalman filtering from 2004 to 2005. The author attributed this to the difficulty teams had making sensor output available to the controlling intelligence, and concluded the use of a Kalman filter to integrate sensor output, in particular navigation sensor output, may have been a key factor.

VII.B. Analysis

The author reviewed the published record in an attempt to determine whether a Kalman filter or other sensor fusion strategy was in use by the teams, and whether teams implemented their own Kalman filter or other sensor fusion strategy, or it was a feature of a COTS component in use by the team.

In general, this was accomplished by searching team the published record for references to key words or substrings such as “kalman”, “filter”, “fusion”, “integrat” (e.g., integrate, integration, integrating, and integrated), “combin” (e.g., combine, combination, combining, and combined), and “navigat” (e.g., navigate, navigation, navigating, and navigated), and reviewing team responses to 2004 GCE SQ 1.c.2, 1.f.1, and 1.g.1 (see Table XXII), and 2005 GCE SQ 2.2.1, 2.3.2, and 2.4.3 (see Table XXIII).

- Team 2004-01

Team 2004-01 stated: “The Inertial sensing unit is based around a Motorola MCS6800 series MCU. The ISU collects inertial guidance data, carries out control orders from The [*sic*] AI/ NAV, and also collects and relays location and vehicle state information for use by the AI/ NAV.” ([8], p. 2). The author concluded Team 2004-01 independently implemented an other sensor fusion strategy.

- Team 2004-02

One AGNC Land Navigator was in use by Team 2004-02 during the 2004 QID and GCE. See Table XXVI. The author concluded the AGNC Land Navigator was a wrapper around the UNCUN1. See paragraph V.C.2.g. AGNC stated the following is a “feature” of the UNCUN1: “GPS and coremicro IMU integration providing precise position and attitude information between GPS updates and during GPS outages.” ([91]), but didn't identify the sensor fusion strategy used to integrate IMU and GPS output. The author concluded Team 2004-02 used a COTS component which implemented an other sensor fusion strategy.

- Team 2004-03

One unknown Crossbow IMU was in use by Team 2004-03 during the 2004 QID and GCE. See Table XXVI. As noted in paragraph V.C.3.e., at least five Crossbow products with different function and series designators have an integrated Kalman filter and either integrated GPS or GPS as an option ([96]). Although Crossbow has since discontinued products which were available at the time of the 2004 QID and GCE, the author considers is likely that multiple products with the capabilities reported by Team 2004-03 were available at the time of the 2004 QID and GCE, and concluded Team 2004-03 used a COTS component which implemented a Kalman filter.

- Team 2004-04

One Smiths Aerospace North Finding Module was in use by Team 2004-04 during the 2004 QID and GCE. See Table XXVI. As noted in paragraph V.C.4.h., Smiths Aerospace has since been acquired by GE. The Smiths Aerospace North Finding Module provides a “GPS/Inertial Kalman Filter Solution” ([168]).

Team 2004-04 stated: “The GPS’s are the only sensors onboard capable of calculating the geolocation of the vehicle. If the GPS signals drop out, the vehicle’s global position becomes uncertain. To overcome this problem, the positioning filter algorithm will continue to calculate a global position during GPS outages by extrapolating a dead reckoning solution based on the shaft encoder and vehicle orientation sensor data. This will allow the vehicle to continue on course for a short period of time; however the solution will gradually drift and the accuracy of the position system will steadily decrease as long as the GPS outage continues. Eventually the error in the system will build up to the point where the vehicle can no longer continue on course with any confidence and the vehicle will have to stop and wait for a GPS reacquisition.” ([44], p. 10).

The author considers it likely the “positioning filter algorithm” reported by Team 2004-04 was a feature of the Smiths Aerospace North Finding Module, and concluded Team 2004-04 used a COTS component which implemented a Kalman filter.

- Team 2004-05

Team 2004-05 stated: “Following a 'Sense-Model-Plan-Act' cycle, sensor data is gathered by SENSOR nodes and digested and/or filtered into a data product for communication to the SUPERVISOR node. This data is supplied to Model nodes (DRIVER and NAVIGATOR) for time-offset correction and integration into a pose estimate and environment model.” ([45], p. 3). The author concluded Team 2004-05 independently implemented an other sensor fusion strategy.

- Team 2004-06

Team 2004-06 stated: “...one TMS2407 class [Digital Signal Processor] ... computes waypoint distance, direction, vehicle orientation, and dead reckoning.” ([114], p. 1). The author concluded Team 2004-06 independently implemented an other sensor fusion strategy.

- Team 2004-07

Team 2004-07 stated: “The DGPS signal will be combined with 'dead reckoning' information from the inertial measurement unit and the axle encoder, and filtered by an Interacting Multiple Model estimator with two constant-velocity models with different levels of process noise.” ([46], p. 8). The author concluded Team 2004-07 independently implemented an other sensor fusion strategy.

- Team 2004-08

One unknown Applanix POS LV was in use by Team 2004-08 during the 2004 QID. See Table XXVI. Applanix stated the POS LV is “fully integrated” ([120]), but did not identify the sensor fusion strategy in use. However, Teams 2004-10, 2005-13, and 2005-14 reported various Applanix sensors were in use which implemented a Kalman filter. The author concluded Team 2004-08 used a COTS component which implemented a Kalman filter.

- Team 2004-09

Team 2004-09 stated: “Sensor fusion also involves a combination of gyroscopic and horizon data to determine vehicle attitude.” and “...GPS data is fused with image information in the planning units to assist in determining path selection and desired vehicle direction.” ([47], p. 3). Via Figure 2 (“Basic Processing Structure”) of the team technical proposal ([47], p. 3), Team 2004-09 reported various navigation sensors provide input into the “Master Planning Unit (MPU)”. The author concluded Team 2004-09 independently implemented an other sensor fusion strategy.

- Team 2004-10

One unknown Applanix INS was in use by Team 2004-10 during the 2004 QID and GCE. See Table XXVI. Applanix stated the POS LV is “fully integrated” ([120]), but did not identify the sensor fusion strategy in use.

Team 2004-10 stated: “Applanix POS unit is utilized for inertial/GPS/DMI instrumentation. The Applanix POS system is a strapdown inertial navigation platform, featuring high-bandwidth, low-latency, Kalman filtering, GPS with azimuth measurement, distance measurement indicator (DMI).” ([77], p. 5). The author concluded Team 2004-10 used a COTS component which implemented a Kalman filter.

- Team 2004-11

Team 2004-11 stated: "The CPU's function is to receive position and environment data from the other systems on board, to analyze the data, make route finding decisions, and to output control signals to the vehicle." and "Most interpretation of sensor data will happen within the CPU and its associated program, although some minor tasks will be handled by the peripherals." ([127], p. 3). Team 2004-11 identified "integration of the odometer and solid state magnetic compass" and "interpretation of GPS data" as functions of two "peripheral microcontrollers" ([127], p. 3). The author concluded Team 2004-11 independently implemented an other sensor fusion strategy.

- Team 2004-12

Team 2004-12 stated: "The vehicle handles GPS outages through a basic inertial and ground contact based velocity estimation algorithm. The vehicle receives acceleration data from the accelerometers (from which actual velocity is estimated), and speedometer and the wheel angle are continuously combined to provide an estimated position (after integration) of the vehicle." ([129], p. 6). The author concluded Team 2004-12 independently implemented an other sensor fusion strategy.

- Team 2004-13

One Rockwell Collins GNP-10 was in use by Team 2004-13 during the 2004 QID and GCE. See Table XXVI. Team 2004-13 stated: "The primary geo-location system will be a Navcom differential GPS StarFire. [Team 2004-13] has chosen the StarFire SF-2050G. The output of this GPS will feed into the second navigation component, the Inertial Navigation System (INS). The INS will be supplied by Rockwell Collins. ... The INS will maintain, using MEMS based technology, an accurate position from the last known valid GPS fix." ([132], p. 5).

Teams 2004-13 and 2004-14 were co-participants during the 2004 QID and GCE. See paragraph V.C.13. Teams 2004-13 and 2004-14 later stated: "An Extended Kalman Filter (EKF) was designed to fuse the inertial measurement unit (IMU) output – coming from a Rockwell Collins GNP-10 – with the GPS measurements from a Navcom Starfire DGPS system to provide high update rate measurements to the vehicle controller." ([135], p. 4).

The author concluded Team 2004-13 independently implemented a Kalman filter.

- Team 2004-14

Team 2004-14 stated: "In the absence of GPS data due to communication outages the IND/DGPS [*sic*] system is aided by a 3D-magnetometer and the vehicle's odometer. The Kalman filter of the Navigation system continuously blends the INS/DGPS data with the odometer and magnetic compass." ([134], p. 6).

Teams 2004-13 and 2004-14 were co-participants during the 2004 QID and GCE. See paragraph V.C.14. Teams 2004-13 and 2004-14 later stated: "An Extended Kalman Filter (EKF) was designed to fuse the inertial measurement unit (IMU) output – coming from a Rockwell Collins GNP-10 – with the GPS measurements from a Navcom Starfire DGPS system to provide high update rate measurements to the vehicle controller." ([135], p. 4).

The author concluded the "navigation system" referred to by Team 2004-14 was not in use during the 2004 QID and GCE, and that Team 2004-14 independently implemented a Kalman filter.

- Team 2004-15

Team 2004-15 stated: "[The challenge vehicle] NAV system will combine the info from the GPS and the integrating compass by using a Kalman filter." ([137], p. 4). The author concluded Team 2004-15 independently implemented a Kalman filter.

- Team 2004-16

Team 2004-16 stated: "Software integrates GPS/inertial/compass/pitch/yaw data for navigation. Sensor data are combined (inertial and GPS using Kalman filtering) and related to additional sensor data for accuracy." ([138]. p. 3). The author concluded Team 2004-16 independently implemented a Kalman filter.

- Team 2004-17

Team 2004-17 stated: "State estimation includes combined filtering from an inertial measurement unit (IMU), a magnetometer, and a DGPS unit to obtain position, heading and tilt angles." ([142], p. 5). The author concluded Team 2004-17 independently implemented an other sensor fusion strategy.

- Team 2004-18

One unknown ISI IMU was in use by Team 2004-18 during the 2004 QID and GCE. See Table XXVI. Team 2004-18 stated: "The output of the GPS will be combined with the INS system utilizing a Kalman filtering approach to geolocate the vehicle within the course." ([48], p. 6). Neither the RRS75 nor ISIS-IMU (see paragraph V.C.18.c.) implement a Kalman filter ([147] and [148]). The author concluded Team 2004-18 independently implemented a Kalman filter.

- Team 2004-19

Team 2004-19 stated: "The heading information, together with the speed of the wheels, combine to give high speed latitude-longitude position of the vehicle."; "This information is fused with the GPS data to correct the drift errors associated with the DRS."; "The data from the GPS unit is fused with the data from the dead reckoning system to both compensate for GPS outages and help correct GPS inaccuracies."; and "GPS outages and inaccuracies are compensated for by the dead reckoning system (DRS). The DRS is comprised of a Precision Navigation Vector-2X digital compass module integrated with two Oak Grigsby 900 Series optical encoders." ([151], p. 3). The author concluded Team 2004-19 independently implemented an other sensor fusion strategy.

- Team 2004-20

One unknown Crossbow INS was in use by Team 2004-20. See Table XXVI. Team 2004-20 stated: "INS and GPS data are combined to maintain both a position relative to recent positions for local navigation, and an absolute position for global navigation." ([107], p. 6).

All five products with AHRS and NAV (combined AHRS and GPS) function designators currently manufactured by Crossbow have an integrated Kalman filter ([96]). Although Crossbow has since discontinued products which were available at the time of the 2004 QID, the author considers it likely that multiple Crossbow AHRS sensors were available at the time of the 2004 QID, and concluded Team 2004-20 used a COTS component which implemented a Kalman filter.

- Team 2004-21

One Garmin GPS V was in use by Team 2004-21. No other navigation sensors were in use by Team 2004-21. See Table XXVI. Team 2004-21 stated: "We plan on making extensive use of the mapping data that is built in to the Garmin GPS V device. It is the only sensing device that will be directly interfaced into the main computer(s), and will form the backbone of our navigation system." ([155], p. 5). The author concluded Team 2004-21 did not implement a sensor fusion strategy.

- Team 2004-22

One unknown u-blox GPS receiver was in use by Team 2004-22 during the 2004 QID. See Table XXVI. Team 2004-22 stated: "...the u-Blox GPS unit has a self-calibrating sensor feed for odometry. Hall-State proximity sensors are attached to each of the front wheels and two to the rear drive shaft. The GPS requires two more feeds for DR mode; a single-axis gyro and a logic high/low for forward or reverse motion. The Kalman filter on the GPS is self-calibrating." ([157], p. 3).

As noted in paragraph V.C.22.g., at least three u-blox products with an integrated Kalman filter are currently available. The author considers is likely that multiple products with the capabilities reported by Team 2004-22 were available at the time of the 2004 QID, and concluded Team 2004-22 used a COTS component which implemented a Kalman filter.

- Team 2004-23

Team 2004-23 stated: “The vehicle receives and deals with all sensor data with the Surround Sensing/Sensor Fusion Module. This includes GPS data, and all external and all internal sensors except the cameras.” ([159], p. 10). The author concluded Team 2004-23 independently implemented an other sensor fusion strategy.

- Team 2004-24

Team 2004-24 stated: “The IMU data is combined with the GPS data within a 15 state Extended Kalman Filter (EKF) when both are present.” ([161], p. 4). The author concluded Team 2004-24 independently implemented a Kalman filter.

- Team 2004-25

Team 2004-25 stated: “The Challenge Vehicle uses a TALIN integrated DGPS/INS system from Honeywell for positioning. ... The integrated system uses Kalman filtering to provide precise position and velocity information at speeds up to 50 Hz.” ([49], p. 12). The author concluded Team 2004-25 used a COTS component which implemented a Kalman filter.

- Team 2005-01

One Northrop Grumman LN-270 was in use by Team 2005-01. See Table XXVIII. A similar Northrop Grumman INS uses a Kalman filter ([223]), but Northrop Grumman did not report the LN-270 has an integrated Kalman filter ([224]). The author concluded Team 2005-01 used a COTS component which implemented an other sensor fusion strategy.

- Team 2005-02

One Smiths Aerospace North Finding Module was in use by Team 2005-02. See Table XXVIII. As noted in paragraph V.C.27.d., Smiths Aerospace has since been acquired by GE. The North Finding Module provides a “GPS/Inertial Kalman Filter Solution” ([168]). The author concluded Team 2005-02 used a COTS component which implemented a Kalman filter.

- Team 2005-03

In response to 2005 SQ 2.4.3 (see Table XXIII), Team 2005-03 stated: “This is all integrated at a C6000 DSP chip as described in section 2.3.4.” ([33], p. 11). In response to 2005 SQ 2.3.4 (see Table XXIII), Team 2005-03 described a sensor integration solution. The author concluded Team 2005-03 independently implemented an other sensor fusion strategy.

- Team 2005-04

Team 2005-04 stated: “Localization, vehicle motion status, and internal state sensing is accomplished using the Novatel GPS with Omnistar HP differential corrections, the Crossbow IMU, wheel speed sensors that were added to the vehicle, engine speed measurements, and brake and throttle position information. These sensors are monitored for changes in their operating state, validated using both dynamic and rule based tests, and finally fused using a Kalman filter based approach to provide continuous position and orientation information even [*sic*] the presence of individual sensor dropouts, reduced accuracies, or complete failures.” ([169], p. 11). The author concluded Team 2005-04 independently implemented a Kalman filter.

- Team 2005-05

One Systron Donner C-MIGITS III was in use by Team 2005-05. See Table XXVIII. An “Optimized 28-State Kalman Filtered Navigation Solution” is a feature of the Systron Donner C-MIGITS III ([225]). The author concluded Team 2005-05 used a COTS component which implemented a Kalman filter.

- Team 2005-06

One Oxford RT3000 was in use by Team 2005-06. See Table XXVIII. A Kalman filter is a feature of the Oxford RT3000 ([226]). The author concluded Team 2005-06 used a COTS component which implemented a Kalman filter.

- Team 2005-07

The author estimated one unknown GPS receiver was in use by Team 2005-07. See Table XXVIII. Team 2005-07 stated: “The key to [Team 2005-07's] approach is a software architecture that allows us to integrate the sensor technology from multiple sensors into single vehicle control signals at real-time speeds. This architecture, MURE, or Mobile Unmanned Robotics Environment, enables us to combine location, terrain data, and real time sensor data with minimum processing and power requirements.” ([118]). The author concluded Team 2005-07 independently implemented an other sensor fusion strategy.

- Team 2005-08

One Honeywell TALIN-5000 was in use by Team 2005-08. See Table XXVIII. Team 2005-08 stated: “A Honeywell TALIN 5000 Inertial Navigator Unit provides a blended navigation solution at a 50Hz update rate. This solution incorporates DGPS data from the NovAtel unit, true groundspeed from a Vansco Doppler radar sensor, and internal acceleration and rotation data from precision accelerometers and a 3-axis ring laser gyro subsystem combined in an internal kalman filter.” ([173], p. 8). The author concluded Team 2005-08 used a COTS component which implemented a Kalman filter.

- Team 2005-09

Team 2005-09 stated: “Localization is accomplished by fusing input from multiple GPS units, a magnetic compass, inertial navigation system, and several shaft encoders. Two Trimble GPS systems provide sub-meter accuracy through an Omnistar subscription. The Trimble GPS units are used primarily by the agriculture community for autonomous field preparation and harvesting. A third GPS is provided by a MIDG-2 inertial navigation system that comes from the remote controlled plane community. This GPS unit is augmented by an internal Inertial Measurement Unit that maintains location during GPS outages. In addition, a Honeywell magnetic compass is used as an alternative source of heading. Additionally, shaft encoders provide odometry at very slow speeds providing information that is needed for dead reckoning.” ([175], p. 7). The author concluded Team 2005-09 independently implemented an other sensor fusion strategy.

- Team 2005-10

One unknown Kearfott INS was in use by Team 2005-10. See Table XXVIII. A “multi-state Kalman filter” is a feature of the Kearfott MILNAV product family ([181]). The author concluded Team 2005-10 used a COTS component which implemented a Kalman filter.

- Team 2005-11

One unknown Crossbow INS was in use by Team 2005-11. See Table XXVIII. Team 2005-11 stated: “The Crossbow NAHRS blends GPS, magnetometer and accelerometer measurements into an Extended Kalman Filter (EKF) algorithm.” ([182], p. 7). The author concluded Team 2005-11 used a COTS component which implemented a Kalman filter.

- Team 2005-12

One unknown Trimble DGPS receiver was in use by Team 2005-12. See Table XXVIII. Team 2005-12 stated: “Dead reckoning, based on front-wheel ABS sensors and steering wheel position, interpolates position between GPS updates and during GPS outages. A Kalman filter optimally combines the two measurements each time a GPS position is received.” ([185], p. 5). The author concluded Team 2005-12 independently implemented a Kalman filter.

- Teams 2005-13 and 2005-14

One unknown Applanix INS was in use by Teams 2005-13 and 2005-14. See Table XXVIII. Teams 2005-13 and 2005-14 stated: “[The challenge vehicle] estimates 6-axis pose, velocity and acceleration (latitude, longitude, altitude, roll, pitch, yaw) by combining inertial sensing, GPS data and odometry using a Kalman filter.” ([11], p. 7 and

[12], p. 7). Teams 2005-13 and 2005-14 later stated: "The [unknown Applanix INS] provides position estimates by fusing inertial and differential GPS position estimates through a Kalman filter." ([24], p. 478). The author concluded Teams 2005-13 and 2005-14 used COTS components which implemented a Kalman filter.

- Team 2005-15

Team 2005-15 reported one unknown NavCom DGPS receiver, unknown Rockwell Collins IMU, PNI TCM2, and OEM speedometer encoder were in use by the team. See Table XXVIII. Team 2005-15 stated: "A Kalman filter fuses these data streams into an estimate of the actual location, heading, and velocity." ([53], p. 9). The author concluded Team 2005-15 independently implemented a Kalman filter.

- Team 2005-16

Team 2005-16 stated: "[The challenge vehicle] achieves its localization through an unscented Kalman filter (UKF)..." ([195], p. 5). The author concluded Team 2005-16 independently implemented a Kalman filter.

- Team 2005-17

One Oxford RT3102 was in use by Team 2005-17. See Table XXVIII. A Kalman filter is a feature of the Oxford RT3102 ([226]). The author concluded Team 2005-17 used a COTS component which implemented a Kalman filter.

- Team 2005-18

Team 2005-18 reported one NovAtel DL-4plus, NavCom SF-2050G, and Northrop Grumman LN-200 were in use by the team. See Table XXVIII. Team 2005-18 stated: "The inputs from these sensors are combined through Kalman filtering to produce an optimal estimation of state." ([197], p. 9). The author concluded Team 2005-18 independently implemented a Kalman filter.

- Team 2005-19

Team 2005-19 reported one Northrop Grumman LN-200, Trimble AgGPS 252, and unknown speed brake sensor were in use by the team. See Table XXVIII. Team 2005-19 stated: "...[Team 2005-19] fuses three sensors into a smooth Bayesian optimal estimate of the vehicle's position and attitude... These three sensors are combined to estimate a fifteen element vehicle state: x, y, z position and velocity, a bias on each accelerometer, vehicle yaw, pitch, and roll, and a bias on each rate gyro." ([55], p. 4).

Team 2005-19 later stated: "The three sensors ... are fused into an estimate of [the challenge vehicle's] position, velocity, and attitude using an extended Kalman Filter (EKF)." ([54], p. 631).

The author concluded Team 2005-19 independently implemented a Kalman filter.

- Team 2005-20

Team 2005-20 stated: "[Team 2005-20] has developed a system that combines two Novatel Pro-Pack LB dual frequency (L1/L2) GPS receivers and NovAtel's SPAN™ (Synchronized Position Attitude Navigation) Technology. This system combines GPS and inertial functionality to provide uninterrupted operation with highly accurate position and attitude measurements. It is augmented with Differential Global Positioning System (DGPS) receivers to provide corrections when in coverage. The system can provide high accuracy position (10cm) and heading at operating speeds of 20 Hz[.]" ([56], pp. 8 - 9).

However, Team 2005-20 also stated: "In motion, the SPAN system provides location information at a 20-Hz rate by combining DGPS and inertial data from an internal Honeywell HG-1700 tactical-grade IMU." ([56], p. 9).

The author concluded Team 2005-20 used a COTS component which implemented an other sensor fusion strategy.

- Team 2005-21

Two Oxford RT3100s were in use by Team 2005-21. See Table XXVIII. A Kalman filter is a feature of the Oxford RT3100 ([226]). The author concluded Team 2005-21 used COTS components which implemented a Kalman filter.

- Teams 2005-22 and 2005-23

A NovAtel ProPak-LBplus and NovAtel HG1700 SPAN were in use by Teams 2005-22 and 2005-23. See Table XXVIII. NovAtel stated: "IMU measurements are used by the GNSS/INS receiver to compute a blended GNSS/INS position, velocity and attitude solution at up to 100 Hz." ([227]), but did not describe how sensor fusion was implemented. The author concluded Teams 2005-22 and 2005-23 used COTS components which implemented an other sensor fusion strategy.

VII.C. Results

Results are presented in Tables XLIV, XLV, and XLVI, and summarized in Tables XLVII, XLVIII, XLIX, L, LI, and LII.

VII.C.1. Differences in the number of teams utilizing a COTS component to integrate navigation sensors from 2004 to 2005

As a percentage of the total number of teams which participated in the 2004 and 2005 GCE (see Table XLVII):

- There was an increase in the number of teams utilizing a COTS component to integrate navigation sensors from 33.3 percent to 60.9 percent, a difference of 27.6 percent.

- There was a corresponding decrease in the number of teams which independently implemented a sensor fusion strategy.

As a percentage of the total number of teams which participated in both the 2004 and 2005 GCE (see Table L):

- There was an increase in the number of teams utilizing a COTS component to integrate navigation sensors from 41.7 percent to 66.7 percent, a difference of 25.0 percent.

- There was a corresponding decrease in the number of teams which independently implemented a sensor fusion strategy.

VII.C.2. Differences in the number of teams utilizing a COTS component which implemented a Kalman filter or independently implementing a Kalman filter from 2004 to 2005

As a percentage of the total number of teams which participated in the 2004 and 2005 GCE (see Table XLVIII):

- There was an increase in the number of teams utilizing a COTS component which implemented a Kalman filter or independently implementing a Kalman filter to integrate navigation sensors from 60.0 percent to 69.6 percent, a difference of 9.6 percent.

As a percentage of the total number of teams which participated in both the 2004 and 2005 GCE (see Table LI):

- There was no change in the number of teams utilizing a COTS component which implemented a Kalman filter or independently implementing a Kalman filter to integrate navigation sensors.

VII.C.3. Differences in the number of teams utilizing a COTS component which implemented a Kalman filter from 2004 to 2005

As a percentage of the total number of teams which participated in the 2004 and 2005 GCE (see Table XLIX):

- There was an increase in the number of teams utilizing a COTS component which implemented a Kalman filter to integrate navigation sensors from 26.6 percent to 43.5 percent, a difference of 16.9 percent.

As a percentage of the total number of teams which participated in both the 2004 and 2005 GCE (see Table LII):

- There was an increase in the number of teams utilizing a COTS component which implemented a Kalman filter to integrate navigation sensors from 33.3 percent to 41.7 percent, a difference of 8.4 percent.

VII.D. Conclusions

Teams which participated in the 2004 GCE completed 1.95 miles of the 2004 GCE course, on average, or approximately 1.4 percent of the reported course length of 142 miles. Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average, or approximately 36.7 percent of the reported course length of 131.6 miles.

Based on the increase as a percentage of the total course length completed from 2004 to 2005, the author concluded there was a correlation between the following key factors and the average number of miles of the 2004 and 2005 GCE courses the teams completed. The author is not attempting to imply causation. However, the following key factors were common to teams which participated in the 2004 and 2005 GCE, in general.

Overall, the author concluded the use of a COTS component to integrate navigation sensors was an example of reducing complexity, and that teams which independently implemented an other sensor fusion strategy diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge to attempt to solve a problem that had been solved by providers of COTS components at the time of the 2004 and 2005 GCE, not a problem of artificial intelligence, and were, in effect, solving a wrong problem. See paragraph XIV.A.3.

VII.D.1. Use a COTS component to integrate navigation sensors

The author concluded the use of a COTS component to integrate navigation sensors was a key factor. COTS components combined navigation sensor output, such as heading, roll, pitch, and yaw, axle rotation, or geolocation information. The author asserts COTS components were more mature and the results more reliable than independently implemented solutions.

In addition, many teams reported the challenge vehicle controlling intelligence was constrained from entering "out-of-bounds areas" by algorithmically or manually classifying these areas as impassable terrain. However, a controlling intelligence which was unable to accurately locate itself could not determine if it was in impassable terrain. Inaccurate geolocation information, specifically GPS sensor failure, was directly implicated in the failure of five teams to complete the 2005 GCE. See paragraph XIV.D.3.b.

The author proposes this may explain the increase in the use of COTS components which provide more reliable geolocation information to the controlling intelligence.

- One of four teams which successfully completed the 2005 GCE, and one of five teams which completed the 2005 GCE course, independently implemented a navigation sensor integration strategy: Team 2005-16. Team 2005-16 had prior experience and significant corporate and academic sponsorship. See Chapter X. The other three teams which successfully completed the 2005 GCE, and other four teams which completed the 2005 GCE course, used a COTS component.

- Counting 2005 GCE co-participants, one of which participated in the 2004 GCE (Teams 2005-13 and 2005-14 and Teams 2005-22 and 2005-23), eight of the nine teams which completed more than 25 percent of the 2005 GCE course (32.9 miles) used a COTS component to integrate navigation sensors.

- Thirteen of 21 teams which participated in the 2005 GCE and which used a COTS component to integrate navigation sensors completed more than 7.4 miles of the 2005 GCE course, more than the maximum number of miles completed by any team which participated in the 2004 GCE.

Alternately, the author concluded the decrease in the number of teams which independently implemented a sensor integration strategy from 2004 to 2005 was a contributing factor to the increase in the average number of miles of the 2005 GCE course teams completed.

- With the exception of Team 2005-16, above, no team which independently implemented a navigation sensor integration strategy completed more than 25 percent of the 2005 GCE course.

VII.D.2. Use a Kalman filter to integrate navigation sensors

The author concluded the use of a Kalman filter to integrate navigation sensors was a key factor.

- One of four teams which successfully completed the 2005 GCE, and one of five teams which completed the 2005 GCE course, independently implemented a Kalman filter: Team 2005-16. Team 2005-16 had prior experience and significant corporate and academic sponsorship. See Chapter X. The other three teams which successfully completed the 2005 GCE, and other four teams which completed the 2005 GCE course, used a COTS component which implemented a Kalman filter.

- Counting 2005 GCE co-participants, one of which participated in the 2004 GCE (Teams 2005-13 and 2005-14 and Teams 2005-22 and 2005-23), five of the nine teams which completed more than 25 percent of the 2005 GCE course (32.9 miles) used a Kalman filter to integrate navigation sensors.

- Fifteen of 21 teams which participated in the 2005 GCE and which used a Kalman filter to integrate navigation sensors completed more than 7.4 miles of the 2005 GCE course, more than the maximum number of miles completed by any team which participated in the 2004 GCE.

Alternately, the author concluded the decrease in the number of teams which independently implemented a sensor integration strategy from 2004 to 2005 was a contributing factor to the increase in the average number of miles of the 2005 GCE course teams completed.

- With the exception of Team 2005-16, above, no team which independently implemented a Kalman filter completed more than 25 percent of the 2005 GCE course.

CHAPTER VIII. SENSOR LIMITATIONS

VIII.A. Discussion

Teams referred to specific limitations of sensors such as sensor resolution, range, or field-of-view throughout the published record. Review of the published record revealed that some teams did not understand the effect of sensor limitations such as range and field-of-view on the speed at which their challenge vehicles would be able to complete portions of the course.

The author concluded sensor limitations had non-obvious consequences and formulated the following hypothesis:

DARPA reduced the difficulty of the 2005 GCE course to:

- increase the maximum effective range for various sensors, allowing challenge vehicles to complete portions of the course at higher speeds, thereby increasing the average speed; and

- mitigate the risk that challenge vehicles would not be able to stop in time to avoid a collision.

VIII.A.1. Calculation of stopping distance

Stopping distance is a function of velocity, the kinetic coefficient of friction, and acceleration due to gravity, and is given by the equation:

$$d_s = \frac{v^2}{(2 \cdot \mu_k \cdot g)}$$

where

d_s = stopping distance,

v = velocity,

μ_k = kinetic coefficient of friction, and

g = acceleration due to gravity

The kinetic coefficient of friction, μ_k, is also referred to as the "dynamic coefficient of friction" or the "sliding coefficient of friction". The phrase "kinetic coefficient of friction" is used herein exclusively.

In general, μ_k will vary depending on the condition of the tires or other road-contacting surfaces and the surface of the road, and must be determined experimentally. For example, the value of μ_k for racing "slicks" used in Formula 1 racing on a dry asphalt surface, such as a race track, may exceed 0.9, while it may be less than 0.1 on the same surface if the surface is wet. Ranges for values considered typical are given by Table XIX.

However, the vast majority of the 2004 and 2005 GCE courses were off-road, meaning that challenge vehicles were not traveling on a paved surface, either asphalt or concrete. Typical road surfaces were a mixture of hard-packed dirt, rock, and loose dirt and gravel on hard-packed dirt or rock. As a result, μ_k will be less than the intermediate values noted above.

Table LIII presents stopping distance for selected values of v and μ_k , including two intermediate values calculated by averaging the minimum and maximum typical values for rubber to asphalt (dry) contact (0.65) and rubber to concrete (dry) contact (0.73).

Initially, a μ_k value of 0.5 was selected based on the best "fit" between Table LIII and values given by Table II ("Stopping Distances") of the Code of Federal Regulations ([228]) for "vehicles other than passenger cars with GVWR of less than 8,000 lbs" and "vehicles with GVWR of not less than 8,000 lbs and not more than 10,000 lbs".

However, a μ_k value of 0.33 was ultimately selected as representative. This value of μ_k results in a total stopping distance of approximately 150 percent of the calculated stopping distance using a μ_k value of 0.5 to compensate for the effect of reaction time on stopping distance.

As used herein, "stopping distance" refers to the stopping distance at the challenge vehicle maximum speed, unless otherwise noted. Although stopping distance is a function of velocity, vehicle maximum speed was selected as representative of the worst case.

VIII.A.2. Calculation of field-of-view limitations

Through geometric analysis, the author determined the maximum distance between the path of travel in a constant-radius turn and the left- or right-limit of field-of-view on a horizontal surface for various sensors in use by the teams. See Figure 38. The relationship is described by:

$$d = r(1 - \cos\alpha)$$

where

d = the maximum distance between the path of travel in a constant-radius turn and the left- or right-limit of field-of-view,

r = turn radius, and

α = one-half the field-of-view of the sensor in use.

Table LIV presents results for constant-radius turns from 10 to 80 ft typical of the minimum design turn radius of vehicles participating in the 2004 and 2005 GCE and two RADARs in common use by the teams: the Eaton EVT-300 and Epsilon Lambda ELSC71-1A in both narrow-scan and wide-scan mode.

As used herein, "field-of-view" refers to the horizontal field-of-view of a sensor.

VIII.A.2.a. Sensors with a field-of-view greater than or equal to 40 degrees would have been able to reliably detect obstacles in every turn of the 2004 and 2005 GCE

The author did not calculate the maximum distance between the path of travel in a constant-radius turn and the left- or right-limit of field-of-view if one-half the field-of-view of a sensor exceeded 20º. Based on an analysis of the 2004 and 2005 GCE, no intersection had a maximum allowed turn radius of less than 20.9 m (see paragraph III.D.). The Team 2004-23 challenge vehicle was the widest challenge vehicle entered in either the 2004 or 2005 GCE, with a width of 2.5 m (8.2 ft). Using the relationship above, the author determined the minimum field-of-view required for a vehicle with the maximum width to make a constant radius turn with a turn radius of 20.9 m without risk of collision was approximately 19.9º. Sensors with a field-of-view greater than or equal to twice the minimum field-of-view would have been able to reliably detect obstacles in every turn of the 2004 and 2005 GCE, and therefore had no field-of-view limitation. For example:

Three Delphi Forewarn ACC3 RADARs were in use by Team 2005-08. See Table XXVII. Team 2005-08 stated: "For [the challenge vehicle], three SCC radars are configured across the front of the vehicle in a manner to provide a 45 degree field of view. This configuration is critical in order to detect potential obstacles while the vehicle is moving around blind corners." ([173], p. 9). Using the relationship identified in paragraph VIII.A.2., the author was able to determine the maximum allowed turn radius at which the three Delphi Forewarn ACC3 RADARs would reliably detect obstacles is approximately 15.1 m (49.6 ft) based on the Team 2005-08 challenge vehicle width of 2.3 m (7.6 ft) ([173], p. 4). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2005 GCE RDDF (see Chapter III.) revealed that no turns had a maximum allowed turn radius of less than 15.1 m.

The following list of sensors with no field-of-view limitation was documented by the author during the review, but is not comprehensive:

- Two unknown cameras were in use by Team 2004-01. See Table XXV. Team 2004-01 stated: "Field of view for both cameras will be approximately 90 degrees horizontally and approx. 70 degrees vertically." ([8], p. 3).

- An estimated three Point Grey Bumblebee stereo camera pairs, FLIR A20M, and unknown AVT camera were in use by Team 2004-02. See Table XXV. Via Table 1 ("Sensor Descriptions") of the team technical proposal ([9], p. 8), Team 2004-02 reported the fields-of-view of the Point Grey Bumblebee stereo camera pairs, FLIR A20M, and unknown AVT camera in use by the team were 100º.

- An unknown Videre Design stereo camera pair was in use by Team 2004-04. See Table XXV. Team 2004-04 stated: "The sensing horizon, or field of view, of the stereo vision system is a function of the focal length of the lenses used. The stereo vision system that will be used on [the challenge vehicle] is manufactured by Videre Design. With the 12.5 mm focal length lenses that we are using, the horizontal and vertical fields of view are 50 degrees and 38 degrees, respectively." ([44], p. 8).

- Five Point Grey Dragonfly cameras were in use by Team 2004-17, two each as a short-range and long-range stereo camera pair, and one as a "road following camera". See Table XXV. Via an un-numbered and un-titled table of the team technical proposal, Team 2004-17 reported the horizontal field-of-view of the long-range stereo camera pair and road following camera was 94.3º, and the horizontal field-of-view of the short-range stereo camera pair was 44.6º ([142], p. 7).

- All SICK LIDAR sensors. No SICK LIDAR sensor in use by teams participating in the 2004 or 2005 GCE had a field-of-view of less than 90º.

VIII.A.2.b. Eaton EVT-300 field-of-view considerations

Eaton stated: "Curved Roads: the combination of yaw rate and object azimuth from the monopulse design allows the system to provide highly accurate collision warnings on curved roads." ([162]). It is unclear this feature would have had any effect on challenge vehicle stopping distance for teams using the Eaton EVT-300, and the author made no attempt to compensate.

VIII.A.3. Maximum effective range for various sensors

Teams which successfully completed the 2005 GCE reported the following maximum effective ranges:

- Team 2005-16 reported ranges of 70 m (229.7 ft) for VISION sensors and 22 m (72.2 ft) for short-range LIDAR sensors ([25], p. 672).

- Teams 2005-13 and 2005-14 reported ranges of 50 m (164.0 ft) for RADAR sensors, 40 m (131.2 ft) and 50 m (164.0 ft) for long-range LIDAR sensors, and 20 m (65.6 ft) for short-range LIDAR sensors ([24], p. 477).

- Team 2005-06 reported a range of "40 to 50 m" for LIDAR sensors ([28], p. 516).

Therefore, the "maximum effective range" for the various sensors in use by teams participating in the 2004 and 2005 GCE was defined as:

- 70.0 m (229.7 ft) for VISION sensors,

- 20.0 m (65.6 ft) for short-range LIDAR sensors similar to the SICK LMS product family,

- 40.0 m (131.2 ft) for long-range LIDAR sensors similar to the Riegl LMS-Q140i, and

- 50.0 m (164.0 ft) for RADAR sensors.

VIII.A.4. Definition of maximum obstacle detection range

The purpose of this analysis was to evaluate the non-obvious consequences of sensor limitations such as range and field-of-view on the speed at which team challenge vehicles were able to complete portions of the course. As a result, the author was interested in the maximum obstacle detection range asserted by the teams prior to the 2004 or 2005 GCE. Therefore, when determining the maximum obstacle detection range for sensors in use by teams participating in the 2004 or 2005 GCE, preference was given to team technical proposals. Results published via the Journal of Field Robotics and other published records were reviewed to determine maximum effective range and to provide additional detail when team technical proposals were unclear.

In general, consistent with the author's interest, the author accepted the maximum range reported by teams participating in the 2004 or 2005 GCE as the maximum obstacle detection range.

VIII.A.4.a. The maximum obstacle detection range for LIDAR sensors is limited by reflectivity

The maximum obstacle detection range for LIDAR sensors is limited by reflectivity. For example, most LIDAR sensors in the SICK LMS product family define both a "typical range" at a specified reflectivity and a maximum range. Teams variously reported either the typical range, maximum range, or some intermediate value as the maximum obstacle detection range. For example:

- One SICK LMS 211-30206 was in use by Team 2004-02. See Table XXV. Team 2004-02 reported the "sensing horizon" of the SICK LMS 211-30206 was 30 m

([9], p. 8). The "typical range" for the SICK LMS 211-30206 is 30 m (98.4 ft) with 10 percent reflectivity, but the "maximum range" is 80 m (262.5 ft) ([74]).

- One SICK LMS 200-30106 was in use by Team 2004-04. See Table XXV. Team 2004-04 stated: "The laser range is up to 30 meters without using any supplementary reflectors." ([44], p. 9). The "typical range" of the SICK LMS 200-30106 is 10 m (32.8 ft) with 10 percent reflectivity, but the maximum range is 80 m (262.5 ft) ([74]).

- One SICK LMS 291-S05 was in use by Team 2004-12. See Table XXV. Team 2004-12 stated: "Forward radar distance sensor - Active Sensing - SICK Laser Measurement System (LMS) 291-S05 to 50 meters." ([129], p. 4). However, the "typical range" for the SICK LMS 291-S05 is 30 m with 10 percent reflectivity ([73]), in lieu of the 50 m reported by Team 2004-12; the maximum range is approximately 80 m with 100 percent reflectivity. The "[typical] new device with clean front window" range for the SICK LMS 291-S05 is 50 m with 30 percent reflectivity.

Because the purpose of this analysis was to evaluate the non-obvious consequences of sensor limitations such as range and field-of-view on the speed at which team challenge vehicles were able to complete portions of the course, the author made no attempt to standardize on the use of a range with a percent reflectivity for LIDAR sensors. Consistent with the author's interest, the author accepted the maximum range reported as the maximum obstacle detection range. When this would have resulted in an obvious error or apparent contradiction the author selected a maximum obstacle detection range, as documented throughout paragraph VIII.B.

VIII.A.4.b. Several teams overstated or overestimated the maximum effective range of sensors in use by the team

Several teams overstated or overestimated the maximum effective range of sensors in use by the team. The following list of sensors was documented by the author during the review, but is not comprehensive:

- Four Laseroptronix LDM 800-RS232 LIDAR sensors were in use by Team 2004-08. See Table XXV. Team 2004-08 stated: "The range finders will ... have a range of 4 to 400 meters." ([76], p. 5). The author considers it unlikely the Laseroptronix LDM 800-RS232 would have had a maximum effective range of 400 m (1312.3 ft) during the 2004 GCE.

- One unknown long-range laser ranger was in use by Team 2004-11. See Table XXV. Team 2004-11 stated: "At the farthest range, our laser range finder detects and returns ranges of large objects and terrain features up to 500 feet away. This instrument is a standard industrial laser rangefinder, set to return ranges at the ground level 500 feet ahead 3 times per second." ([127], p. 5). The author considers it unlikely the long-range laser ranger would have had a maximum effective range of 152.4 m (500 ft) during the 2004 GCE.

- One Eaton EVT-300 was in use by Team 2004-15. See Table XXV. Team 2004-15 stated: "An active 24.725 GHz Doppler radar system (Eaton VORAD EVT-300) with a sensing horizon of 100 meters ... will also be utilized for obstacle detection/avoidance as well as enhanced road following capability." ([137], p. 3). The author considers it unlikely the Eaton EVT-300 would have had a maximum effective range of 100 m (328.1 ft) during the 2004 GCE.

- Two unknown SICK LIDAR sensors were in use by Team 2004-16. See Table XXV. Team 2004-16 stated: "...radar, sonar and laser range finders for distance determination between own vehicle and obstacle/other vehicles (1-100m)." ([138], p. 4). No SICK LIDAR sensors had a maximum effective range of 100 m.

- Three unknown RADARs were in use by Team 2004-18. See Table XXV. The "Horizon" of 1000 ft reported by Team 2004-18 ([48], p. 6) conforms to GMH Engineering product literature for DRS 1000 RADARs, which stated the "Max. Target Distance" is "over 1000 ft" ([229]). The author considers it unlikely the unknown RADARs would have had a maximum effective range of 304.8 m (1000 ft) during the 2004 GCE.

- One SICK DME 2000 was in use by Team 2004-19. See Table XXV. Team 2004-19 stated, in part: "The ultrasonic and laser rangefinders have an effective range of approximately 35 feet..." ([151], p. 2). The SICK DME 2000 has a "measurement range" of 2.0 m (6.7 ft) in "proximity mode" and 130 m (426.5 ft) in "reflector mode" ([222]). Reflector mode requires the DME 2000 to be accurately positioned so that the beam from the device impinges on a reflector. The author considers it unlikely the SICK DME 2000 would have had a maximum effective range of 130 m (426.5 ft) during the 2004 GCE.

- A proprietary video system was in use by Team 2004-22. See Table XXV. Team 2004-22 stated: "The video system is the only true look-ahead sensor..." and "Early look ahead determines obstacles as far as 1,200 feet. Expected look-ahead detection at high speeds is between 800 and 1000 feet." ([157], p. 4). The author considers it unlikely the proprietary video system would have had a maximum effective range of 243.8 m (800.0 ft) during the 2004 GCE.

- One Optech ILRIS-3D was in use by Team 2005-10. See Table XXVII. Team 2005-10 stated: "One Optech ILRIS-3D three dimensional laser range finder is mounted on the roof. Its ... range is approximately 500 meters." ([176], p. 3). The author considers it unlikely the Optech ILRIS-3D would have had a maximum effective range of 500.0 m (1640.4 ft) during the 2005 GCE.

VIII.A.4.c. Eaton RADAR sensor maximum obstacle detection range considerations

Eaton reported the "Maximum Range limit" of the Eaton VBOX is 500 ft ([106]), the "Average Range limit" of the Eaton VBOX is 350 ft ([106]), and the "Operating Range" of the Eaton EVT-300 is 350 ft ([162]). Teams variously reported the maximum range limit, average range limit, or operating range of Eaton RADAR sensors in use by the teams as the maximum obstacle detection range.

VIII.B. Analysis

The author performed a comprehensive review of published records to determine the effect of VISION, STEREO, LIDAR, and RADAR sensor range and field-of-view on stopping distance and obstacle detection. Sensors which were discounted (see paragraph V.B.4.) were not included in the analysis. Errors in published records were resolved as documented throughout this paragraph.

VIII.B.1. Team 2004-01

- Team 2004-01 stated: "If less than optimum conditions exist speed will be significantly reduced. At no time will the vehicle attempt to overrun it's [*sic*] sensing capabilities. ([8], p. 7). Team 2004-01 was one of only five teams which participated in the 2004 QID and GCE to refer specifically to sensor range limiting the speed of the challenge vehicle.

- Unknown cameras and unknown SICK LIDAR sensors were in use by Team 2004-01. See Table XXV.

VIII.B.1.a. Stopping distance

Team 2004-01 reported a relatively complex description of how the team determined the estimated stopping distance of their challenge vehicle: "The system updates every 125 ms. At most the maximum time from detection to response would be slightly less than 2 system updates, approx. 250ms. The Pneumatic braking system offers very fast actuation time (<50ms). The maximum reaction time from sensing an obstacle to initiating braking is less than 300 ms (<2 system updates plus brake actuation time), which corresponds to 20 feet at 45 miles per hour (66 ft/sec). Adding the 75-foot measured stopping distance of our test jeep (at 45 MPH) gives a total stopping distance of 95 feet. Because the weight of our race vehicle is 60% of the test vehicle, and has over 30% more tire contact area we expect stopping distances to be reduced at least 10-20%. This should put the stopping distance within the range of the laser system and well within the sensing range of vision. We will verify these figures during testing." ([8], p. 7).

However:

- The Team 2004-01 challenge vehicle was purpose-built, but the estimated stopping distance of the challenge vehicle was calculated using the actual stopping distance of a stock Jeep Cherokee.

- There is no evidence the reduction in stopping distance due to suspension and tire effects anticipated by Team 2004-01 was experimentally verified.

- The kinetic coefficient of friction calculated using the actual stopping distance of a stock Jeep Cherokee on “loose dirt and gravel” exceeds the kinetic coefficient of friction experimentally determined by the Michigan State Police using a “police-package” 2001 Jeep Cherokee, the last model offered, at the DaimlerChrysler Proving Grounds in October, 2000 on asphalt (dry) ([230]).

  The average stopping distances of 50 ft (35 mph) and 75 ft (45 mph) calculated using a stock Jeep Cherokee on *loose dirt and gravel* ([8], p. 5) corresponds to a kinetic coefficient of friction between 0.8 and 0.9. See Table LIII.

  The average stopping distances of 152 ft (60.3 mph) and 154 ft (60.3 mph) experimentally determined by the Michigan State Police for the 2WD and 4WD, respectively, police package 2001 Jeep Cherokee on *asphalt (dry)* corresponds to a kinetic coefficient of friction between 0.8 and 0.9.

The author considers it unlikely, in the absence of experimental verification of estimated stopping distance on *loose dirt and gravel*, Teal 2004-01 was able to equal or exceed the average stopping distance experimentally determined by the Michigan State Police on *asphalt (dry)*. As a result, a stopping distance corresponding to a top speed of 45 mph is used herein in lieu of the estimated stopping distance reported by Team 2004-01. At the representative μ_k, the Team 2004-01 challenge vehicle stopping distance at a speed of 45 mph was 62.5 m (205.0 ft).

VIII.B.1.a.i. Unknown cameras

Team 2004-01 alternately stated: “Cameras will be mounted approximately 5 feet high with the image center angled downward, corresponding to a point approximately 150 feet from the front of the vehicle.” ([8], p. 3) and “Maximum obstacle sensing is approximately 250 feet for the vision systems...” ([8], p. 7). As a result, it is unclear if the maximum obstacle detection range is the 150 ft “aiming point” for the unknown cameras or the 250 ft “maximum obstacle sensing” distance. The 150 ft “aiming point” is used herein as the maximum obstacle detection range at which Team 2004-01 anticipated obstacles would reliably be detected. The challenge vehicle stopping distance:

- exceeded the 45.7 m (150.0 ft) maximum obstacle detection range of the unknown cameras in use by the team.

- did not exceed the maximum effective range of VISION sensors.

VIII.B.1.a.ii. Unknown SICK LIDAR sensors

Team 2004-01 stated: "Maximum obstacle sensing is approximately ... 200 feet for the laser scanner." ([8], p. 7). The challenge vehicle stopping distance:

- exceeded the 61.0 m (200.0 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors in use by the team.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.1.b. Field-of-view limitations

Team 2004-01 stated: "Field of view for both cameras will be approximately 90 degrees horizontally..." ([8], p. 3). The field-of-view of the unknown cameras in use by the team equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.2. Team 2004-02

- Team 2004-02 stated: "The top speed of [the challenge vehicle] is estimated to be approximately 100 miles per hour, as per manufacturer specifications. However, sensing range and programming constraints limit the vehicle's speed to 50 mph." ([9], p. 14). Team 2004-02 was one of only five teams which participated in the 2004 QID and GCE to refer specifically to sensor range limiting the speed of the challenge vehicle.

- A SICK LMS 211-30206, Point Grey Bumblebee stereo camera pairs, FLIR A20M, unknown AVT camera, and Epsilon Lambda ELSC71-1A were in use by Team 2004-02. See Table XXV.

VIII.B.2.a. Stopping distance

At the representative μ_k, the Team 2004-02 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.2.a.i. SICK LMS 211-30206

Via Table 1 ("Sensor Descriptions") of the team technical proposal ([9], p. 8), Team 2004-02 reported the "sensing horizon" of the SICK LMS 211-30206 in use by the team was 30.0 m (98.4 ft). The Team 2004-02 challenge vehicle stopping distance:

- exceeded the 30.0 m (98.4 ft) maximum obstacle detection range of the SICK LMS 211-30206.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.2.a.ii. Point Grey Bumblebee stereo camera pairs, FLIR A20M, and unknown AVT camera

Via Table 1 ("Sensor Descriptions") of the team technical proposal ([9], p. 8), Team 2004-02 reported the "sensing horizon" of the Point Grey Bumblebee stereo camera pairs, FLIR A20M, and unknown AVT camera in use by the team was 50.0 m (164.0 ft). The Team 2004-02 challenge vehicle stopping distance:

- exceeded the 50.0 m (164.0 ft) maximum obstacle detection range of the Point Grey Bumblebee stereo camera pairs, FLIR A20M, and unknown AVT camera.
- exceeded the maximum effective range of VISION sensors.

VIII.B.2.a.iii. Epsilon Lambda ELSC71-1A

Team 2004-02 reported a "range up to 110 meters" for the Epsilon Lambda ELSC71-1A in use by the team ([9], p. 8). The Team 2004-02 challenge vehicle stopping distance:

- exceeded the 30.0 m (98.4 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in wide-scan mode.
- did not exceed the 110.0 m (360.9 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in narrow-scan mode.
- exceeded the maximum effective range of RADAR sensors.

VIII.B.2.b. Field-of-view limitations

VIII.B.2.b.i. Epsilon Lambda ELSC71-1A

At the challenge vehicle stopping distance of 77.1 m (253.0 ft), the width of the lane being actively swept by the Epsilon Lambda ELSC71-1A in narrow-scan mode is approximately 21.7 m (71.1 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2004-02 challenge vehicle width of 1.8 m (6.0 ft) ([9], p. 3), the maximum allowed turn radius at which the Epsilon Lambda ELSC71-1A in narrow-scan mode would reliably detect obstacles is approximately 93.9 m (308.0 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed 41 turns had a turn radius of less than 93.9 m, requiring changes in bearing ranging from -54 to 73 degrees.

- The challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been unable to detect an obstacle 0.4 m (1.5 ft) from the path of travel in narrow-scan mode.

- Although the challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been able to detect an obstacle approximately 2.7 m (9.0 ft) from the path of travel in wide-scan mode, maximum speed would have been limited to 30 mph, less than the 48 mph allowed by course geometry, due to decreased stopping distance based on the 30.0 m (98.4 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in wide-scan mode.

VIII.B.2.b.ii. Point Grey Bumblebee stereo camera pairs, FLIR A20M, and unknown AVT camera

Via Table 1 ("Sensor Descriptions") of the team technical proposal ([9], p. 8), Team 2004-02 reported the fields-of-view of the Point Grey Bumblebee stereo camera pairs, FLIR A20M, and unknown AVT camera in use by the team were 100º. The fields-of-view of the Point Grey Bumblebee stereo camera pairs, FLIR A20M, and unknown AVT camera equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.3. Team 2004-03

- Team 2004-03 stated: "Top vehicle chassis speed 65 mph (no sensing). Top vehicle speed 25 mph (full sensing)." ([92], p. 7). A speed of 25 mph is used herein. Team 2004-03 was one of only five teams which participated in the 2004 QID and GCE to refer specifically to sensor range limiting the speed of the challenge vehicle.

- Unknown Cognex cameras, an unknown camera, and an Epsilon Lambda ELSC71-1A were in use by Team 2004-03. See Table XXV.

VIII.B.3.a. Stopping distance

At the representative μ_k , the challenge vehicle stopping distance at a speed of 25 mph was 19.3 m (63.3 ft).

VIII.B.3.a.i. Unknown Cognex cameras and unknown camera

Team 2004-03 stated: "Cameras have a range of 100 meters." ([92], p. 7). The Team 2004-03 challenge vehicle stopping distance:

- did not exceed the 100.0 m (328.1 ft) maximum obstacle detection range of the unknown Cognex cameras and unknown camera.

- did not exceed the maximum effective range of VISION sensors.

VIII.B.3.a.ii. Epsilon Lambda ELSC71-1A

Team 2004-03 stated: "Millimeter Wave (MW) sensor Model # ELSC71-1A, manufactured by Epsilon Lamba [*sic*], (same 77Ghz sensor as all the other teams). This is an active sensor which is based on RF radiation and has a range of 40 meters." ([92], p. 5). The maximum obstacle detection range reported by Team 2004-03 does not correspond to the maximum range of the Epsilon Lambda ELSC71-1A in wide-scan or narrow-scan mode. The Epsilon Lambda ELSC71-1A was a popular sensor during the 2004 GCE, and its reported capabilities well-documented. As a result, a maximum obstacle detection range of 30.0 m (98.4 ft) in wide-scan mode is asserted. The author accepted the maximum obstacle detection range of 40.0 (131.2 ft) reported by Team 2004-03 in narrow-scan mode. The 2004-03 challenge vehicle stopping distance:

- did not exceed the 30.0 m (98.4 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in wide-scan mode.
- did not exceed the 40.0 m (131.2 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in narrow-scan mode.
- did not exceed the maximum effective range of RADAR sensors.

VIII.B.3.b. Field-of-view limitations

VIII.B.3.b.i. Unknown Cognex cameras and unknown camera

Team 2004-03 did not report field-of-view for the unknown Cognex cameras and unknown camera in use by the team.

VIII.B.3.b.ii. Epsilon Lambda ELSC71-1A

Team 2004-03 did not report field-of-view for the Epsilon Lambda ELSC71-1A in use by the team. The Epsilon Lambda ELSC71-1A was a popular sensor during the 2004 GCE, and its reported capabilities well-documented. As a result, a field-of-view of ±20º in wide-scan mode and ±8º in narrow-scan mode is asserted. At the 40.0 m (131.2 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in narrow-scan mode the width of the lane being actively swept by the Epsilon Lambda ELSC71-1A is approximately 11.2 m (36.9 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2004-03 challenge vehicle width of 0.5 m (1.5 ft) ([92], p. 9), the maximum allowed turn radius at which the Epsilon Lambda ELSC71-1A in narrow-scan mode would reliably detect obstacles is approximately 23.5 m (77.1 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed that no turns had a maximum allowed turn radius of less than 23.5 m. As a result, there was no field-of-view limitation.

VIII.B.4. Team 2004-04

- Team 2004-04 stated: "Since [the challenge vehicle] is built using a standard Isuzu Trooper, its top speed is on the order of 90 mph. However, the realized top speed will be limited to 40-50mph..." ([44], p. 12). A top speed of 50 mph was selected.

- An unknown Videre Design stereo camera pair, unknown cameras, unknown long-range RADAR, and SICK LMS 200-30106 were in use by the team. See Table XXV.

VIII.B.4.a. <u>Stopping distance</u>

At the representative μ_k, the challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.4.a.i. <u>Unknown Videre Design stereo camera pair and unknown cameras</u>

Team 2004-04 did not report maximum obstacle detection ranges for the unknown Videre Design stereo camera pair and unknown cameras in use by the team via the team technical proposal ([44]). The Team 2004-04 challenge vehicle stopping distance:

- exceeded the maximum effective range for VISION sensors.

VIII.B.4.a.ii. <u>Unknown long-range RADAR</u>

Team 2004-04 stated: "The PRECO Preview long range RADAR system provides range data at distances up to 100 feet." ([44], p. 6). No PRECO Preview has a range of 100 ft. The author concluded an unknown long-range RADAR was in use by the team. See paragraph V.C.4. The author selected a range of 30.5 m (100.0 ft) as the maximum obstacle detection range of the unknown long-range RADAR. The Team 2004-04 challenge vehicle stopping distance:

- exceeded the 30.5 m (100.0 ft) maximum obstacle detection range of the unknown long-range RADAR.

- exceeded the maximum effective range of RADAR sensors.

VIII.B.4.a.iii. <u>SICK LMS 200-30106</u>

Team 2004-04 stated: "The laser range is up to 30 meters without using any supplementary reflectors." ([44], p. 9). The author notes the SICK LMS 200-30106 has a "typical range" of 10 m with 10 percent reflectivity. See paragraph VIII.A.4. The Team 2004-04 challenge vehicle stopping distance:

- exceeded the 30.0 m (98.4 ft) maximum obstacle detection range of the SICK LMS 200-30106.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.4.b. Field-of-view limitations

VIII.B.4.b.i. Unknown Videre Design stereo camera pair and unknown cameras

Team 2004-04 stated: "The sensing horizon, or field of view, of the stereo vision system is a function of the focal length of the lenses used. The stereo vision system that will be used on [the challenge vehicle] is manufactured by Videre Design. With the 12.5 mm focal length lenses that we are using, the horizontal and vertical fields of view are 50 degrees and 38 degrees, respectively." ([44], p. 8). The field-of-view of the unknown Videre Design stereo camera pair equaled or exceeded 40º. See paragraph VIII.A.2.

Team 2004-04 did not report field-of-view of the unknown cameras in use by the team.

VIII.B.4.b.ii. Unknown long-range RADAR

Team 2004-04 did not report field-of-view of the unknown long-range RADAR in use by the team.

VIII.B.5. Team 2004-05

- Team 2004-05 stated: "Vehicle top speed has been reduced (gear ratios) to 55 mph." ([45], p. 13).

- Unknown SICK LIDAR sensors, an unknown Eaton RADAR, and a Point Grey Bumblebee stereo camera pair were in use by Team 2004-05. See Table XXV.

VIII.B.5.a. Stopping distance

At the representative μ_k, the challenge vehicle stopping distance at a speed of 55 mph was 93.3 m (306.2 ft).

VIII.B.5.a.i. Unknown SICK LIDAR sensors

Team 2004-05 reported a range of 45.7 m (150.0 ft) for the unknown SICK LIDAR sensors in use by the team ([45], p. 12). The challenge vehicle stopping distance:

- exceeded the 45.7 m (150.0 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.5.a.ii. Unknown Eaton RADAR

Team 2004-05 reported a range of 91.4 m (300.0 ft) for the unknown Eaton RADAR in use by the team ([45], p. 12). The challenge vehicle stopping distance:

- exceeded the 91.4 m (300.0 ft) maximum obstacle detection range of the unknown Eaton RADAR.
- exceeded the maximum effective range of RADAR sensors.

VIII.B.5.a.iii. Point Grey Bumblebee stereo camera pair

Team 2004-05 did not report the maximum obstacle detection range for the Point Grey Bumblebee stereo camera pair in use by the team. The Team 2004-05 challenge vehicle stopping distance:

- exceeded the maximum effective range of VISION sensors.

VIII.B.5.b. Field-of-view limitations

VIII.B.5.b.i. Unknown Eaton RADAR

Team 2004-05 reported a field-of-view of “12 degrees” for the unknown Eaton RADAR in use by the team ([45], p. 12). At the maximum obstacle detection range of 91.4 m (300.0 ft) the width of the lane being actively swept by the unknown Eaton RADAR is approximately 19.2 m (63.1 ft). Using the equation above, the author was able to determine:

- Based on the Team 2004-05 challenge vehicle width of 2.2 m (7.3 ft) ([45], p. 1), the maximum allowed turn radius at which the unknown Eaton RADAR would reliably detect obstacles is approximately 203.9 m (669.0 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed that 182 turns had a maximum allowed turn radius of less than 203.9 m, requiring changes in bearing ranging from -54 to 73 degrees.
- The challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been unable to detect an obstacle 0.25 m (0.83 ft) from the path of travel.

VIII.B.5.b.ii. Point Grey Bumblebee stereo camera pair

Team 2004-05 did not report field-of-view for the Point Grey Bumblebee stereo camera pair in use by the team.

VIII.B.6. Team 2004-06

A proprietary stereo camera pair was in use by Team 2004-06. See Table XXV. Team 2004-06 stated ([114], p. 3):

> The vision system will resolve an obstacle the size of a human at a distance of 875′ and have good range information within 300′. The precision of the depth match is +/-5′ at a 100′ range. Thus, the top speed will be limited by the capability of the vehicle, which we estimate to be about 100 MPH.
>
> The latency of the system consists of several delays. First, the shutter is about 1000 µS long. Then, the first line is read out about 100 µS later. The cameras are inverted, so the area closest to the vehicle is read out first. The distance and obstacle avoidance computations are done on a line-by-line basis, and there is a one-line delay, or 60 µS delay for each stage, and the processing goes through 4 stages, for a total of 240 µS. The vehicle will abandon top speed at any non-conforming visual situation. This has a delay of about 100 µS to communicate with the master motor controller, which then talks to the individual motors, and this has a 1000 µS delay. The motors will respond immediately, but will have a mechanical delay of about 5000 µS. However, the cameras have a frame time of 60Hz, meaning that worst case, an event won’t be captured for 18,000 µS later. Thus, worst case, the vehicle will travel less than about 5 feet at 100MPH before reacting to an obstacle.

Team 2004-06 estimated the challenge vehicle reaction time as 18,000 µs (0.018 s). At 100 mph, the challenge vehicle would be traveling approximately 146.6 ft/s. In 0.018 s, the challenge vehicle would travel 2.64 ft. The author was unable to determine if this was the “less than about 5 feet” referred to by the team technical proposal ([114]), confirm this was how Team 2004-06 calculated the distance the challenge vehicle would travel during the reaction time, determine if the top speed of the challenge vehicle was 200 mph, in lieu of 100 mph, or determine if the reaction time was twice that reported by Team 2004-06. The 2004 GCE course-wide speed limit of 60 mph is used herein.

VIII.B.6.a. Stopping distance

The author selected the range at which the proprietary stereo camera pair provided "good range information" of 91.4 m (300.0 ft) as the maximum obstacle detection range. At the representative μ_k, the Team 2004-06 challenge vehicle stopping distance at a speed of 60 mph was 111.1 m (364.4 ft), which

- exceeded the maximum obstacle detection range of 91.4 m (300.0 ft) of the proprietary stereo camera pair.
- exceeded the maximum effective range of VISION sensors.

VIII.B.6.b. Field-of-view limitations

Team 2004-06 did not report field-of-view for the proprietary stereo camera pair in use by the team.

VIII.B.7. Team 2004-07

- Team 2004-07 stated: "We plan to limit the top speed to 45 mph, because according to spec that is the maximum relative velocity at which the radar will function. If we could be sure there were no obstacles ahead, the physical top speed of the vehicle is at least 90 mph." ([46], p. 9). Team 2004-07 was one of only five teams which participated in the 2004 QID and GCE to refer specifically to sensor range limiting the speed of the challenge vehicle.
- An unknown SICK LIDAR sensor, Epsilon Lambda ELSC71-1A, FLIR Omega, and Sony DFW-VL500 cameras were in use by Team 2004-07. See Table XXV.

VIII.B.7.a. Stopping distance

At the representative μ_k, the Team 2004-07 challenge vehicle stopping distance at a speed of 45 mph was 62.5 m (205.0 ft).

VIII.B.7.a.i. Unknown SICK LIDAR sensor

Team 2004-07 stated: "This ladar system has at least 10 meters range..." ([46], p. 7). The Team 2004-07 challenge vehicle stopping distance:

- exceeded the 10.0 m (32.8 ft) maximum obstacle detection range of the unknown SICK LIDAR sensor.
- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.7.a.ii. Epsilon Lambda ELSC71-1A

Team 2004-07 stated: "One Epsilon Lambda Electronics ELSC71-1A 3D Radar. Mounted at the front of the truck, this is an active forward-pointing 76.5-GHz radar with two modes, narrow-scan and wider-scan. In wider-scan mode (which we will probably use more frequently) the radar beam is swept across a 40-degree horizontal arc and has a maximum range of 30 meters. In narrow-scan mode (which we might use at high speeds) the radar beam is swept across a 16-degree horizontal arc and has a maximum range of 40 meters." ([46], p. 6).

The Team 2004-07 challenge vehicle stopping distance:

- exceeded the 30.0 m (98.4 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in wide-scan mode.
- exceeded the 40.0 m (131.2 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in narrow-scan mode.
- exceeded the maximum effective range of RADAR sensors.

VIII.B.7.a.iii. FLIR Omega and Sony DFW-VL500 cameras

Team 2004-07 did not report maximum obstacle detection range of the FLIR Omega or Sony DFW-VL500 cameras in use by the team. The Team 2004-07 challenge vehicle stopping distance:

- did not exceed the maximum effective range of VISION sensors.

VIII.B.7.b. Field-of-view limitations

VIII.B.7.b.i. Epsilon Lambda ELSC71-1A

At the 62.5 m (205.0 ft) challenge vehicle stopping distance the width of the lane being actively swept by the Epsilon Lambda ELSC71-1A in narrow-scan mode is approximately 17.6 m (57.6 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2004-07 challenge vehicle width of 2.0 m (6.6 ft) ([46], p. 2), the maximum allowed turn radius at which the Epsilon Lambda ELSC71-1A would reliably detect obstacles is approximately 103.0 m (338.0 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed that 53 turns had a maximum allowed turn radius of less than 103.0 m, requiring changes in bearing ranging from -54 to 73 degrees.

- The challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been unable to detect an obstacle 0.4 m (1.5 ft) from the path of travel in narrow-scan mode.

- Although the challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been able to detect an obstacle approximately 2.7 m (9.0 ft) from the path of travel in wide-scan mode, maximum speed would have been limited to 30 mph, much less than the 48 mph allowed by course geometry, due to decreased stopping distance based on the 30.0 m (98.4 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in wide-scan mode.

VIII.B.7.b.ii. FLIR Omega and Sony DFW-VL500 cameras

Team 2004-07 did not report field-of-view of the FLIR Omega or Sony DFW-VL500 cameras in use by the team.

VIII.B.8. Team 2004-08

- Team 2004-08 stated: “Our vehicle’s top speed is fifty-five miles per hour.” ([76], p. 8).

- Laseroptronix LDM 800-RS232 LIDAR sensors, a Laseroptronix Sea-Lynx, and Cohu 1330 cameras were in use by Team 2004-08. See Table XXV.

VIII.B.8.a. Stopping distance

At the representative μ_k , the Team 2004-08 challenge vehicle stopping distance at a speed of 55 mph was 93.3 m (306.2 ft).

VIII.B.8.a.i. Laseroptronix LDM 800-RS232 LIDAR sensors

Team 2004-08 stated: “The range finders will ... have a range of 4 to 400 meters.” ([76], p. 5). A hyperlink on the manufacturer website ([231]) to a “PDF file of this product” for the Laseroptronix LDM 800-RS232 led to manufacturer product literature for the Laseroptronix LDM 600-232. Laseroptronix reported the technical details for the LDM 600, LDM 800, and LDM 1000 are virtually identical with the exception of their ranges, which are 600 m, 800 m, and 1000 m respectively ([220]). A maximum obstacle detection range of 400 m was selected.

The Team 2004-08 challenge vehicle stopping distance:

- did not exceed the 400.0 m (1312.3 ft) maximum obstacle detection range of the Laseroptronix LDM 800-RS232 LIDAR sensors.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.8.a.ii. Laseroptronix Sea-Lynx

Team 2004-08 stated, in part: "This system can see through snow, rain and fog at a range of 50 to 350 meters..." ([76], p. 5). Laseroptronix reported the "gated range" of the Sea-Lynx was 40 m to 1500 m, in lieu of the 50 m to 350 m reported by Team 2004-08 ([221]).

The Laseroptronix Sea-Lynx has characteristics of both VISION and long-range LIDAR sensors. The Team 2004-08 challenge vehicle stopping distance:

- did not exceed the 350.0 m (1148.3 ft) maximum obstacle detection range of the Laseroptronix Sea-Lynx.
- exceeded the maximum effective ranges of VISION sensors.
- exceeded the maximum effective range of long-range LIDAR sensors.

VIII.B.8.a.iii. Cohu 1330 cameras

Team 2004-08 did not report maximum obstacle detection range for the first Cohu 1330 camera in use by the team. Team 2004-08 stated: "The second camera ... will be focused to look up to 100 meters in front of the vehicle." ([76], p. 4). The Team 2004-08 challenge vehicle stopping distance:

- did not exceed the 100.0 m (328.1 ft) maximum obstacle detection range of the second Cohu 1330 camera.
- exceeded the maximum effective range of VISION sensors.

VIII.B.8.b. Field-of-view limitations

VIII.B.8.b.i. Laseroptronix LDM 800-RS232 LIDAR sensors

The Laseroptronix LDM 800-RS232 is a simple laser range finder, not a scanning laser range finder similar to other LIDAR sensors in use by the teams. Team 2004-08 reported the laser range finders were "attached to the skin of the vehicle" ([76], p. 5) and therefore fixed-mount. As a result, the Laseroptronix LDM 800-RS232 LIDAR sensors in use by the team have no field-of-view and cannot provide detailed profiling information for obstacles which do not intersect line-of-sight.

VIII.B.8.b.ii. Laseroptronix Sea-Lynx

Team 2004-08 did not report field-of-view for the Laseroptronix Sea-Lynx in use by the team, but stated: "...we can use it to determine range to any object in the field of view of the system." ([76], p. 5). Laseroptronix stated the field-of-view for the Sea-Lynx is 7.5 degrees or "about 15 meter at 100 meter in distance [*sic*]" ([221]). However, the field-of-view would be either approximately 8.5 degrees if 15 m is visible at 100 m, or approximately 13 m would be visible at 100 m if the field-of-view is 7.5 degrees. A field-of-view of 7.5 degrees, or 13.0 m (43.0 ft) at 100.0 m (328.1 ft), is used herein.

At 100.0 m (328.1 ft), the width of the lane being actively swept by the Laseroptronix Sea-Lynx is approximately 13.0 m (43.0 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2004-08 challenge vehicle width of 2.2 m (7.2 ft) ([76], p. 2), the maximum allowed turn radius at which the Laseroptronix Sea-Lynx would reliably detect obstacles is approximately 508.7 m (1669.0 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed 474 turns had a maximum allowed turn radius of less than 508.7 m, requiring changes in bearing ranging from -54 to 73 degrees.

- The challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been unable to detect an obstacle 0.10 m (0.32 ft) from the path of travel.

VIII.B.8.b.iii. Cohu 1330 cameras

Team 2004-08 did not report field-of-view for the Cohu 1330 cameras in use by the team.

VIII.B.9. Team 2004-09

- Team 2004-09 stated: “The top speed of the basic vehicle is in excess of 100 mph, but it is planned that the vehicle will not exceed 60 mph during the challenge race.” ([38], p. 9).

- An unknown SICK LIDAR sensor and unknown camera were in use by Team 2004-09. See Table XXV.

VIII.B.9.a. Stopping distance

At the representative μ_k , the Team 2004-09 challenge vehicle stopping distance at a speed of 60 mph was 111.1 m (364.4 ft).

VIII.B.9.a.i. Unknown SICK LIDAR sensor

Team 2004-09 reported the unknown SICK LIDAR sensor had “an angular resolution of 1⁄4º, or 2.5 inches at 50 ft distance” ([38], p. 7). A maximum obstacle detection range of 15.2 m (50.0 ft) was selected. The Team 2004-09 challenge vehicle:

- exceeded the 15.2 m (50.0 ft) maximum obstacle detection range of the unknown SICK LIDAR sensor.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.9.a.ii. Unknown camera

Team 2004-09 reported the unknown camera had "a resolution of at least 1⁄4 inch at 10 feet, and 1 inch at 40 feet" ([38], p. 7). A maximum obstacle detection range of 12.2 m (40.0 ft) was selected. The Team 2004-09 challenge vehicle stopping distance:

- exceeded the 12.2 m (40.0 ft) maximum obstacle detection range of the unknown camera.

- exceeded the maximum effective range of VISION sensors.

VIII.B.9.b. Field-of-view limitations

Team 2004-09 stated: "We are assuming a field of view of approximately 50º, which is customary for commercial video camera lenses." ([38], p. 7). The field-of-view of the unknown camera equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.10. Team 2004-10

- Team 2004-10 stated: "The vehicle has a top speed adequate to complete the prescribed course within the allotted duration." ([77], p. 6). Team 2004-10 later reported a maximum speed of 36 mph during the 2004 GCE ([39], p. 31).

- Unknown SICK LIDAR sensors and a Riegl LMS-Q140i were in use by Team 2004-10 during the 2004 GCE. See Table XXV.

VIII.B.10.a. Stopping distance

Team 2004-10 did not report range for the unknown SICK LIDAR sensors in use by the team via the team technical proposal ([77]). However, Team 2004-10 later reported the maximum obstacle detection range of the long-range LIDAR sensor ("Forward LIDAR") in use by the team was 75 m, and the maximum obstacle detection range of the short-range LIDAR sensor ("Supplemental LIDAR") was 25 m ([39], p. 12). The author concluded the unknown SICK LIDAR sensors were the short-range LIDAR sensors and Riegl LMS-Q140i was the long-range LIDAR sensor in use by the team. At the representative μ_k, the Team 2004-10 challenge vehicle stopping distance at a speed of 36 mph was 40.0 m (131.2 ft).

VIII.B.10.a.i. Unknown SICK LIDAR sensors

The Team 2004-10 challenge vehicle stopping distance:

- exceeded the 25.0 m (82.0 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.10.a.ii. Riegl LMS-Q140i

The Team 2004-10 challenge vehicle stopping distance:

- did not exceed the 75.0 m (246.1 ft) maximum obstacle detection range of the LMS-Q140i.

- did not exceed the maximum effective range of long-range LIDAR sensors.

VIII.B.10.b. Field-of-view limitations

Team 2004-10 did not report field-of-view for the Riegl LMS-Q140i in use by the team via the team technical proposal ([77]). Team 2004-10 later stated: "The Riegl LMS Q140i Airborne line-scanner that [the challenge vehicle] uses, operates with a 60-degree field of view..." ([39], p. 13). The field-of-view of the Riegl LMS-Q140i in use by the team equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.11. Team 2004-11

- Team 2004-11 stated: "The top speed of the vehicle will comply with the given standards." ([127], p. 9). The 2004 GCE course-wide speed limit of 60 mph is used herein.

- An unknown long-range laser ranger, unknown scanning laser range finder, and unknown Omnivision sensor were in use by Team 2004-11. See Table XXV.

VIII.B.11.a. Stopping distance

At the representative μ_k , the Team 2004-11 challenge vehicle stopping distance at the 2004 GCE course-wide speed limit of 60 mph was 111.1 m (364.4 ft).

VIII.B.11.a.i. Unknown long-range laser ranger

Team 2004-11 stated: "At the farthest range, our laser range finder detects and returns ranges of large objects and terrain features up to 500 feet away. This instrument is a standard industrial laser rangefinder, set to return ranges at the ground level 500 feet ahead 3 times per second." ([127], p. 5). The Team 2004-11 challenge vehicle stopping distance:

- did not exceed the 152.4 m (500.0 ft) maximum obstacle detection range of the unknown long-range laser ranger.

- exceeded the maximum effective range of long-range LIDAR sensors.

VIII.B.11.a.ii. Unknown scanning laser range finder

Team 2004-11 stated: "The closest practical range at which objects will be detected is between 100 and 200 feet, when the scanning laser rangefinder will begin returning ranges. The laser instrument is mounted at 90 inches from ground level, and is aimed at ground level 200 feet ahead of the vehicle." ([127], p. 5). A maximum obstacle detection range of 61.0 m (200.0 ft) was selected. The Team 2004-11 challenge vehicle stopping distance:

- exceeded the 61.0 m (200.0 ft) maximum obstacle detection range of the unknown scanning laser range finder.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.11.a.iii. Unknown Omnivision sensor

Team 2004-11 did not report maximum obstacle detection range for the unknown Omnivision sensor in use by the team. The Team 2004-11 challenge vehicle stopping distance:

- exceeded the maximum effective range of VISION sensors.

VIII.B.11.b. Field-of-view limitations

VIII.B.11.b.i. Unknown long-range laser ranger

Team 2004-11 reported the long-range laser ranger is "set at a fixed angle". As a result, the unknown long-range laser ranger has no field-of-view and cannot provide detailed profiling information for obstacles which do not intersect line-of-sight.

VIII.B.11.b.ii. Unknown Omnivision sensor

Team 2004-11 did not report field-of-view for the unknown Omnivision sensor in use by the team.

VIII.B.12. Team 2004-12

- Team 2004-12 stated: "The top speed of the vehicle is 40 mph, implemented as a software-controlled limit." ([129], p. 8).

- A SICK LMS 291-S05 was in use by Team 2004-12. See Table XXV.

VIII.B.12.a. Stopping distance

At the representative μ_k, the Team 2004-12 challenge vehicle stopping distance at a speed of 40 mph was 49.4 m (162.0 ft).

Team 2004-12 stated: “Forward radar distance sensor - Active Sensing - SICK Laser Measurement System (LMS) 291-S05 to 50 meters.” ([129], p. 4). The Team 2004-12 challenge vehicle stopping distance:

- did not exceed the 50.0 m (164.0 ft) maximum obstacle detection range of the SICK LMS 291-S05.
- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.13. Team 2004-13

- Team 2004-13 stated: “The top speed of the vehicle is 60MPH...” ([232], p. 7).
- Unknown SICK LIDAR sensors, an unknown camera, and an unknown Epsilon Lambda RADAR were in use by Team 2004-13. See Table XXV.

VIII.B.13.a. Stopping distance

At the representative μ_k, the Team 2004-13 challenge vehicle stopping distance at a speed of 60 mph was 111.1 m (364.4 ft).

VIII.B.13.a.i. Unknown SICK LIDAR sensors

Team 2004-13 stated: “The LADAR system will be primarily used for detecting obstacles at large distances in front of the vehicle. It has the capability of detecting targets at a maximum range of 80 m...” ([232], p. 3). The Team 2004-13 challenge vehicle stopping distance:

- exceeded the 80.0 m (262.5 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.
- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.13.a.ii. Unknown camera

Team 2004-13 stated: “A maximum sensing distance of up to 100 m will be achievable on flat straight paths.” ([232], p. 3). The Team 2004-13 challenge vehicle stopping distance:

- exceeded the 100.0 m (328.1 ft) maximum obstacle detection range of the unknown camera.

- exceeded the maximum effective range of VISION sensors.

VIII.B.13.a.iii. Unknown Epsilon Lambda RADAR

Team 2004-13 stated: "The RADAR system (from Epsilon Lambda) may be used, primarily for detecting obstacles at large distances in front of the vehicle. It is capable of detecting targets at a maximum range of 110 m with a range resolution of 1 m. The microwave beam is mechanically scanned horizontally over a maximum angular range of ± 20º with an azimuth angular resolution of 1.8º." ([232], p. 3).

The "maximum range" reported by Team 2004-13 corresponds to the range of the Epsilon Lambda ELSC71-1A in narrow-scan mode, but the "maximum angular range" of ±20º corresponds to the "azimuth scan" of the Epsilon Lambda ELSC71-1A in wide-scan mode. The Epsilon Lambda ELSC71-1A has a range of 30 m in wide-scan mode, and a field-of-view of ±8º in narrow-scan mode. Therefore, for the purposes of this analysis, the use of the Epsilon Lambda ELSC71-1A by Team 2004-13 is asserted.

The Team 2004-13 challenge vehicle stopping distance:

- exceeded the 110.0 m (360.9 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in narrow-scan mode.
- exceeded the 30.0 m (98.4 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in wide-scan mode.
- exceeded the maximum effective range of RADAR sensors.

VIII.B.13.b. Field-of-view limitations

VIII.B.13.b.i. Unknown camera

Team 2004-13 did not report field-of-view of the unknown camera in use by the team.

VIII.B.13.b.ii. Unknown Epsilon Lambda RADAR

For the purposes of this analysis, the use of the Epsilon Lambda ELSC71-1A by Team 2004-13 is asserted. At the 110.0 m (360.9 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in narrow-scan mode the width of the lane being actively swept by the Epsilon Lambda ELSC71-1A is approximately 30.9 m (101.4 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2004-13 challenge vehicle width of 1.5 m (5.0 ft) ([232], p. 10), the maximum allowed turn radius at which the Epsilon Lambda ELSC71-1A would reliably detect obstacles is approximately 78.3 m (256.9 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed that 31 turns had a maximum allowed turn radius of less than 78.3 m, requiring changes in bearing ranging from -54 to 73 degrees.

- The challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been unable to detect an obstacle 0.4 m (1.5 ft) from the path of travel in narrow-scan mode.

- Although the challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been able to detect an obstacle approximately 2.74 m (9.0 ft) from the path of travel in wide-scan mode, maximum speed would have been limited to 30 mph, much less than the 48 mph allowed by course geometry, due to decreased stopping distance based on the 30.0 m (98.4 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in wide-scan mode.

VIII.B.14. Team 2004-14

- Team 2004-14 stated: “The top speed of the vehicle is 40 miles per hour.” ([134], p. 7).

- Unknown cameras, unknown SICK LIDAR sensors, and an unknown Epsilon Lambda RADAR were in use by Team 2004-14. See Table XXV.

VIII.B.14.a. Stopping distance

At the representative μ_k , the Team 2004-14 challenge vehicle stopping distance at a speed of 40 mph was 49.4 m (162.0 ft).

VIII.B.14.a.i. Unknown cameras

Team 2004-14 stated: “A maximum sensing distance of up to 100 m will be achievable on flat straight paths.” ([134], p. 3). The Team 2004-14 challenge vehicle stopping distance:

- did not exceed the 100.0 m (328.1 ft) maximum obstacle detection range of the unknown cameras.

- did not exceed the maximum effective range of VISION sensors.

VIII.B.14.a.ii. Unknown SICK LIDAR sensors

2004-14 stated: “The LADAR system will be primarily used for detecting obstacles at large distances in front of the vehicle. It has the capability of detecting targets at a maximum range of 80 m...” ([134], p. 3). The Team 2004-14 challenge vehicle stopping distance:

- did not exceed the 80.0 m (262.5 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.
- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.14.a.iii. Unknown Epsilon Lambda RADAR

Team 2004-14 stated: "The RADAR system (from Epsilon Lambda) will be primarily used for detecting obstacles at large distances in front of the vehicle. It is capable of detecting targets at a maximum range of 110 m with a range resolution of 1 m. The microwave beam is mechanically scanned horizontally over a maximum angular range of ± 20º with an azimuth angular resolution of 1.8º." ([134], p. 4).

The "maximum range" reported by Team 2004-14 corresponds to the range of the Epsilon Lambda ELSC71-1A in narrow-scan mode, but the "maximum angular range" of ±20º corresponds to the "azimuth scan" of the Epsilon Lambda ELSC71-1A in wide-scan mode. The Epsilon Lambda ELSC71-1A has a range of 30 m in wide-scan mode, and a field-of-view of ±8º in narrow-scan mode. Therefore, for the purposes of this analysis, the use of the Epsilon Lambda ELSC71-1A by Team 2004-14 is asserted.

The Team 2004-14 challenge vehicle stopping distance:

- did not exceed the 110.0 m (360.9 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in narrow-scan mode.
- exceeded the 30.0 m (98.4 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in wide-scan mode.
- did not exceed the maximum effective range of RADAR sensors.

VIII.B.14.b. Field-of-view limitations

VIII.B.14.b.i. Unknown cameras

Team 2004-14 did not report field-of-view of the unknown cameras in use by the team.

VIII.B.14.b.ii. Unknown Epsilon Lambda RADAR

For the purposes of this discussion, the use of the Epsilon Lambda ELSC71-1A by Team 2004-14 is asserted. At the 110.0 m (360.9 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in narrow-scan mode the width of the lane being actively swept by the Epsilon Lambda ELSC71-1A is approximately 30.9 m (101.4 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2004-14 challenge vehicle width of 1.8 m (5.8 ft) ([134], p. 11), the maximum allowed turn radius at which the Epsilon Lambda ELSC71-1A would reliably detect obstacles is approximately 91.5 m (300.0 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed that 40 turns had a maximum allowed turn radius of less than 91.5 m, requiring changes in bearing ranging from -54 to 73 degrees.

- The challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been unable to detect an obstacle 0.4 m (1.5 ft) from the path of travel in narrow-scan mode.

- Although the challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been able to detect an obstacle approximately 2.74 m (9.0 ft) from the path of travel in wide-scan mode, maximum speed would have been limited to 30 mph, much less than the 48 mph allowed by course geometry, due to decreased stopping distance based on the 30.0 m (98.4 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in wide-scan mode.

VIII.B.15. Team 2004-15

- Team 2004-15 stated: “Top speed of vehicle has not been tested, but current design mandates that top speed be limited to 50 MPH.” ([137], p. 5).

- A SICK LMS 211-30206 and an Eaton EVT-300 were in use by Team 2004-15. See Table XXV.

VIII.B.15.a. Stopping distance

At the representative μ_k, the Team 2004-15 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.15.b. SICK LMS 211-30206

Team 2004-15 stated: “A 2-D active scanning laser ranger with an 80-meter sensing horizon ... will be used for object detection and relative positioning.” ([137], p. 3). The Team 2004-15 challenge vehicle stopping distance:

- did not exceed the 80.0 m (262.5 ft) maximum obstacle detection range of the SICK LMS 211-30206.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.15.c. Eaton EVT-300

Team 2004-15 stated: "An active 24.725 GHz Doppler radar system (Eaton VORAD EVT-300) with a sensing horizon of 100 meters ... will also be utilized for obstacle detection/avoidance as well as enhanced road following capability." ([137], p. 3). The Team 2004-15 challenge vehicle stopping distance:

- did not exceed the 100.0 m (328.1 ft) maximum obstacle detection range of the Eaton EVT-300.
- exceeded the maximum effective range of RADAR sensors.

VIII.B.15.c.i. Field-of-view limitations

Team 2004-15 stated: "An active 24.725 GHz Doppler radar system (Eaton VORAD EVT-300) with a ... 12 degree field of view will also be utilized for obstacle detection/avoidance as well as enhanced road following capability." ([137], p. 3).

At the 77.1 m (253.0 ft) challenge vehicle stopping distance the width of the lane being actively swept by the Eaton EVT-300 is approximately 16.2 m (53.2 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2004-15 challenge vehicle width of 1.8 m (5.9 ft) ([137], p. 6), the maximum allowed turn radius at which the Eaton EVT-300 would reliably detect obstacles is approximately 163.4 m (536.1 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed that 124 turns had a maximum allowed turn radius of less than 163.4 m, requiring changes in bearing ranging from -54 to 73 degrees.
- The challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been unable to detect an obstacle 0.25 m (0.83 ft) from the path of travel.

VIII.B.16. Team 2004-16

- Team 2004-16 reported the top speed of the challenge vehicle was "30 mph." ([138], p. 6).
- Unknown cameras, unknown RADAR, and unknown SICK LIDAR sensors were in use by Team 2004-16. See Table XXV.

VIII.B.16.a. Stopping distance

At the representative μ_k, the Team 2004-16 challenge vehicle stopping distance at a top speed of 30 mph was 27.8 m (91.1 ft).

VIII.B.16.a.i. Unknown cameras

Team 2004-16 stated: "Passive cameras, 2 fixed front wide-angle IR sensitive CCD cameras for visual acquisition of terrain, obstacles, other vehicles (1-90m)..." ([138], p. 4). The Team 2004-16 challenge vehicle stopping distance:

- did not exceed the 90.0 m (295.3 ft) maximum obstacle detection range of the unknown cameras.
- did not exceed the maximum effective range of VISION sensors.

VIII.B.16.a.ii. Unknown RADAR

Team 2004-16 stated: "...radar, sonar and laser range finders for distance determination between own vehicle and obstacle/other vehicles (1-100m)." ([138], p. 4). The Team 2004-16 challenge vehicle stopping distance:

- did not exceed the 100.0 m (328.1 ft) maximum obstacle detection range of the unknown RADAR.
- did not exceed the maximum effective range of RADAR sensors.

VIII.B.16.b. Unknown SICK LIDAR sensors

Team 2004-16 stated: "...radar, sonar and laser range finders for distance determination between own vehicle and obstacle/other vehicles (1-100m)." ([138], p. 4). The Team 2004-16 challenge vehicle stopping distance:

- did not exceed the 100.0 m (328.1 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.
- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.16.c. Field-of-view limitations

Team 2004-16 did not report field-of-view for the unknown cameras or unknown RADAR in use by the team.

VIII.B.17. Team 2004-17

- Team 2004-17 stated: "For a variety of reasons, the top safe vehicle speed (whether controlled by a human via the joystick or by the on-board computers) is 40 mph." ([142], p. 13).
- Point Grey Dragonfly cameras and SICK LMS 221-30206 LIDAR sensors were in use by Team 2004-17. See Table XXV.

VIII.B.17.a. Stopping distance

At the representative μ_k, the Team 2004-17 challenge vehicle stopping distance at a speed of 40 mph was 49.4 m (162.0 ft).

Team 2004-17 divided the sensors in use by the team into "short-range" (less than 30 m) and "long-range" (greater than 30 m) sensors. Two Point Grey Dragonfly cameras in use as a stereo camera pair and one SICK LMS 221-30206 each were in use as short-range sensors and long-range sensors. Because Team 2004-17 did not report a maximum obstacle detection range for the long-range sensors in use by the team, the author was unable to determine if the Team 2004-17 challenge vehicle stopping distance exceeded the maximum obstacle detection range for the long-range sensors in use by the team. The following analysis is based on the 30.0 m (98.4 ft) maximum obstacle detection range for short-range sensors in use by the team.

VIII.B.17.a.i. Point Grey Dragonfly stereo camera pair

The Team 2004-17 challenge vehicle stopping distance:

- exceeded the 30.0 m (98.4 ft) maximum obstacle detection range of the Dragonfly stereo camera pair.
- did not exceed the maximum effective range of VISION sensors.

VIII.B.17.a.ii. SICK LMS 221-30206

The Team 2004-17 challenge vehicle stopping distance:

- exceeded the 30.0 m (98.4 ft) maximum obstacle detection range of the SICK LMS 221-30206.
- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.17.b. Field-of-view limitations

Via an un-numbered table, Team 2004-17 reported field-of-view of 44.6º for the Point Grey Dragonfly stereo camera pair in use by the team ([142], p. 7). The field-of-view of the Dragonfly stereo camera pair equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.18. Team 2004-18

- Team 2004-18 stated: "The top speed of the vehicle is 68±5 mph." ([48], p. 10). The 2004 GCE course-wide speed limit of 60 mph is used herein.

- Unknown RADARs, a SICK LMS 220-30106, and an unknown stereo camera pair were in use by Team 2004-18. See Table XXV.

VIII.B.18.a. Stopping distance

At the representative μ_k , the Team 2004-18 challenge vehicle stopping distance at a speed of 60 mph was 111.1 m (364.4 ft).

VIII.B.18.a.i. Unknown RADARs

Team 2004-18 stated: "The Doppler radar sensors are planned to be DRS 1000 units from GMH engineering." ([48], p. 12). In the absence of an affirmative statement by Team 2004-18 that GMH Engineering DRS 1000 RADAR was in use, the author concluded the RADAR sensors in use by the team were unknown. However, for the purposes of this analysis the use of GMH Engineering DRS 1000 RADARs is asserted.

The maximum range of 304.8 m (1000.0 ft) for GMH Engineering DRS 1000 RADARs reported by Team 2004-18 ([48], p. 6) conforms to manufacturer literature, which stated the "Max. Target Distance" is "over 1000 ft" ([229]). The Team 2004-18 challenge vehicle stopping distance:

- did not exceed the 304.8 m (1000.0 ft) maximum obstacle detection range of the GMH Engineering DRS 1000 RADARs.

- exceeded the maximum effective range of RADAR sensors.

VIII.B.18.a.ii. SICK LMS 220-30106

Team 2004-18 alternately reported the maximum obstacle detection range of the SICK LMS 220-30106 was 150 m (see paragraph V.C.18.f.) and 100 ft ([48], p. 6). The lesser range of 30.5 m (100.0 ft) is used herein. The Team 2004-18 challenge vehicle stopping distance:

- exceeded the 30.5 m (100.0 ft) range of the SICK LMS 220-30106.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.18.a.iii. Unknown stereo camera pair

Team 2004-18 reported the maximum obstacle detection range of the unknown stereo camera pair was 91.4 m (300.0 ft) ([48], p. 6). The Team 2004-18 challenge vehicle stopping distance:

- exceeded the 91.4 m (300.0 ft) maximum obstacle detection range of the unknown stereo camera pair.

- exceeded the maximum effective range of VISION sensors.

VIII.B.18.b. Field-of-view limitations

VIII.B.18.b.i. Unknown RADARs

Team 2004-18 stated: “The beam diverges at a 6 deg angle...” ([48], p. 12). At the Team 2004-18 challenge vehicle stopping distance of 111.1 m (364.4 ft), the width of the lane being actively swept by the DRS 1000 is approximately 23.4 m (76.6 ft).

Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2004-18 challenge vehicle width of 1.4 m (4.5 ft) ([48], p. 13), the maximum allowed turn radius at which the GMH Engineering DRS 1000 RADARs would reliably detect obstacles is approximately 125.3 m (411.1 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed that 76 turns had a maximum allowed turn radius of less than 125.3 m, requiring changes in bearing ranging from -54 to 73 degrees.

- The challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been unable to detect an obstacle 0.25 m (0.83 ft) from the path of travel.

VIII.B.18.b.ii. Unknown stereo camera pair

Team 2004-18 did not report field-of-view for the stereo camera pair in use by the team.

VIII.B.19. Team 2004-19

- Team 2004-19 reported the top speed of the challenge vehicle was 30 mph ([151], p. 4).

- An unknown stereo camera pair and a SICK DME 2000 were in use by Team 2004-19. See Table XXV.

VIII.B.19.a. Stopping distance

At the representative μ_k, the Team 2004-19 challenge vehicle stopping distance at a speed of 30 mph of was 27.8 m (91.1 ft).

VIII.B.19.a.i. Unknown stereo camera pair

Team 2004-19 stated: "The range of the stereo vision system is limited mainly by the visibility on the course." ([151], p. 2) and "The stereo vision system has … an effectively infinite depth of field." ([151], p. 3). In later sections, Team 2004-19 stated: "We are still working on our stereo vision system, and have not yet interfaced it with the vehicles computing system." ([151], p. 4) and "We are also looking forward to testing the robustness of our stereo vision system to determine how it handles dust and other airborne matter." ([151], p. 4).

As a result, the author concluded Team 2004-19 had no realistic expectation for the range of the unknown stereo camera pair in use by the team. The Team 2004-19 challenge vehicle stopping distance:

- did not exceed the maximum effective range of VISION sensors.

VIII.B.19.a.ii. SICK DME 2000

Team 2004-19 stated, in part: "The ... laser rangefinders have an effective range of approximately 35 feet..." ([151], p. 2). The Team 2004-19 challenge vehicle stopping distance:

- exceeded the 10.7 m (35.0 ft) maximum obstacle detection range of the SICK DME 2000.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.19.b. Field-of-view limitations

VIII.B.19.b.i. Unknown stereo camera pair

Team 2004-19 stated: "The stereo vision system has an extremely wide field of view (~180 degrees)…" ([151], p. 3). The field-of-view of the unknown stereo camera pair in use by Team 2004-19 equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.19.b.ii. SICK DME 2000

The SICK DME 2000 is not a scanning laser range finder similar to other SICK LIDAR sensors in use by teams participating in the 2004 or 2005 GCE. As a result, the SICK DME 2000 has no field-of-view and cannot provide detailed profiling information for obstacles which do not intersect line-of-sight.

VIII.B.20. Team 2004-20

- Team 2004-20 stated: "Our general approach is to not out-drive our stopping distance. We insist on good ground profiling data from the laser rangefinder out to our stopping distance. Pitch will be factored into the stopping distance computation, and rough ground will be covered at slower speed so that the vehicle sees shock levels well under 1G vertically. We will not exceed 40MPH at any time." ([107], p. 3). Team 2004-20 was one of five teams which participated in the 2004 QID and GCE to refer specifically to sensor range limiting the speed of the challenge vehicle.

- A SICK LMS 221-30206, Eaton EVT-300, and Unibrain Fire-i 400 were in use by Team 2004-20. See Table XXV.

VIII.B.20.a. Stopping distance

At the representative μ_k , the Team 2004-20 challenge vehicle stopping distance at a speed of 40 mph was 49.4 m (162.0 ft).

VIII.B.20.a.i. SICK LMS 221-30206

Team 2004-20 stated: "The primary sensor is the well-known SICK LMS 221, mounted high on the vehicle on a semi-custom tilt head. ... This is an active sensor with a maximum useful range of 45 meters. This range is reduced on dark surfaces." ([107], p. 5). Team 2004-20 is one of two teams which participated in the 2004 QID and GCE to refer specifically to the reflectivity limitation inherent in the use of LIDAR sensors. The Team 2004-20 challenge vehicle stopping distance:

- exceeded the 45.0 m (147.6 ft) maximum obstacle detection range of the SICK LMS 221-30206.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.20.a.ii. Eaton EVT-300

Team 2004-20 alternately stated: "This unit can sense car-sized targets at up to 100 meters, but is much more limited in range when sensing less solid targets." ([107], p. 5); "The unit has a nominal range of 100 meters..." ([107], p. 5); and "The VORAD radar ... detects buildings and cars at 50 meters, and chain link fences at about 8-10 meters." ([107], p. 9). A range of 50.0 m (164.0 ft) is used herein as the maximum obstacle detection range. The Team 2004-20 challenge vehicle stopping distance:

- did not exceed the 50.0 m (164.0 ft) maximum obstacle detection range of the Eaton EVT-300.

- did not exceed the maximum effective range of RADAR sensors.

VIII.B.20.a.iii. Unibrain Fire-i 400

Team 2004-20 did not report the maximum obstacle detection range of the Unibrain Fire-i 400 in use by the team. The Team 2004-20 challenge vehicle stopping distance:

- did not exceed the maximum effective range of VISION sensors.

VIII.B.20.b. Field-of-view limitations

VIII.B.20.b.i. Eaton EVT-300

Technical detail reported by the team technical proposal ([107]) generally conforms to manufacturer documentation, however Team 2004-20 did not report the RADAR beam width reported by Eaton: "Monopulse: determines azimuth or angular distance of up to 20 different vehicles or objects within its 12ºradar beam width." ([162]).

At the Team 2004-20 challenge vehicle stopping distance of 49.4 m (162.0 ft) the width of the lane being actively swept by the Eaton EVT-300 is 10.4 m (34.1 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2004-20 challenge vehicle width of 2.0 m (6.6 ft) ([107], p. 13), the maximum allowed turn radius at which the Eaton EVT-300 would reliably detect obstacles is approximately 182.5 m (598.9 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed that 147 turns had a maximum allowed turn radius of less than 182.5 m, requiring changes in bearing ranging from -54 to 73 degrees.

- The challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been unable to detect an obstacle 0.25 m (0.83 ft) from the path of travel.

VIII.B.20.b.ii. Unibrain Fire-i 400

Team 2004-20 did not report field-of-view for the Unibrain Fire-i 400 in use by the team.

VIII.B.21. Team 2004-21

- Team 2004-21 stated: "The top speed will be from 50 to 60 MPH." ([155], p. 10). A top speed of 60 mph is used herein.

- One Epsilon Lambda ELSC71-1A was in use by Team 2004-21. See Table XXV.

VIII.B.21.a. Stopping distance

At the representative μ_k , the Team 2004-21 challenge vehicle stopping distance at a speed of 60 mph was 111.1 m (364.4 ft).

Team 2004-21 stated: “We will use a Radar system for long range sensing... (See the Appendix below for product details.)” ([155], p. 6). The Team 2004-21 technical proposal “Appendix” appears to be a copy of manufacturer product literature for the Epsilon Lambda ELSC71-1A. The “Appendix” reported the “operating range” of the Epsilon Lambda ELSC71-1A is 30 m in wide-scan mode and 110 m in narrow-scan mode. The Team 2004-21 challenge vehicle stopping distance:

- exceeded the 30.0 m (98.4 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in wide-scan mode.
- exceeded the 110.0 m (360.9 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in narrow-scan mode.
- exceeded the maximum effective range of RADAR sensors.

VIII.B.21.b. Field-of-view limitations

At the 110.0 m or (360.9 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in narrow-scan mode, the width of the lane being actively swept by the Epsilon Lambda ELSC71-1A is approximately 30.9 m (101.4 ft).

Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2004-21 challenge vehicle width of 1.2 m (4.0 ft) ([155], p. 12), the maximum allowed turn radius at which the Epsilon Lambda ELSC71-1A would reliably detect obstacles is approximately 62.5 m (205.0 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed that 19 turns had a maximum allowed turn radius of less than 62.5 m, requiring changes in bearing ranging from -54 to 73 degrees.
- The challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been unable to detect an obstacle 0.4 m (1.5 ft) from the path of travel in narrow-scan mode.
- Although the challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been able to detect an obstacle approximately 2.7 m (9.0 ft) from the path of travel in wide-scan mode, maximum speed would have been limited to 30 mph, much less than the 48 mph allowed by course geometry, due to decreased stopping distance based on the

30 m (98.4 ft) maximum obstacle detection range of the Epsilon Lambda ELSC71-1A in wide-scan mode.

VIII.B.22. Team 2004-22

- Team 2004-22 stated: "Vehicle top speed: Approximately 70 mph." ([157], p. 7). The 2004 GCE course-wide speed limit of 60 mph is used herein.

- A proprietary video system was in use by Team 2004-22. See Table XXV.

VIII.B.22.a. Stopping distance

At the representative μ_k , the Team 2004-22 challenge vehicle stopping distance at a speed of 60 mph was 111.1 m (364.4 ft).

Team 2004-22 stated: "The video system is the only true look-ahead sensor..." and "Early look ahead determines obstacles as far as 1,200 feet. Expected look-ahead detection at high speeds is between 800 and 1000 feet." ([157], p. 4). The author selected a maximum obstacle detection range of 243.8 m (800.0 ft). The Team 2004-22 challenge vehicle stopping distance:

- did not exceed the 243.8 m (800.0 ft) maximum obstacle detection range of the proprietary video system.

- exceeded the maximum effective range of VISION sensors.

VIII.B.22.b. Field-of-view limitations

Team 2004-22 stated: "The video system has approximately 160-degree field of view (FOW) [*sic*] and will never allow the DGC vehicle to out turn the video system field of regard." ([157], p. 4). The field-of-view of the proprietary video system in use by Team 2004-22 equaled or exceeded 40º. See paragraph VIII.A.2.

Team 2004-22 was the only team to participate in the 2004 QID or GCE to refer specifically to driving into obstacles which are undetectable based on the field-of-view limitations of the challenge vehicle's sensors.

VIII.B.23. Team 2004-23

- Team 2004-23 stated: "The top speed of the vehicle under automatic control will be 50 mph." ([159], p. 12).

- Unknown SICK LIDAR sensors, unknown Eaton RADARs, and unknown cameras were in use by Team 2004-23. See Table XXV.

VIII.B.23.a. Stopping distance

Team 2004-23 stated: “The estimated stopping distance at 45 mph is 116 feet on pavement (u=0.90) and 151 feet off-road (u=0.5). We will conduct experiments ... to verify the stopping distances at various speeds and tire inflations.” ([159], p. 12). Team 2004-23 is one of two teams which participated in the 2004 QID and GCE to specifically state a stopping distance in their technical proposal, and the only team to specifically refer to the kinetic coefficient of friction under off-road conditions, as “u=0.5”, above.

At the representative μ_k , the Team 2004-23 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.23.a.i. Unknown SICK LIDAR sensors

Team 2004-23 stated: “Four SICK LADARs (Model: LMS 221) are to be used. These are 2-D laser rangefinders (active sensors) with 180 degree scanning spectrum and have maximum scanning distance of 80 meters[.] The actual range, of course, depends on the reflectivity of the target, but our experience to date indicates that 40 meters is a reasonable minimum operational range.” ([159], p. 8). Team 2004-23 is one of two teams which participated in the 2004 QID and GCE to refer specifically to the inherent reflectivity limitation in the use of LIDAR. The Team 2004-23 challenge vehicle stopping distance:

- exceeded the 40.0 m (131.2 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.

- exceeded the maximum effective range of short-range LIDAR sensors.

At the Team 2004-23 μ_k of 0.5, the Team 2004-23 challenge vehicle stopping distance at a speed of 45 mph was 46.0 m (151.0 ft), and would have exceeded the 40.0 m (131.2 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.

VIII.B.23.a.ii. Unknown Eaton RADARs

Team 2004-23 stated: “2 Eaton-Vorad radars are mounted (front and rear) for providing 150 m range target tracking.” ([159], p. 9). The Team 2004-23 challenge vehicle stopping distance:

- did not exceed the 150.0 m (492.1 ft) maximum obstacle detection range of the unknown Eaton RADARs.

- exceeded the maximum effective range of RADAR sensors.

At the Team 2004-23 μ_k of 0.5, the Team 2004-23 challenge vehicle stopping distance at a speed of 45 mph was 46.0 m (151.0 ft), and would not have exceeded the 150.0 m (492.1 ft) maximum obstacle detection range of the unknown Eaton RADARs.

VIII.B.23.a.iii. Unknown cameras

Team 2004-23 stated: "With single B&W cameras we have performed lane detection with a range of 75m with a frame rate of 20 frames per second on slower machines in a system we developed for Delphi/GM in 2001. As the present vision systems are all still in development, we cannot provide exact range and latency information." ([159], p. 9). Although Team 2004-23 was unable to report a maximum obstacle detection range, the author considers it reasonable that it would equal or exceed the maximum obstacle detection range of 75 m realized several years before the 2004 GCE. The Team 2004-23 challenge vehicle stopping distance:

- exceeded the 75.0 m (246.1 ft) maximum obstacle detection range of the unknown cameras.
- exceeded the maximum effective range of VISION sensors.

VIII.B.23.b. Field-of-view limitations

VIII.B.23.b.i. Unknown Eaton RADARs

Although technical detail reported by the team technical proposal ([159]) generally conforms to manufacturer documentation, Team 2004-23 did not report the RADAR beam width reported by Eaton. All Eaton RADARs in use by teams participating in the 2004 and 2005 GCE had a field-of-view of ±6º. As a result, a field-of-view of ±6º is asserted.

At the challenge vehicle stopping distance of 77.1 m (253.0 ft), the width of the lane being actively swept by the unknown Eaton RADARs is 16.2 m (53.2 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2004-23 challenge vehicle width of 2.5 m (8.2 ft) ([159], p. 14), the maximum allowed turn radius at which the unknown Eaton RADARs would reliably detect obstacles is approximately 227.1 m (745.0 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed that 206 turns had a maximum allowed turn radius of less than 227.1 m, requiring changes in bearing ranging from -54 to 73 degrees.
- The challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been unable to detect an obstacle 0.25 m (0.83 ft) from the path of travel.

VIII.B.23.b.ii. Unknown cameras

Team 2004-23 did not report the field-of-view of the unknown cameras in use by the team.

VIII.B.24. Team 2004-24

- Team 2004-24 stated: “The top speed of the vehicle is expected to be ~25 mph.” ([161], p. 7).

- Unknown cameras, an unknown LIDAR sensor, and an unknown Eaton RADAR were in use by the team. See Table XXV.

VIII.B.24.a. Stopping distance

At the representative μ_k, the Team 2004-24 challenge vehicle stopping distance at a speed of 25 mph was 19.3 m (63.3 ft).

VIII.B.24.a.i. Unknown cameras

Team 2004-24 did not report the maximum obstacle detection range of the unknown cameras in use by the team. The Team 2004-24 challenge vehicle stopping distance:

- did not exceed the maximum effective range of VISION sensors.

VIII.B.24.a.ii. Unknown LIDAR sensor

Team 2004-24 did not report the maximum obstacle detection range of the unknown LIDAR sensor in use by the team. The Team 2004-24 challenge vehicle stopping distance:

- did not exceed the maximum effective range of short-range LIDAR sensors.

VIII.B.24.a.iii. Unknown Eaton RADAR

Team 2004-24 stated: “The Eaton VORAD radar provides tracking data on up to 20 objects. This data includes azimuth, distance and closing speed.” ([161], p. 5). However, Team 2004-24 did not report the maximum obstacle detection range of the unknown Eaton RADAR sensor in use by the team. The Team 2004-24 challenge vehicle stopping distance:

- did not exceed the maximum effective range of RADAR sensors.

VIII.B.24.b. Field-of-view limitations

VIII.B.24.b.i. Unknown cameras

Team 2004-24 did not report the field-of-view of the unknown cameras in use by the team.

VIII.B.24.b.ii. Unknown Eaton RADAR

Although technical detail reported by the team technical proposal ([161]) generally conforms to manufacturer documentation, Team 2004-24 did not report the RADAR beam width reported by Eaton. All Eaton RADARs in use by teams participating in the 2004 and 2005 GCE had a field-of-view of ±6º. As a result, a field-of-view of ±6º is asserted.

At the challenge vehicle stopping distance of 19.3 m (63.3 ft), the width of the lane being actively swept by the unknown Eaton RADAR was 4.1 m (13.3 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2004-24 challenge vehicle width of 1.8 m (6.0 ft) ([161], p. 9), the maximum allowed turn radius at which the unknown Eaton RADAR would reliably detect obstacles is approximately 166.8 m (547.4 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed that 128 turns had a maximum allowed turn radius of less than 166.8 m, requiring changes in bearing ranging from -54 to 73 degrees.

- The challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been unable to detect an obstacle 0.25 m (0.83 ft) from the path of travel.

VIII.B.25. Team 2004-25

- Team 2004-25 stated: “The top speed of the vehicle is approximately 35 miles per hour.” ([49], p. 14).

- An unknown camera, unknown SICK LIDAR sensors, and unknown Eaton RADARs were in use by Team 2004-25. See Table XXV.

VIII.B.25.a. Stopping distance

At the representative μ_k, the Team 2004-25 challenge vehicle stopping distance at a speed of 35 mph was 37.8 m (124.0 ft).

VIII.B.25.b. Unknown camera

Team 2004-25 did not report the maximum obstacle detection range of the unknown camera in use by the team. The Team 2004-25 challenge vehicle stopping distance:

- did not exceed the maximum effective range of VISION sensors.

VIII.B.25.b.i. Unknown SICK LIDAR sensors

Team 2004-25 did not report the maximum obstacle detection range of the unknown SICK LIDAR sensors in use by the team. The Team 2004-25 challenge vehicle stopping distance:

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.25.b.ii. Unknown Eaton RADARs

Team 2004-25 did not report the maximum obstacle detection range of the unknown Eaton RADARs in use by the team. The Team 2004-25 challenge vehicle stopping distance:

- did not exceed the maximum effective range of RADAR sensors.

VIII.B.25.c. Field-of-view limitations

VIII.B.25.c.i. Unknown camera

Team 2004-25 did not report field-of-view of the unknown camera in use by the team.

VIII.B.25.c.ii. Unknown Eaton RADARs

Team 2004-25 stated: “Two Eaton VORAD radar units are mounted to the front of the Challenge Vehicle, each with a horizontal field of view of approximately 14 degrees.” ([49], p. 10).

At the challenge vehicle stopping distance of 37.8 m (124.0 ft), the width of the lane being actively swept by the unknown Eaton RADARs was 9.3 m (30.5 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2004-25 challenge vehicle width of 1.4 m (4.7 ft) ([49], p. 17), the maximum allowed turn radius at which the unknown Eaton RADARs would reliably detect obstacles is approximately 95.3 m (312.7 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2004 GCE RDDF (see Chapter III.) revealed that 42 turns had a maximum allowed turn radius of less than 95.3 m, requiring changes in bearing ranging from -54 to 73 degrees.

- The challenge vehicle could have entered a constant-radius turn of 46.1 m (151.2 ft) at speed (see paragraph III.C.1.), and been unable to detect an obstacle 0.34 m (1.13 ft) from the path of travel.

VIII.B.26. Team 2005-01

- Team 2005-01 did not report challenge vehicle top speed. The 2005 GCE course-wide speed limit of 50 mph is used herein.

- An unknown AVT camera, FLIR A20M, Point Grey Bumblebee stereo camera pairs, unknown Eaton RADAR, Amphitech OASys, unknown RADAR, SICK LMS 211-30206, and unknown SICK LIDAR sensors were in use by the team. See Table XXVII.

VIII.B.26.a. Stopping distance

Team 2005-01 stated: "The range of sensors and stopping distances used by [the challenge vehicle] is displayed in Figure 4. This display indicates the sensor, number used, and each sensor's range. [Team 2005-01] has also determined the required distance to stop at specific vehicle speeds. This information is used to insure that [the challenge vehicle] always has enough time and space to complete all necessary stops." ([10], p. 9).

Via Figure 4 ("Sensing & Stopping Distances") of the team technical proposal ([10], p. 9), Team 2005-01 reported "Suggested Highway stopping distances" for speeds of 20, 30, 40, 50, and 60 mph. It is unclear if these stopping distances were calculated for the Team 2005-01 challenge vehicle on loose dirt and gravel or asphalt (dry), although Team 2005-01 referred to them as "Suggested *Highway* stopping distances" [emphasis added], implying that they were calculated for asphalt (dry).

These stopping distances correspond to a kinetic coefficient of friction ranging from 0.33 to 0.5. See paragraph VIII.A.1. and Table LIII. A stopping distance corresponding to a kinetic coefficient of friction of 0.33 was selected as representative of the worst case. At the representative μ_k, the Team 2005-01 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.26.a.i. Unknown AVT camera, FLIR A20M, and Point Grey Bumblebee stereo camera pairs

Via Figure 4 ("Sensing & Stopping Distances") of the team technical proposal ([10], p. 9), Team 2005-01 reported a maximum obstacle detection range of 45.7 m (150.0 ft) for the unknown AVT camera, FLIR A20M, and Point Grey Bumblebee stereo camera pairs in use by the team. The challenge vehicle stopping distance:

- exceeded the 45.7 m (150.0 ft) maximum obstacle detection range of the unknown AVT camera, FLIR A20M, and Point Grey Bumblebee stereo camera pairs.
- exceeded the maximum effective range of VISION sensors.

VIII.B.26.a.ii. Unknown Eaton RADAR and unknown RADAR

Via Figure 4 ("Sensing & Stopping Distances") of the team technical proposal ([10], p. 9), Team 2005-01 reported a maximum obstacle detection range of 100.6 m (330.0 ft) for the unknown Eaton RADAR and unknown RADAR in use by the team. The challenge vehicle stopping distance:

- did not exceed the 100.6 m (330.0 ft) maximum obstacle detection range of the unknown Eaton RADAR and unknown RADAR.
- exceeded the maximum effective range of RADAR sensors.

VIII.B.26.a.iii. Amphitech OASys

Via Figure 4 ("Sensing & Stopping Distances") of the team technical proposal ([10], p. 9), Team 2005-01 reported a maximum obstacle detection range of 182.9 m (600.0 ft) for the Amphitech OASys in use by the team. The challenge vehicle stopping distance:

- did not exceed the 182.9 m (600.0 ft) maximum obstacle detection range of the Amphitech OASys.
- exceeded the maximum effective range of RADAR sensors.

VIII.B.26.a.iv. SICK LMS 211-30206 and unknown SICK LIDAR sensors

Via Figure 4 ("Sensing & Stopping Distances") of the team technical proposal ([10], p. 9), Team 2005-01 reported a maximum obstacle detection range of 82.3 m (270.0 ft) for the SICK LMS 211-30206 and unknown SICK LIDAR sensors in use by the team. The challenge vehicle stopping distance:

- did not exceed the 82.3 m (270.0 ft) maximum obstacle detection range of the SICK LMS 211-30206 and unknown SICK LIDAR sensors.
- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.26.b. Field-of-view limitations

Via Figure 4 ("Sensing & Stopping Distances") of the team technical proposal ([10], p. 9), Team 2005-01 reported the field-of-view of all sensors in use by the team equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.27. Team 2005-02

- Team 2005-02 did not report challenge vehicle top speed. The 2005 GCE course-wide speed limit of 50 mph is used herein.

- SICK LMS 291-S05 LIDAR sensors and an unknown camera were in use by the team. See Table XXVII.

VIII.B.27.a. Stopping distance

At the representative μ_k, the Team 2005-02 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.27.a.i. SICK LMS 291-S05 LIDAR sensors

Team 2005-02 did not report maximum obstacle detection range for the SICK LMS 291-S05 LIDAR sensors in use by the team. The Team 2005-02 challenge vehicle stopping distance:

- exceeded the maximum effective range of short-range LIDAR sensors.

Team 2005-02 later stated the "Terrain Smart Sensor" was the primary obstacle detection sensor, and stated, in part: "...the laser scans at a distance of ~20 m ahead of the vehicle..." ([50], p. 607). This distance conforms to the maximum effective range for short-range LIDAR sensors. See paragraph VIII.A.3.

Team 2005-02 stated: "During the DARPA events, the maximum controlled velocity of the [the challenge vehicle] was 25 miles per hour; so, in the first pass, the entire path was set to a conservative 18 mph except in path segments where the RDDF speed limit was lower." ([50], p. 606), although throughout the Journal of Field Robotics ([50]) Team 2005-02 referred to an "obstacle avoidance speed" of 16 mph.

The maximum safe speed of the challenge vehicle with a maximum obstacle detection range of 20.0 m (65.6 ft) is approximately 25 mph. See Table LIII. The author considers the "maximum controlled velocity" and maximum effective range reported by Team 2005-02 validates the maximum safe speed of 25 mph based on the maximum effective range of 20.0 m (65.6 ft) for short-range LIDAR sensors. At a notional course-wide speed limit of 25 mph, a team could have completed the 2005 GCE course in 6.81 hours. See paragraph VIII.D.4.

VIII.B.27.a.ii. Unknown camera

Team 2005-02 did not report maximum obstacle detection range for the unknown camera in use by the team. The Team 2005-02 challenge vehicle stopping distance:

- exceeded the maximum effective range of VISION sensors.

VIII.B.27.b. Field-of-view limitations

Team 2005-02 did not report field-of-view for the unknown camera in use by the team.

VIII.B.28. Team 2005-03

- Team 2005-03 did not report challenge vehicle top speed. The 2005 GCE course-wide speed limit of 50 mph is used herein.

- A proprietary LIDAR sensor was in use by the team. See Table XXVII.

VIII.B.28.a. Stopping distance

At the representative μ_k, the Team 2005-03 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft). Team 2005-03 did not report the maximum obstacle detection range for the proprietary LIDAR sensor in use by the team. The challenge vehicle stopping distance:

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.28.b. Field-of-view limitations

Team 2005-03 stated: "The 64-element LADAR system has a 360-degree field of view..." ([33], p. 7). The field-of-view of the proprietary LIDAR sensor in use by the team equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.29. Team 2005-04

- Team 2005-04 did not report challenge vehicle top speed. The 2005 GCE course-wide speed limit of 50 mph is used herein.

- SICK LMS 221-30206 LIDAR sensors, an Eaton EVT-300, proprietary RADAR, and unknown stereo camera pair were in use by the team. See Table XXVII.

VIII.B.29.a. Stopping distance

At the representative μ_k, the Team 2005-04 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.29.a.i. SICK LMS 221-30206 LIDAR sensors

Via Figure 6 ("Sensor coverage") of the team technical proposal ([169], p. 9), Team 2005-04 reported a maximum obstacle detection range of 80.0 m (262.5 ft) for the SICK LMS 221-30206 LIDAR sensors in use by the team. The Team 2005-04 challenge vehicle stopping distance:

- did not exceed the 80.0 m (262.5 ft) maximum obstacle detection range of the SICK LMS 221-30206 LIDAR sensors.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.29.a.ii. Eaton EVT-300

Via Figure 6 ("Sensor coverage") of the team technical proposal ([169], p. 9), Team 2005-04 reported a maximum obstacle detection range of 110.0 m (360.9 ft) for the Eaton EVT-300 in use by the team. The Team 2005-04 challenge vehicle stopping distance:

- did not exceed the 110.0 m (360.9 ft) maximum obstacle detection range of the Eaton EVT-300.

- exceeded the maximum effective range of RADAR sensors.

VIII.B.29.a.iii. Proprietary RADAR

Via Figure 6 ("Sensor coverage") of the team technical proposal ([169], p. 9), Team 2005-04 reported a maximum obstacle detection range of 50.0 m (164.0 ft) for the proprietary RADAR in use by the team. The Team 2005-04 challenge vehicle stopping distance:

- exceeded the 50.0 m (164.0 ft) maximum obstacle detection range of the proprietary RADAR.

- exceeded the maximum effective range of RADAR sensors.

VIII.B.29.a.iv. Unknown stereo camera pair

Via Figure 6 ("Sensor coverage") of the team technical proposal ([169], p. 9), Team 2005-04 reported a maximum obstacle detection range of 45.0 m (147.6 ft) for the unknown stereo camera pair in use by the team. The Team 2005-04 challenge vehicle stopping distance:

- exceeded the 45.0 m (147.6 ft) maximum obstacle detection range of the unknown stereo camera pair.

- exceeded the maximum effective range of VISION sensors.

VIII.B.29.b. Field-of-view limitations

VIII.B.29.b.i. Proprietary RADAR and unknown stereo camera pair

Team 2005-04 did not report field-of-view for the various sensors in use by the team. However, via Figure 6 ("Sensor coverage") of the team technical proposal ([169], p. 9), Team 2005-04 included a sketch of the effective fields-of-view. Based on review of the sketch, the author concluded the field-of-view of the proprietary RADAR and unknown stereo camera pair in use by the team equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.29.b.ii. Eaton EVT-300

Team 2005-04 did not report the RADAR beam width reported by Eaton: "Monopulse: determines azimuth or angular distance of up to 20 different vehicles or objects within its 12º radar beam width." ([162]).

At the Team 2005-04 challenge vehicle stopping distance of 77.1 m (253.0 ft) the width of the lane being actively swept by the Eaton EVT-300 is 16.2 m (53.2 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2005-04 challenge vehicle width of 1.5 m (5.0 ft) ([169], p. 3), the maximum allowed turn radius at which the Eaton EVT-300 would reliably detect obstacles is approximately 139.1 m (456.4 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2005 GCE RDDF (see Chapter III.) revealed that 142 turns had a maximum allowed turn radius of less than 139.1 m, requiring changes in bearing ranging from -46 to 46 degrees.

VIII.B.30. Team 2005-05

- Team 2005-05 did not report challenge vehicle top speed. The 2005 GCE course-wide speed limit of 50 mph is used herein.

- Unknown SICK LIDAR sensors and a Mobileye ACP5 were in use by the team. See Table XXVII.

- Team 2005-05 stated one of the objectives of the path planning algorithm in use by the team was to "avoid all ladar-detected positive or negative obstacles by a distance of at least one half-truck-width" ([34], p. 11). Team 2005-05 was the only team which participated in either the 2004 or 2005 GCE to refer specifically to an obstacle avoidance distance of one-half the track width. See paragraph VIII.A.2.

VIII.B.30.a. Stopping distance

At the representative μ_k , the Team 2005-05 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.30.a.i. Unknown SICK LIDAR sensors

Team 2005-05 stated: “It is reasonable to expect these ladars to detect significant negative obstacles at up to 20 meters, and significant positive obstacles up to 80 meters away.” ([34], p. 6). The Team 2005-05 challenge vehicle stopping distance:

- did not exceed the 80.0 m (262.5 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.30.a.ii. Mobileye ACP5

Team 2005-05 did not report the maximum obstacle detection range of the Mobileye ACP5 in use by the team. The Team 2005-05 challenge vehicle stopping distance:

- exceeded the maximum effective range of VISION sensors.

VIII.B.30.b. Field-of-view limitations

VIII.B.30.b.i. Unknown SICK LIDAR sensor

Team 2005-05 stated: “At least one of these ladars on [the challenge vehicle] will be servomotor-actuated and movable to any azimuthal direction within a 180 degree arc, e.g., in the direction of a turn.” ([34], p. 5). Team 2005-05 did not report a “servomotor-actuated” LIDAR sensor was actually in use by the team during the 2005 GCE ([170]). However, Team 2005-05 was the one of three teams which participated in the 2005 GCE to refer specifically to an actuated sensor capable of detecting obstacles in the direction the challenge vehicle is turning.

The author notes that a LIDAR sensor with a 180 degree field-of-view would theoretically be able to detect obstacles between the path of travel and the center of a turning circle of arbitrary turn radius. The position and orientation of the mount point on the vehicle would determine at what height obstacles would be detected.

VIII.B.30.b.ii. Mobileye ACP5

Team 2005-05 stated: “The prototype system developed by Mobileye uses a miniature lipstick analog CCD camera with a typical 45 degree horizontal field of view..." ([34], p. 8). The field-of-view of the Mobileye ACP5 in use by the team equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.31. Team 2005-06

- Team 2005-06 did not report challenge vehicle top speed. The 2005 GCE course-wide speed limit of 50 mph is used herein.
- Unknown SICK LIDAR sensors were in use by the team. See Table XXVII.

VIII.B.31.a. Stopping distance

At the representative μ_k , the Team 2005-06 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft). Team 2005-06 stated the unknown SICK LIDAR sensors: "...are used for short range obstacle detection (up to 50 meters)." ([172], p. 9). The Team 2005-06 challenge vehicle stopping distance:

- exceeded the 50.0 m (164.0 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.
- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.31.b. Field-of-view limitations

Team 2005-06 stated: "Two Sick LMS 291 units are mounted vertically... The other Sick LMS 291 is mounted horizontally on the center of the vehicle and is used for analyzing terrain features." ([172], p. 9). However, Team 2005-06 did not report the position or orientation of the unknown LIDAR sensors in use by the team via the team technical proposal. Team 2005-06 later stated: "...we built a platform that oscillated back and forth, so that the LADAR units would scan all of the terrain in front of the vehicle repeatedly." and "We designed both oscillating mounts to cover a thirty degree range..." ([28], p. 514). At the 50.0 m (164.0 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors the width of the lane being actively swept by the unknown SICK LIDAR sensors is 26.8 m (87.9 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2005-06 challenge vehicle width of 1.8 m (5.9 ft) ([41], [42], and [43]), the maximum allowed turn radius at which the unknown SICK LIDAR sensors would reliably detect obstacles is approximately 26.4 m (86.7 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2005 GCE RDDF (see Chapter III.) revealed that 7 turns had a maximum allowed turn radius of less than 26.4 m, requiring changes in bearing ranging from -46 to 46 degrees.

Visual analysis revealed the oscillating mounts in use by Team 2005-06 were installed over the left and right track. Because the unknown SICK LIDAR sensors in use by Team 2005-06 were not mounted on the centerline of the vehicle, there was no practical field-of-view limitation during the 2005 GCE.

However, although Team 2005-06 stated the oscillating mounts: "...offered redundant coverage in the center of the path so that if one sensor failed, the vehicle could still sense obstacles most likely to be directly in its path." ([28], p. 514), if one sensor failed, the vehicle would not be able to reliably detect obstacles in the direction of a turn. Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2005-06 challenge vehicle width of 1.8 m (5.9 ft) ([41], [42], and [43]), the maximum allowed turn radius at which the unknown SICK LIDAR sensors would reliably detect obstacles is approximately 52.8 m (173.3 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2005 GCE RDDF (see Chapter III.) revealed that 38 turns had a maximum allowed turn radius of less than 52.8 m, requiring changes in bearing ranging from -46 to 46 degrees.

VIII.B.32. Team 2005-07

- The Team 2005-07 technical proposal was not available for review. See paragraph V.C.32. As a result, the 2005 GCE course-wide speed limit of 50 mph is used herein.

- Unknown SICK LIDAR sensors and unknown stereo camera pairs were in use by the team. See Table XXVII.

VIII.B.32.a. Stopping distance

At the representative μ_k , the Team 2005-07 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.32.a.i. Unknown SICK LIDAR sensors

The Team 2005-07 challenge vehicle stopping distance:

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.32.a.ii. Unknown stereo camera pairs

The Team 2005-07 challenge vehicle stopping distance:

- exceeded the maximum effective range of VISION sensors.

VIII.B.33. Team 2005-08

- Team 2005-08 did not report challenge vehicle top speed. The 2005 GCE course-wide speed limit of 50 mph is used herein.

- Riegl LMS-Q120 LIDAR sensors, SICK LMS 291-S14 and 211-30106 LIDAR sensors, Delphi Forewarn ACC3 RADARs, a Sony DFW-VL500 stereo camera pair, and unknown cameras were in use by the team. See Table XXVII.

VIII.B.33.a. Stopping distance

At the representative μ_k, the Team 2005-08 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.33.a.i. Riegl LMS-Q120 LIDAR sensors

Team 2005-08 stated: “Two Riegl Q120 LADAR units ... are mounted in the roof sensor suite with 10 and 30 meter lookahead...” ([173], p. 9). A maximum obstacle detection range of 30.0 m (98.4 ft) was selected. The Team 2005-08 challenge vehicle stopping distance:

- exceeded the 30.0 m (98.4 ft) maximum obstacle detection range of the Riegl LMS-Q120 LIDAR sensors.

- exceeded the maximum effective range of long-range LIDAR sensors.

VIII.B.33.a.ii. SICK LMS 291-S14 and 211-30106 LIDAR sensors

Team 2005-08 did not report maximum obstacle detection range of the SICK LMS 291-S14 and 211-30106 LIDAR sensors in use by the team. The Team 2005-08 challenge vehicle stopping distance:

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.33.a.iii. Delphi Forewarn ACC3 RADARs

Team 2005-08 stated: “Smart Cruise Control radars ... detect objects in the vehicle’s path up to 500 feet (152 meters) ahead.” ([173], p. 9). The Team 2005-08 challenge vehicle stopping distance:

- did not exceed the 152.4 m (500.0 ft) maximum obstacle detection range of the Forewarn ACC3 RADARs.

- exceeded the maximum effective range of RADAR sensors.

VIII.B.33.a.iv. Sony DFW-VL500 stereo camera pair and unknown cameras

Team 2005-08 did not report maximum obstacle detection range of the Sony DFW-VL500 stereo camera pair and unknown cameras in use by the team. The Team 2005-08 challenge vehicle stopping distance:

- exceeded the maximum effective range of VISION sensors.

VIII.B.33.b. Field-of-view limitations

Via Figure 6 (“Sensor position and envelopes”) of the team technical proposal ([173], p. 12), Team 2005-08 reported the fields-of-view of the Riegl LMS-Q120 LIDAR sensors, Delphi Forewarn ACC3 RADARs, Sony DFW-VL500 stereo camera pair, and unknown cameras in use by the team equaled or exceeded 40°. See paragraph VIII.A.2.

VIII.B.34. Team 2005-09

- Team 2005-09 did not report challenge vehicle top speed. The 2005 GCE course-wide speed limit of 50 mph is used herein.

- Unknown SICK LIDAR sensors were in use by the team. See Table XXVII.

VIII.B.34.a. Stopping distance

At the representative μ_k, the Team 2005-09 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft). Team 2005-09 reported the unknown SICK LIDAR sensors provided: “...two-dimensional range/distance map up to 40 meters...” ([175], p. 7). The Team 2005-09 challenge vehicle stopping distance:

- exceeded the 40.0 m (131.2 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.35. Team 2005-10

- Team 2005-10 stated: “We said in our application video ... that we had tested [the challenge vehicle] to 35 mph and that we hoped to test to 65 mph by the end of July. We have recently allowed the [the challenge vehicle] to drive at 75 mph for 2 miles in fully autonomous mode and it did so successfully.” ([176], p. 6). The 2005 GCE course-wide speed limit of 50 mph is used herein.

- Unknown SICK LIDAR sensors, Cognex DVT 542C cameras, an unknown stereo camera pair, and Optech ILRIS-3D were in use by the team. See Table XXVII.

VIII.B.35.a. Stopping distance

At the representative μ_k , the Team 2005-10 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.35.a.i. Unknown SICK LIDAR sensors

Team 2005-10 stated: "...their effective range is approximately 30 meters." ([176], p. 3). The Team 2005-10 challenge vehicle stopping distance:

- exceeded the 30.0 m (98.4 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.
- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.35.a.ii. Cognex DVT 542C cameras

Team 2005-10 stated: "...effective range is approximately 40 meters." ([176], p. 3). The Team 2005-10 challenge vehicle stopping distance:

- exceeded the 40.0 m (131.2 ft) maximum obstacle detection range of the Cognex DVT 542C cameras.
- exceeded the maximum effective range of VISION sensors.

VIII.B.35.a.iii. Unknown stereo camera pair

Team 2005-10 stated: "...its range is approximately 35 meters." ([176], p. 3). The Team 2005-10 challenge vehicle stopping distance:

- exceeded the 35.0 m (114.8 ft) maximum obstacle detection range of the unknown stereo camera pair.
- exceeded the maximum effective range of VISION sensors.

VIII.B.35.a.iv. Optech ILRIS-3D

Team 2005-10 stated: "...its range is approximately 500 meters." ([176], p. 3). The Team 2005-10 challenge vehicle stopping distance:

- did not exceed the 500.0 m (1640.4 ft) maximum obstacle detection range of the Optech ILRIS-3D.
- exceeded the maximum effective range of long-range LIDAR sensors.

VIII.B.35.b. Field-of-view limitations

VIII.B.35.b.i. Cognex DVT 542C cameras

Team 2005-10 stated: “Their field of view is 30 degrees...” ([176], p. 3). At the 40.0 m (131.2 ft) maximum obstacle detection range of the Cognex DVT 542C cameras the width of the lane being actively swept by the Cognex DVT 542C cameras is 21.4 m (70.3 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the Team 2005-10 challenge vehicle width of 1.8 m (5.9 ft) ([41], [42], and [43]), the maximum allowed turn radius at which the Cognex DVT 542C cameras would reliably detect obstacles is approximately 26.4 m (86.7 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2005 GCE RDDF (see Chapter III.) revealed that 7 turns had a maximum allowed turn radius of less than 26.4 m, requiring changes in bearing ranging from -46 to 46 degrees.

VIII.B.35.b.ii. Unknown stereo camera pair

Team 2005-10 stated: “Its field of view is 45 degrees...” ([176], p. 3). The field-of-view of the unknown stereo camera pair equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.35.b.iii. Optech ILRIS-3D

Team 2005-10 stated: “Its field of view is 40 degrees...” ([176], p. 3). The field-of-view of the Optech ILRIS-3D equaled or equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.36. Team 2005-11

- Team 2005-11 did not report challenge vehicle top speed. The 2005 GCE course-wide speed limit of 50 mph is used herein.

- Unknown SICK LIDAR sensors were in use by the team. See Table XXVII.

VIII.B.36.a. Stopping distance

At the representative μ_k, the Team 2005-11 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft). Team 2005-11 did not report the maximum obstacle detection range of the unknown SICK LIDAR sensors in use by the team. The Team 2005-11 challenge vehicle stopping distance:

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.37. Team 2005-12

- Team 2005-12 did not report challenge vehicle top speed. The 2005 GCE course-wide speed limit of 50 mph is used herein.

- A Point Grey Bumblebee stereo camera pair was in use by the team. See Table XXVII.

VIII.B.37.a. Stopping distance

At the representative μ_k, the Team 2005-12 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft). Team 2005-12 stated: "Obstacles can be reliably detected at 50ft..." ([185], p. 5). The Team 2005-12 challenge vehicle stopping distance:

- exceeded the 15.2 m (50.0 ft) maximum obstacle detection range of the Bumblebee stereo camera pair.

- exceeded the maximum effective range of VISION sensors.

VIII.B.37.b. Field-of-view limitations

Team 2005-12 stated: "Obstacles can be reliably detected ... with a horizontal field of view of 70º." ([185], p. 5). The field-of-view of the Point Grey Bumblebee stereo camera pair equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.38. Teams 2005-13 and 2005-14

- Team 2005-13 reported "peak speeds" of 54 mph ([11], p. 2) and 38.2 mph ([11], p. 15), and "reliable obstacle avoidance" at 35 mph ([11], p. 2). Team 2005-14 reported "peak speeds" of 40 mph ([12], p. 2) and 38.2 mph ([12], p. 2), and "reliable obstacle avoidance" at 35 mph ([12], p. 2). The "reliable obstacle avoidance" speed of 35 mph is used herein.

- A Riegl LMS-Q140i, unknown SICK LIDAR sensors, and a Navtech DS2000 were in use by the teams. See Table XXVII.

VIII.B.38.a. Stopping distance

At the representative μ_k, the challenge vehicle stopping distance at a speed of 35 mph was 37.8 m (124.0 ft).

VIII.B.38.a.i. Riegl LMS-Q140i

Teams 2005-13 and 2005-14 reported a maximum obstacle detection range for the Riegl LMS-Q140i of 150.0 m (492.1 ft) ([11], p. 7 and [12], p. 8). The challenge vehicle stopping distance:

- did not exceed the 150.0 m (492.1 ft) maximum obstacle detection range of the Riegl LMS-Q140i.
- did not exceed the maximum effective range of long-range LIDAR sensors.

VIII.B.38.a.ii. Unknown SICK LIDAR sensors

Teams 2005-13 and 2005-14 reported a maximum obstacle detection range for the unknown SICK LIDAR sensors of 50.0 m (164.0 ft) ([11], p. 8 and [12], p. 8). The challenge vehicle stopping distance:

- did not exceed the 50.0 m (164.0 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.
- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.38.a.iii. Navtech DS2000

Teams 2005-13 and 2005-14 reported a maximum obstacle detection range for the Navtech DS2000 of 70.0 m (229.7 ft) ([11], p. 8 and [12], p. 8). The challenge vehicle stopping distance:

- did not exceed the 70.0 m (229.7 ft) maximum obstacle detection range of the Navtech DS2000.
- did not exceed the maximum effective range of RADAR sensors.

The author notes that Teams 2005-13 and 2005-14 reported a minimum obstacle detection range for the Navtech DS2000 of 40.0 m (131.2 ft) ([11], p. 8 and [12], p. 8).

VIII.B.38.b. Field-of-view limitations

VIII.B.38.b.i. Riegl LMS-Q140i

Teams 2005-13 and 2005-14 reported field-of-view of 60º for the Riegl LMS-Q140i ([11], p. 7 and [12], p. 8). The field-of-view of the Riegl LMS-Q140i equaled or exceeded 40º. See paragraph VIII.A.2.

Teams 2005-13 and 2005-14 were two of three teams which participated in the 2005 GCE to refer specifically to an actuated sensor capable of detecting obstacles in the direction the challenge vehicle is turning. Teams 2005-13 and 2005-14 stated: "The effective field of view with pointing is 240 degrees (180 degree gimbal yaw plus 60 degree laser scanner field-of-view)..." ([11], p. 7 and [12], p. 8).

VIII.B.38.b.ii. Navtech DS2000 RADAR

Teams 2005-13 and 2005-14 stated: "The 360 degree RADAR used for obstacle detection is mounted on the brush guard. Most of the RADAR's scan is obscured by the vehicle or brush guard. Its effective field of view is 70 degrees..." ([11], p. 8 and [12], p. 8). The field-of-view of the Navtech DS2000 equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.39. Team 2005-15

- Team 2005-15 stated: "The top speed of the vehicle is 55 MPH in 4-wheel drive." ([53], p. 8). The 2005 GCE course-wide speed limit of 50 mph is used herein.
- Unknown SICK LIDAR sensors and a proprietary stereo camera pair were in use by the team. See Table XXVII.

VIII.B.39.a. Stopping distance

At the representative μ_k , the Team 2005-15 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.39.a.i. Unknown SICK LIDAR sensors

Team 2005-15 stated: "The maximum look-ahead distance of these sensors is 80 m." ([53], p. 9). The Team 2005-15 challenge vehicle stopping distance:

- did not exceed the 80.0 m (262.5 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.
- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.39.a.ii. Proprietary stereo camera pair

Team 2005-15 stated: "As a mid-range (10 m < R <20m) obstacle sensing system, a stereo vision system ... is used. It detects object [*sic*] up to a distance of 25 m..." ([53], p. 9). A maximum obstacle detection range of 25.0 m (82.0 ft) is used herein. The Team 2005-15 challenge vehicle stopping distance:

- exceeded the 25.0 m (82.0 ft) maximum obstacle detection range of the proprietary stereo camera pair.
- exceeded the maximum effective range of VISION sensors.

VIII.B.39.b. Field-of-view limitations

VIII.B.39.b.i. Proprietary stereo camera pair

Team 2005-15 did not report field-of-view of the proprietary stereo camera pair in use by the team.

VIII.B.40. Team 2005-16

- Team 2005-16 reported a "top speed" of 42 mph and "Waypoint navigation at 35 mph" ([195], p. 13). The waypoint navigation speed of 35 mph is used herein.
- Unknown SICK LIDAR sensors and an unknown camera were in use by the team. See Table XXVII.

VIII.B.40.a. Stopping distance

At the representative μ_k , the Team 2005-16 challenge vehicle stopping distance at a speed of 35 mph was 37.8 m (124.0 ft).

VIII.B.40.a.i. Unknown SICK LIDAR sensors

Team 2005-16 stated: "The laser system provides accurate short-range perception, up to a range of approximately 25 meters." ([195], p. 6). The Team 2005-16 challenge vehicle stopping distance:

- exceeded the 25.0 m (82.0 ft) range of the unknown SICK LIDAR sensors.
- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.40.a.ii. Unknown camera

Team 2005-16 did not report maximum obstacle detection range for the unknown camera in use by the team, and alternately stated: "The camera provides an enhanced range relative to the laser..." and "...the camera does not provide range data." ([195], p. 7). The Team 2005-16 challenge vehicle stopping distance:

- did not exceed the maximum effective range of VISION sensors.

VIII.B.40.b. Field-of-view limitations

VIII.B.40.b.i. Unknown camera

Team 2005-16 did not report field-of-view for the unknown camera in use by the team.

VIII.B.41. Team 2005-17

- Team 2005-17 stated: "...[the challenge vehicle's] top speed is around 25 miles/hour." ([140], p. 11).

- Unknown SICK LIDAR sensors were in use by the team. See Table XXVII.

VIII.B.41.a. Stopping distance

At the representative μ_k, the Team 2005-17 challenge vehicle stopping distance at a speed of 25 mph was 19.3 m (63.3 ft). Team 2005-17 reported five SICK LIDAR sensors were in use by the team, and stated: "Three of these sensors are mounted on the front of the vehicle looking at a distance of 25m, 29m, and 30m along the direction of the vehicle's motion. The remaining two sensors are mounted on the left and right of the vehicle, scanning from 3m from the 'shoulder' of the vehicle to 30m in front of the 'nose'." ([140], p. 5). However, the author concluded two unknown SICK LIDAR sensors, in lieu of the five reported by Team 2005-17 via the team technical proposal, were in use by the team. See paragraph V.C.41.a.

Team 2005-17 later stated: "The top lidar was aimed at 25 m in front of the robot, whereas the bottom lidar was aimed at 7 m in front of the robot." ([196], p. 575). A maximum obstacle detection range of 25.0 m (82.0 ft) was selected. The Team 2005-17 challenge vehicle stopping distance:

- did not exceed the 25.0 m (82.0 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.

- did not exceed the maximum effective range of short-range LIDAR sensors.

VIII.B.42. Team 2005-18

- Team 2005-18 reported an expected maximum speed of 40 mph ([197], p. 5).

- SICK LMS 221-30206, 291-S14, and 291-S05 LIDAR sensors, a Riegl LMS-Q120i, and Point Grey Dragonfly cameras were in use by the team. See Table XXVII.

VIII.B.42.a. Stopping distance

At the representative μ_k, the Team 2005-18 challenge vehicle stopping distance at a speed of 40 mph was 49.4 m (162.0 ft).

VIII.B.42.a.i. SICK LMS 221-30206, 291-S14, and 291-S05 LIDAR sensors

Team 2005-18 reported maximum obstacle detection ranges of 30 and 80 m via the team technical proposal ([197], p. 10). Via Table II ("Sensors used on [the challenge vehicle]”) of the Journal of Field Robotics ([54], p. 790), Team 2005-18 reported maximum obstacle detection ranges of 3, 20, 35, and 80 m for the various LIDAR sensors in use by the team. Team 2005-18 stated: “...in race configuration, the forward facing bumper LADAR sensor was only used to assist in the detection of the boundaries of the roads for the road-following module.” ([54], p. 808). It is unclear if the “forward facing bumper LADAR sensor” was mounted horizontally with a range of 80.0 m, or “pointed 3 m away”, however Team 2005-18 stated: “One of these LADAR units is enclosed in the front bumper, providing reliable detection of large obstacles independent of range.” ([197], p. 10). As a result, the author concluded the maximum obstacle detection range of the various LIDAR sensors in use by the team was 80.0 m (262.5 ft). The Team 2005-18 challenge vehicle stopping distance:

- did not exceed the 80.0 m (262.5 ft) maximum obstacle detection range of the various LIDAR sensors.
- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.42.a.ii. <u>Riegl LMS-Q120i</u>

Team 2005-18 stated: “We have also mounted a Reigl [*sic*] LMS Q-120i LADAR on Alice... This LADAR is be pointed [*sic*] out at approximately 65 meters...” ([197], p. 10). The Team 2005-18 challenge vehicle stopping distance:

- did not exceed the 65.0 m (213.3 ft) maximum obstacle detection range of the Riegl LMS-Q120i.
- exceeded the maximum effective range of long-range LIDAR sensors.

VIII.B.42.a.iii. <u>Point Grey Dragonfly cameras</u>

Team 2005-18 did not report maximum obstacle detection range for the Point Grey Dragonfly cameras in use by the team. The Team 2005-18 challenge vehicle stopping distance:

- did not exceed the maximum effective range of VISION sensors.

VIII.B.42.b. <u>Field-of-view limitations</u>

Team 2005-18 did not report field-of-view of the Riegl LMS-Q120i and Point Grey Dragonfly cameras in use by the team.

VIII.B.43. Team 2005-19

- Team 2005-19 did not report challenge vehicle top speed. The 2005 GCE course-wide speed limit of 50 mph is used herein.

- Unknown SICK LIDAR sensors were in use by the team. See Table XXVII.

VIII.B.43.a. Stopping distance

At the representative μ_k, the Team 2005-19 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft). Team 2005-19 reported the unknown SICK LIDAR sensors were "nominally capable of returning up to 80 meter ranges" ([55], p. 5). The Team 2005-19 challenge vehicle stopping distance:

- did not exceed the 80.0 m (262.5 ft) maximum obstacle detection range of the unknown SICK LIDAR sensors.

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.44. Team 2005-20

- Team 2005-20 stated: "[The challenge vehicle] travels at speeds up to 60 mph..." ([56], p. 2). The 2005 GCE course-wide speed limit of 50 mph is used herein.

- An indeterminate number of unknown LIDAR sensor(s), unknown RADAR(s), and unknown stereo camera pair(s) were in use by the team. See Table XXVII.

VIII.B.44.a. Stopping distance

Team 2005-20 stated: "The estimated stopping distance under disable emergency stop at a the top speed of 60 mph is less than 175 ft from signal to final stop." ([56], p. 10). The stopping distance corresponds to a kinetic coefficient of friction of approximately 0.7. See Table LIII. However, Team 2005-20 did not report the estimated stopping distance was confirmed by the team on surfaces similar to those expected to be encountered during the 2005 GCE. As a result, a stopping distance corresponding to a speed of 50 mph and kinetic coefficient of friction of 0.33 is used herein in lieu of the top speed and estimated stopping distance reported by Team 2005-20. At the representative μ_k, the Team 2005-20 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.44.a.i. Unknown LIDAR sensor(s)

Via Table 1 ("Sensor Allocations") of the team technical proposal ([56], p. 11), Team 2005-20 reported a maximum obstacle detection range of 61.0 m (200.0 ft) for the unknown LIDAR sensor(s) in use by the team. The Team 2005-20 challenge vehicle stopping distance:

- exceeded the 61.0 m (200.0 ft) maximum obstacle detection range of the unknown LIDAR sensor(s).

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.44.a.ii. Unknown RADAR(s)

Via Table 1 ("Sensor Allocations") of the team technical proposal ([56], p. 11), Team 2005-20 reported a maximum obstacle detection range of greater than 61.0 m (200.0 ft) for the unknown RADAR(s) in use by the team. Via Figure 3 ("Sensor Arrangement and Range") of the team technical proposal ([56], p. 11), Team 2005-20 reported a maximum obstacle detection range of 121.9 m (400.0 ft) for the unknown RADAR(s) in use by the team. A maximum obstacle detection range of 121.9 m (400.0 ft) was selected. The Team 2005-20 challenge vehicle stopping distance:

- did not exceed the 121.9 m (400.0 ft) maximum obstacle detection range of the unknown RADAR(s).
- exceeded the maximum effective range of RADAR sensors.

VIII.B.44.a.iii. Unknown stereo camera pair(s)

Via Table 1 ("Sensor Allocations") of the team technical proposal ([56], p. 11), Team 2005-20 reported a maximum obstacle detection range of 61.0 m (200.0 ft) for the unknown stereo camera pair(s) in use by the team. The Team 2005-20 challenge vehicle stopping distance:

- exceeded the 61.0 m (200.0 ft) maximum obstacle detection range of the unknown stereo camera pair(s).
- exceeded the maximum effective range of VISION sensors.

VIII.B.44.b. Field-of-view limitations

VIII.B.44.b.i. Unknown RADAR(s)

Via Table 1 ("Sensor Allocations") of the team technical proposal ([56], p. 11), Team 2005-20 reported field-of-view of 12º for the unknown RADAR in use by the team. Team 2005-20 did not report challenge vehicle width via the team technical proposal ([56]). Although Team 2005-20 participated in the 2004 GCE as Team 2004-18, the Team 2004-18 challenge vehicle was based on a different platform. As a result, the author estimated the width of the Team 2005-20 challenge vehicle as 2.0 m.

At the Team 2005-20 challenge vehicle stopping distance of 77.1 m (253.0 ft) the width of the lane being actively swept by the unknown RADAR(s) is 16.2 m (53.2 ft). Using the relationship identified in paragraph VIII.A.2. the author was able to determine:

- Based on the estimated Team 2005-20 challenge vehicle width of 2.0 m (6.6 ft), the maximum allowed turn radius at which the unknown RADAR(s) would reliably detect obstacles is approximately 182.5 m (598.8 ft). Review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2005 GCE RDDF (see Chapter III.) revealed that 193 turns had a maximum allowed turn radius of less than 182.5 m, requiring changes in bearing ranging from -46 to 46 degrees.

VIII.B.44.b.ii. Unknown stereo camera pair(s)

Via Table 1 ("Sensor Allocations") of the team technical proposal ([56], p. 11), Team 2005-20 reported field-of-view of 43º for the unknown stereo camera pair(s) in use by the team. The field-of-view of the unknown stereo camera pair(s) equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.45. Team 2005-21

- Team 2005-21 stated: "[The challenge vehicle] has a top speed of 65 mph..." ([160], p. 2). The 2005 GCE course-wide speed limit of 50 mph is used herein.

- Unknown SICK LIDAR sensors, an unknown Ibeo LIDAR sensor, and unknown cameras were in use by the team. See Table XXVII.

VIII.B.45.a. Stopping distance

At the representative μ_k, the Team 2005-21 challenge vehicle stopping distance at a speed of 50 mph was 77.1 m (253.0 ft).

VIII.B.45.a.i. Unknown SICK LIDAR sensors

Team 2005-21 did not report maximum obstacle detection range of the unknown SICK LIDAR sensors in use by the team. The Team 2005-21 challenge vehicle stopping distance:

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.45.a.ii. Unknown Ibeo LIDAR sensor

Team 2005-21 reported a maximum obstacle detection range of 80.0 m (262.5 ft) for the unknown Ibeo LIDAR sensor in use by the team ([160], p. 10). The Team 2005-21 challenge vehicle stopping distance:

- did not exceed the 80.0 m (262.5 ft) maximum obstacle detection range of the unknown Ibeo LIDAR sensor.

- exceeded the maximum effective range of long-range LIDAR sensors.

VIII.B.45.a.iii. Unknown cameras

Team 2005-21 did not report maximum obstacle detection range for the unknown cameras in use by the team. The Team 2005-21 challenge vehicle stopping distance:

- exceeded the maximum effective range of VISION sensors.

VIII.B.45.b. Field-of-view limitations

VIII.B.45.b.i. Unknown Ibeo LIDAR sensor

Team 2005-21 reported a "240-degree scan area" for the unknown Ibeo LIDAR sensor in use by the team ([160], p. 10). The field-of-view of the unknown Ibeo LIDAR sensor equaled or exceeded 40º. See paragraph VIII.A.2.

VIII.B.45.b.ii. Unknown cameras

Team 2005-21 did not report field-of-view for the unknown cameras in use by the team.

VIII.B.46. Team 2005-22

- Team 2005-22 reported a "top speed of 25mph" ([58], p. 2).
- An unknown SICK LIDAR sensor and a Point Grey Bumblebee stereo camera pair were in use by the team. See Table XXVII.

VIII.B.46.a. Stopping distance

At the representative μ_k , the Team 2005-22 challenge vehicle stopping distance at a speed of 25 mph was 19.3 m (63.3 ft).

VIII.B.46.a.i. Unknown SICK LIDAR sensor

Team 2005-22 stated: "The advertised range of the [unknown SICK LIDAR sensor] is 80m, but [the challenge vehicle's] software only uses LIDAR data at a maximum range of 40m." ([58], p. 6). The Team 2005-22 challenge vehicle stopping distance:

- did not exceed the 40.0 m (131.2 ft) maximum obstacle detection range of the unknown SICK LIDAR sensor.
- did not exceed the maximum effective range of short-range LIDAR sensors.

VIII.B.46.a.ii. Point Grey Bumblebee stereo camera pair

Team 2005-22 stated: “The Bumblebee is capable of processing image points to a range of 30-40m...” ([58], p. 6). The Team 2005-22 challenge vehicle stopping distance:

- did not exceed the 40.0 m (131.2 ft) maximum obstacle detection range of the Point Grey Bumblebee stereo camera pair.
- did not exceed the maximum effective range of VISION sensors.

VIII.B.46.b. Field-of-view limitations

Team 2005-22 did not report field-of-view for the Point Grey Bumblebee stereo camera pair in use by the team.

VIII.B.47. Team 2005-23

- Team 2005-23 reported a “top speed of 25mph” ([164], p. 2).
- Unknown SICK LIDAR sensors and a Point Grey Bumblebee stereo camera pair were in use by the team. See Table XXVII.

VIII.B.47.a. Stopping distance

At the representative μ_k, the Team 2005-23 challenge vehicle stopping distance at a speed of 25 mph was 19.3 m (63.3 ft).

VIII.B.47.a.i. Unknown SICK LIDAR sensors

Team 2005-23 did not report maximum obstacle detection range for the unknown SICK LIDAR sensors in use by the team. The Team 2005-23 challenge vehicle stopping distance:

- did not exceed the maximum effective range of short-range LIDAR sensors.

VIII.B.47.a.ii. Point Grey Bumblebee stereo camera pair

Team 2005-23 did not report maximum obstacle detection range for the Point Grey Bumblebee stereo camera pair in use by the team. The Team 2005-23 challenge vehicle stopping distance:

- did not exceed the maximum effective range of VISION sensors.

VIII.B.47.b. Field-of-view limitations

Team 2005-23 did not report field-of-view for the Point Grey Bumblebee stereo camera pair in use by the team.

VIII.C. Results

Tabulated results are presented by Tables LV, LVI, LVII, LVIII, LIX, and LX. Summarized results are presented by Tables LXI, LXII, LXIII, and LXIV.

The author calculated the average ratio of stopping distance to range for sensors in use by teams which participated in both the 2004 and 2005 GCE based on both maximum obstacle detection range and maximum effective range. This value is referred to herein as the "average range ratio".

VIII.C.1. 2004

Overall:

- No team which participated in the 2004 QID and GCE did not report challenge vehicle top speed.
- Teams did not report maximum obstacle detection range for 14 of 71 sensors (20 percent).
- Challenge vehicle stopping distance exceeded the maximum obstacle detection range of 34 of 71 sensors (48 percent). The average range ratio was 1.61, corresponding to an average stopping distance 1.61 times greater than the average maximum obstacle detection range. See Table LXI.
- Challenge vehicle stopping distance exceeded the maximum effective range of 46 of 66 sensors (70 percent). The average range ratio was 1.88, corresponding to an average stopping distance 1.88 times greater than the average maximum effective range. See Table LXII.
- Twenty-three of 25 teams (92 percent) reported at least one sensor with a field-of-view which equaled or exceeded 40º. See paragraph VIII.A.2. Although Team 2004-06 did not report field-of-view for the proprietary stereo camera pair in use by the team (see paragraph VIII.B.6.b.) and Team 2004-08 did not report field-of-view for the Cohu 1330 cameras in use by the team (see paragraph VIII.B.8.b.iii.), the author considers it likely the field-of-view of these sensors equaled or exceeded 40º.

Several teams reported a top speed corresponding to a stopping distance between the maximum effective ranges for the various sensors in use by the team: Teams 2004-01, 2004-07, 2004-10, 2004-14, 2004-16, 2004-17, 2004-19, 2004-20, and 2004-25. For example:

Prior to the 2004 GCE, Team 2004-10 stated: “The vehicle has a top speed adequate to complete the prescribed course within the allotted duration.” ([77], p. 6). After the 2004 GCE, Team 2004-10 reported a “peak speed” of 36 mph during the 2004 GCE ([39], p. 31). The maximum speed realized by the Team 2004-10 challenge vehicle during the 2004 GCE corresponded to a stopping distance which exceeded both the maximum obstacle detection range and maximum effective range of the unknown SICK LIDAR sensors in use by the team, but not the Riegl LMS-Q140i in use by the team. The author considers it likely this was intentional.

Challenge vehicle stopping distance was between the maximum obstacle detection range and maximum effective range of sensors in use by Teams 2004-14 and 2004-20. As a result, the author reviewed team performance during the 2004 QID and GCE to evaluate this pattern.

Teams 2004-01, 2004-19, and 2004-20 were not selected to participate in the 2004 GCE. Four of the remaining six teams were among the top five teams in terms of 2004 GCE course length completed: Teams 2004-10, 2004-14, 2004-07, and 2004-17. The only team in the top five which was not represented was Team 2004-06. A single proprietary stereo camera pair was in use by Team 2004-06; multiple sensors with different ranges were not in use by the team.

The author determined that challenge vehicle stopping distance exceeded the maximum obstacle detection range of:

- all sensors for 10 of 23 (43 percent),
- one or more sensors for seven of 23 (30 percent), and
- no sensors for six of 23 (26 percent)

teams which participated in the 2004 QID and GCE. See Table LXIII.

The author determined that challenge vehicle stopping distance exceeded the maximum effective range of:

- all sensors for 14 of 25 (56 percent),
- one or more sensors for nine of 25 (36 percent), and
- no sensors for two of 25 (8 percent)

teams which participated in the 2004 QID and GCE. See Table LXIV.

Only one team which participated in the 2004 QID and GCE reported a challenge vehicle top speed corresponding to a stopping distance which did not exceed both the maximum obstacle detection range and maximum effective range of all sensors in use by the team: Team 2004-03. On the day of the 2004 GCE, Team 2004-03 officially withdrew prior to start ([30]).

Team 2004-24 reported a challenge vehicle top speed corresponding to a stopping distance which did not exceed the maximum effective range of all sensors in use by the team. However, Team 2004-24 did not report the maximum obstacle detection range of the sensors in use by the team.

All teams which relied on a single sensor for obstacle detection reported a challenge vehicle top speed corresponding to a stopping distance which exceeded the maximum effective range of the sensor in use by the team: Teams 2004-06, 2004-12, 2004-21, and 2004-22.

VIII.C.2. 2005

Overall:

- Eleven of 23 teams (48 percent) which participated in the 2005 GCE did not report challenge vehicle top speed. As a result, a stopping distance corresponding to the 2005 GCE course-wide speed limit of 50 mph was selected.

- Teams did not report maximum obstacle detection range for 17 of 60 sensors (28 percent).

- Challenge vehicle stopping distance exceeded the maximum obstacle detection range of 16 of 60 sensors (27 percent). The average range ratio was 1.16, corresponding to an average stopping distance 1.16 times greater than the average maximum obstacle detection range. See Table LXI.

- Challenge vehicle stopping distance exceeded the maximum effective range of 49 of 60 sensors (82 percent). The average range ratio was 2.31, corresponding to an average stopping distance 2.31 times greater than the average maximum effective range. See Table LXII.

- Twenty-two of 23 teams (96 percent) reported at least one sensor with a field-of-view which equaled or exceeded 40º. See paragraph VIII.A.2. The unknown SICK LIDAR sensors in use by Team 2005-06 had a field-of-view of ±15 degrees. However, visual analysis revealed the oscillating mounts in use by Team 2005-06 were installed over the left and right track. Because the unknown SICK LIDAR sensors in use by Team 2005-06 were not mounted on the centerline of the vehicle, there was no practical field-of-view limitation during the 2005 GCE. See paragraph VIII.B.31.b.

When the author reviewed team performance during the 2005 GCE to evaluate the pattern discussed in paragraph VIII.C.1., he noted that several teams reported a maximum obstacle detection range exceeding the maximum obstacle detection range reported for the same sensors in use by the team during the 2004 QID and GCE. For example: Team 2005-01 participated in the 2004 QID and GCE as Team 2004-02. Team 2005-01 reported a maximum obstacle detection range of 82.3 m for the SICK LMS 211-30206 in use by the team (see paragraph VIII.B.26.a.iv.), however Team 2004-02 reported a maximum obstacle detection range of 30.0 m for the same sensor (see paragraph VIII.B.2.a.i.). The author considers it unlikely Team 2005-01 more than quadrupled the maximum effective range of short-range LIDAR sensors in use by the team.

In addition, almost one-half (48 percent) of teams participating in the 2005 GCE did not report challenge vehicle top speed, and five teams did not report maximum obstacle detection range for any sensors in use by the team.

As a result, the author concluded it would not be possible to realistically determine for which teams challenge vehicle stopping distance did not exceed both maximum obstacle detection range and maximum effective range of the various sensors in use by the team.

However, the author calculated the average range ratio for teams which participated in both the 2004 and 2005 GCE based on maximum obstacle detection range and maximum effective range. See Table LXV. See paragraph VIII.C.3.

The author determined that challenge vehicle stopping distance exceeded the maximum obstacle detection range of:

- all sensors for four of 18 (22 percent),
- one or more sensors for six of 18 (33 percent), and
- no sensors for eight of 18 (44 percent)

teams which participated in the 2005 GCE. See Table LXIII.

The author determined that challenge vehicle stopping distance exceeded the maximum effective range of:

- all sensors for 16 of 23 (70 percent),
- one or more sensors for four of 23 (17 percent), and
- no sensors for three of 23 (13 percent)

teams which participated in the 2005 GCE. See Table LXIV.

VIII.C.3. Comparison of 2004 results to 2005 results

The author calculated the average range ratio for sensors in use by teams which participated in both the 2004 and 2005 GCE to determine if there was an overall reduction between the 2004 and 2005 GCE based on the maximum obstacle detection range, which was the maximum theoretical range, and the maximum effective range, which was the maximum observed range.

The average range ratio based on the maximum obstacle detection range decreased between the 2004 and 2005 GCE from 1.55 to 0.90. However, the average range ratio based on the maximum effective range increased between the 2004 and 2005 GCE from 1.88 to 2.07. See Table LXV.

VIII.C.4. Effect of the representative kinetic coefficient of friction

The author selected a μ_k of 0.33 as representative. Realistically, μ_k was different for each challenge vehicle due to a number of factors such as reaction time and tire selection. As a result, it is possible that the real stopping distances of some challenge vehicles was less than the stopping distance calculated using the representative μ_k, or that the relationship between stopping distance and velocity was not adequately described by the equation given in paragraph VIII.A.1.

Teams participating in the 2004 and 2005 GCE would have had to experimentally determine μ_k for their challenge vehicles under similar off-road conditions to be able to evaluate the effect of maximum obstacle detection range and maximum effective range. However, only one team which participated in the 2004 or 2005 GCE experimentally determined μ_k for their challenge vehicle: Team 2004-23 (see paragraph VIII.B.23.a.). The μ_k experimentally determined by Team 2004-23 under off-road conditions corresponds to the value initially selected by the author based on the best "fit" between Table LIII and values given by Table II ("Stopping Distances") of the Code of Federal Regulations ([228]) for "vehicles other than passenger cars with GVWR of less than 8,000 lbs" and "vehicles with GVWR of not less than 8,000 lbs and not more than 10,000 lbs".

Several teams reported estimated stopping distances for their challenge vehicles: Teams 2004-01 (see paragraph VIII.B.1.), 2004-23 (see paragraph VIII.B.23.), Team 2005-01 (see paragraph VIII.B.26.), and Team 2005-20 (see paragraph VIII.B.44.). However, the estimated stopping distances reported generally corresponded with a μ_k greater than the representative μ_k, and were therefore not typical of road surfaces encountered during the 2004 or 2005 GCE.

VIII.C.5. Effect of slope

There was significant difference in observed slope between waypoints for the 2004 and 2005 GCE courses. See paragraph II.C.7.b.

One of the consequences of the reduction in the number of miles of slope greater than five degrees was an overall "flattening" of the course, making it easier for long-range sensors such as VISION sensors and RADAR to detect obstacles at ranges consistent with challenge vehicle stopping distances, and ultimately increasing the speed at which challenge vehicles were able to travel.

VIII.C.6. Effect of reaction time

As noted above, a value of μ_k of 0.33 was selected as representative to compensate for the effect of reaction time. However, reaction time will vary for each challenge vehicle according to the challenge vehicle's controlling intelligence.

VIII.C.7. Effect of tire selection

Although at least one team reported Mattracks treads were in use by the team: Team 2004-21 ([155]), the majority reported tires suitable for the off-road conditions typical of the 2004 and 2005 GCE course were in use. Team technical proposals referred to "off-road", "mud terrain", "off-road racing", "pneumatic", "standard", "rubber", "ATV style", and "all-terrain" tires; some referred to manufacturer-specific information, such as "Mickey Thompson Baja Claw Radial" and "BF Goodrich Baja T/A KR (Kevlar-belted)"; and others referred simply to "tires" or make no reference to the type of tires in use by the team. The phrase "off-road tires" is used herein.

Because different off-road tires were in use by each team and the suspension, chassis, and weight distribution of each challenge vehicle were unique, μ_k will be different for each challenge vehicle. On a paved surface the differences might be readily apparent. However, because loose dirt and gravel result in a surface more prone to slippage road condition is expected to have more of an impact on μ_k than tire selection, if off-road tires were in use.

VIII.C.8. Effects of anti-lock brakes

Seventeen teams which participated in the 2004 and 2005 GCE selected a commercially-available SUV or truck as challenge vehicle platform. See Table XIV. Several teams reported the vehicle selected as challenge vehicle platform had anti-lock brakes. The effects of anti-lock brakes were not considered in this analysis.

VIII.D. Conclusions

VIII.D.1. Stopping distance

Review of the published record supports a conclusion that the number of sensors for which stopping distance exceeded maximum obstacle detection range decreased between the 2004 QID and GCE and the 2005 GCE from 48 to 27 percent. However, this is misleading because it is based on the maximum obstacle detection range reported by the teams. The number of sensors for which stopping distance exceeded maximum effective range increased between the 2004 QID and GCE and the 2005 GCE from 70 to 82 percent.

Overall, the author concluded teams did not have realistic estimates for the maximum effective ranges of the various sensors in use, and that, in general, team strategies were based on the maximum theoretical range, and not the maximum observed range.

Despite this, the optimum strategy was intuitive: the stopping distance corresponding to the maximum speed of the challenge vehicle may exceed the maximum effective range of short-range sensors, but must not exceed the maximum effective range of long-range sensors. Because the maximum effective ranges for VISION, short-range LIDAR, long-range LIDAR, and RADAR sensors were based on the maximum observed ranges reported by successful teams, the author considers it likely that these ranges were consistent with the state-of-the-art during the 2005 GCE, and represent the community's best effort.

Because of this, and because this strategy was employed by three of four successful teams (Teams 2005-13, 2005-14, and 2005-16), the author was tempted to conclude the use of complementary sensors to extend obstacle detection range and allow driving at higher speeds was a key factor. However, no team failed to complete the 2005 GCE due to inability to stop before collision with an obstacle, and Team 2005-06 successfully completed the 2005 GCE without the use of complementary sensors.

As a result, and in consideration of the failure analysis performed by the author (see Chapter XIII.), the author concluded the lack of realistic estimates for the maximum effective ranges of the various sensors in use had no practical impact on team performance during the 2005 GCE, but that realistic estimation may have been an indicator of prior experience or adequate test and evaluation.

VIII.D.2. Field-of-view limitations

The author concluded at least one sensor with a field-of-view which equaled or exceeded 40° was in use by each team which participated in the 2004 QID and GCE and 2005 GCE, and that, as a result, there was no field-of-view limitation. However, the author concluded field-of-view limitations, in combination with ability to provide a point-map of the environment, may have contributed to the decreased use of RADAR and increased use of LIDAR noted in paragraph VI.D.

VIII.D.3. Average range ratio

The average range ratio based on the maximum theoretical detection range decreased between the 2004 and 2005 GCE from 1.55 to 0.90. However, this is misleading because it is based on the maximum obstacle detection range reported by the teams. The average range ratio based on the maximum observed range actually increased between the 2004 and 2005 GCE from 1.88 to 2.07.

Review of the results revealed teams generally overestimated maximum obstacle detection range for the various sensors in use. Eight of 11 2004 teams participating in both the 2004 and 2005 GCE reported an average maximum effective range greater than the average maximum obstacle detection range for all teams. Eight of nine 2005 teams participating in both the 2004 and 2005 GCE reported an average maximum effective range greater than the average maximum obstacle detection range.

In addition, review of the results revealed teams generally overestimated their ability to detect obstacles at ranges which would allow the challenge vehicle to come to a complete stop at the vehicle top speed. Only one team which participated in both the 2004 and 2005 GCE reported a challenge vehicle top speed corresponding to a stopping distance which did not exceed either the average maximum obstacle detection range or average maximum effective range for the sensors in use by the team: Teams 2004-16 and 2005-17.

The average range ratio for four of 12 teams which participated in both the 2004 and 2005 GCE decreased between 2004 and 2005: Teams 2004-10 and 2005-13, 2004-13 and 2005-15, 2004-18 and 2005-20, and 2004-25 and 2005-22. On average, these teams completed 2.09 miles of the 2004 GCE course and 68.1 miles of the 2005 GCE course.

On average, teams which participated in the 2004 GCE completed 1.95 miles of the 2004 GCE course and teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course. Based on the limited number of teams participating in both the 2004 and 2005 GCE which reported an average maximum effective range greater than the average maximum obstacle detection range, the author was unable to conclude the decrease in average range ratio was a key factor for these teams.

VIII.D.4. Overall conclusions

Although overestimation of sensor maximum obstacle detection range, field-of-view limitations, and increase in average range ratio had no practical impact, these problems were systemic and revealed fundamental misunderstandings about the capabilities of various sensors in use by teams participating in the 2004 or 2005 GCE. In general, teams had a difficult time visualizing the interaction of the challenge vehicle with the environment.

It is likely teams participating in the 2004 or 2005 GCE considered the need to fully apply the brakes to cause their challenge vehicle to come to a complete stop. For example, Team 2005-01 stated: “There are two cases for braking – brake the vehicle to 0 mph, or brake to a value greater than zero. If the vehicle velocity is commanded to zero, than the brakes are immediately and fully applied.” ([10], p. 12). Several teams described the use of anti-lock braking systems to prevent the challenge vehicle from entering a slide, or to maintaining control of challenge vehicle heading while coming to a complete stop.

However, the expected failure mode of a challenge vehicle during the 2004 or 2005 GCE was a full brake slide during which the vehicle would be unable to maintain its heading, turn sideways, and collide with an obstacle such as the raised berms defining the 2005 GCE course (see paragraph II.C.7.a.), increasing the potential for a tripped rollover ([40]). The consequences of a rollover event were significant, as the inability to reliably detect obstacles at speed or stop before colliding with an obstacle might have resulted in damage to, or the destruction of, the challenge vehicle.

The average course segment lengths for the 2004 and 2005 GCE of 88.6 m (290.7 ft) and 72.3 m (237.2 ft), respectively, approach the stopping distance of a challenge vehicle at the 2004 and 2005 GCE course-wide speed limits of 60 and 50 mph, respectively of 111.1 m (364.4 ft) and 77.1 m (253.0 ft) at the representative μ_k of 0.33. However, the maximum speed reported by Team 2004-10 during the 2004 GCE was 36 mph ([39], p. 31) and the maximum speed reported by Team 2005-16 during the 2005 GCE was 38.0 mph ([25], p. 688). As a result, a challenge vehicle would have been able to come to a complete stop in a distance less than the average course segment length and from a speed less than the course-wide speed limit. The author concluded limiting the speed at which a challenge vehicle was traveling was a more significant contributing factor to reliable obstacle avoidance than accurate estimation of sensor maximum obstacle detection range or elimination or other resolution of field-of-view limitations.

In addition, the author concluded:

- All teams participating in the 2004 and 2005 GCE had sensors capable of reliably detecting obstacles at a notional course-wide speed limit of 15 mph, virtually guaranteeing they would be able to complete the course in less than ten hours. See paragraph II.C.7.b.

- A stopping distance of 20.0 m (65.6 ft) corresponds to a speed of 25.5 mph (11.4 m/s). At a notional course-wide speed limit of 25 mph, a team could have completed the 2004 GCE course in 7.14 hours and the 2005 GCE course in 6.81 hours. See Table XIII.

  Team 2005-16 successfully completed the 2005 GCE, placing first with a time of 06:53:58 hours (6.90 hours). Therefore, any team using short-range LIDAR sensors with a maximum effective range of 20.0 m for obstacle detection was potentially able to complete the course in less time than Team 2005-16 without exceeding a speed of 25 mph or the maximum effective range for short-range LIDAR sensors.

  Despite having extended maximum effective range to 70.0 m with a VISION sensor, and reaching a top speed of 38.0 mph, Team 2005-16 did not complete the

2005 GCE in less than 6.81 hours. This appears to contradict the author's conclusion that long-range sensors typical of those in use by the teams were not required to successfully complete the 2005 GCE.

However, the failure analysis performed by the author (see Chapter XIII. and Chapter XV.) indicates inadequate test and evaluation, even among potentially disruptive teams, was the cause of most team failures to successfully complete the 2004 and 2005 GCE, not obstacle and path detection failures.

The evidence does not support a conclusion no challenge vehicle was capable of successfully completing the 2004 or 2005 GCE without exceeding a speed of 25 mph, or that the use of sensors with ranges exceeding those of short-range LIDAR sensors was required to complete the 2004 or 2005 GCE course because this was, in general, not attempted. The format of the Grand Challenge as a race encouraged the teams to focus on completing the Grand Challenge in the least possible time, in many cases to their detriment and to the detriment of the community as a whole.

Nevertheless, the author concluded the *effective use* of long-range sensors provided a sensing advantage, and determined team placement.

Overall, analysis supports a conclusion that some teams were able to effectively visualize the interaction of the challenge vehicle with the environment. The author considers this a key factor. The author proposes the ability to effectively visualize the interaction of the challenge vehicle with the environment was influenced by experience, sponsorship, or test and evaluation.

CHAPTER IX. COMPUTING HARDWARE AND EQUIPMENT

IX.A. Discussion

Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average, and teams which participated in the 2004 GCE completed 1.95 miles of the 2004 GCE course, on average. Based on the increase in the number of miles of the 2005 GCE course completed, the author proposed an increase in processing power available to the controlling intelligence was a key factor.

To determine if there was an increase in processing power between the 2004 and 2005 GCE the author reviewed 2004 and 2005 technical proposals and concluded insufficient technical detail was reported to determine the quantity, manufacturer, and model number of computing hardware and equipment in use by the teams. The author concluded that meaningful comparison between the computing hardware and equipment in use by the teams which participated in the 2004 QID and GCE and 2005 GCE using existing benchmarks would not be productive.

IX.B. Analysis

However, the author reviewed the published record and evaluated the computing hardware and equipment in use by teams which participated in both the 2004 and 2005 GCE to determine if there was an increase in the number of computers or an increase in the number of processors.

- Teams 2004-02 and 2005-01

Team 2004-02 stated: "The Challenge Vehicle will utilize five (5) shock-mounted Pentium class servers and one (1) National Instruments Compact Field Point system. Four of the five servers are motherboard-based 19" rack-mounted computers, 2 server-unit (2U) form-factor in height. The fifth server is a Dell Optiplex, standard desktop PC." ([9], p. 5).

Team 2005-01 stated: "[The challenge vehicle] utilizes five (5) shock-mounted Pentium class servers and one (1) National Instruments Compact Field Point system. The five servers are motherboard-based 19" rack-mounted computers, 2 server-unit (2U) form-factor in height." ([10], p. 4).

The author concluded there was no increase in processing power.

Teams 2004-02 and 2005-01 reported sufficient technical detail to determine the quantity, manufacturer, and model number of computing hardware and equipment in use by the team.

• Teams 2004-04 and 2005-02

Team 2004-04 stated: "[The challenge vehicle] uses a network of four single board computers, a PhyCore MPC565 PowerPC microcontroller, a military ruggedized Itronix GoBook II notebook computer, and a D.Module.C6713 Digital Signal Processor (DSP) to distribute the processing and intelligence required for the Grand Challenge." ([44], p. 3).

Team 2005-02 stated ([167], pp. 5 - 6):

> The high level computational needs are met in the deployed system via the utilization of single processor computing nodes targeted at individual computational needs...
>
> The individual computing node hardware architecture was selected based on the subjective evaluation of commercial off-the-shelf hardware. Evaluation criteria were centered on performance and power consumption. The deployed system maintains a homogenous hardware solution with respect to motherboard, ram, enclosure, and system storage. A processor family was selected based on power consumption measurement and performance to allow tailoring based on performance requirements with the objective of power requirement reduction. Currently three processor speeds are deployed.

Team 2005-02 later stated ([50], pp. 604 - 605):

> The high-level computational needs are met in the deployed system via the utilization of eight single-processor computing nodes targeted at individual computational needs...
>
> The individual computing node hardware architecture was selected based on the subjective evaluation of commercial off-the-shelf hardware. Evaluation criteria were centered on performance and power consumption. The deployed system maintains a homogenous hardware solution with respect to the motherboard, random access memory (RAM), enclosure, and system storage. The AMD K8 64-bit microprocessor family was selected based on power consumption measurement and performance to allow tailoring based on performance requirements with the objective of

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power requirement reduction.  Currently, three
processor speeds are deployed: 2.0 GHz, 2.2 GHz, and
2.4 GHz.  The processors are hosted in off-the-shelf
motherboards and utilize solid-state flash cards for
booting and long-term storage.  Each processing node
is equipped with 512 to 1028 MB of RAM.
```

The author concluded there was an increase in processing power.

- Teams 2004-06 and 2005-03

Team 2004-06 reported an unknown number of “TI TMS2406” processors, one “TMS2407 class DSP”, and three “TI TMS6414 processors running at 1 Ghz each” were in use by the team ([114], pp. 1 - 2).

Team 2005-03 stated: “The entire camera and navigation system is enabled by the use of 10 embedded TI C6416 DSP processors running assembly code.” ([33], p. 3).

The author concluded there was an increase in processing power.

- Teams 2004-07 and 2005-05

Team 2004-07 stated: “Two 1.5-GHz Intel processors will be used for vision processing tasks while a third is used to calculate obstacle-free trajectories, and a fourth will do state estimation based on input from the GPS, compass, and vehicle speed sensor, and send control signals to the steering, accelerator, and brake actuators to keep the vehicle on the target trajectory. One 1-GHz EPIA M-10000 VIA processor handles information from the radar.” ([46], p. 3).

Team 2005-05 stated: “Our experience has generally been that we are not processor-limited and that a single laptop computer is sufficient to do all the tasks of processing laser range data, planning trajectories, and controlling the vehicle. The important exception is computer vision which does tend to be processing-intensive and is performed on its own processor, either another laptop or custom hardware such as the single board computer, based on a single Motorola PowerPC 7410 (G4) processor, supplied by Mobileye LTD.” ([34], p. 3).

Team 2005-05 later stated: “A second design aim was to keep the computational architecture as simple as possible. The core tasks of autonomous driving do not require a large amount of computational power. We worked to keep the software running on a single laptop computer. Unburdened by a rack full of computers, we were able to retain working space in the vehicle, but more importantly, any team member could plug in their laptop with a universal serial bus (USB) cable and run the vehicle.” ([170], p. 529).

The author concluded there was a significant decrease in processing power.

Teams 2004-07 and 2005-05 was the only team which reported a decrease or significant decrease in processing power between the 2004 and 2005 GCE.

- Teams 2004-08 and 2005-07

Team 2004-08 stated: “The computing systems involved in our design require the use of 5 computers.” ([76], p. 3), but reported no additional identifying information for the computers in use by the team.

The Team 2005-07 technical proposal was unavailable for review and Team 2005-07 did not publish its results via the Journal of Field Robotics. See paragraph V.C.32. Available published records ([233] and [118]) did not report the computing hardware and equipment in use by Team 2005-07.

The author concluded insufficient technical detail was reported to determine if there was an increase in processing power between the 2004 and 2005 GCE.

- Teams 2004-10 and 2005-13

Team 2004-10 reported “Pentium III PC104 Stacks”, one “Itanium 2 Based Server, 4 Processors”, and one “Xeon Based Computer, Dual processors” were in use by the team ([77], p. 3). Team 2005-13 reported four “Pentium III PC104 stacks” and seven “Pentium M Compact PCI computers” were in use by the team ([11], p. 4).

The author concluded there was an increase in processing power.

- Teams 2004-13 and 2005-15

Team 2004-13 stated: “Here is a list of the computers and their module assignment: Vehicle control: embedded computer or ruggedized laptop. Obstacle and environmental sensing: rugged PC with PCI interface card. Road / path finding: ruggedized laptop, firewire frame grabber and PCMCIA interface. Path planning: ruggedized laptop. [Challenge vehicle controlling intelligence]: ruggedized laptop. A number of simple microcontrollers will be used to interface the computers to sensors and actuators.” ([232], p. 2).

Team 2005-15 stated: “We use two 750 MHz Pentium-4 embedded systems built as a PC104+ stack.” ([53], p. 6).

Team 2004-13 did not report the number of computers in use by the team. As a result, the author was unable to determine if multiple modules shared a single computer, for example if modules “Vehicle control”, “Road / path finding”, and “[Challenge vehicle] Brain” shared a single “ruggedized laptop”, or if each was assigned to an individual laptop. In addition, Team 2004-13 stated module “Vehicle control” was assigned to an “embedded computer *or* ruggedized laptop” (*emphasis added*). As a result, the author concluded Team 2004-13 had not determined how many computers were in use by the team at the time the team technical proposal was submitted for review. The Team 2004-13 technical proposal is undated.

The author concluded insufficient technical detail was reported by Team 2004-13 to determine if there was an increase in available processing power between the 2004 and 2005 GCE.

- Teams 2004-16 and 2005-17

Team 2004-16 reported “Two ATHLON Pc’s” were in use by the team ([138], p. 3).

Team 2005-17 stated: “A single, garden variety mother board is replaced by two Dell Power Edge 750 computers and two mini-ITX boards.” ([140], p. 2).

Team 2005-17 later stated: “The computing system... provides the computational power of [the challenge vehicle]. The computers labeled 'Main Machine' and 'Extra Machine' are Dell PowerEdge 750s... The other two computers 'NTP Machine' and 'Disk Logger Machine' are mini-ITX boards...” ([196], p. 560).

Regardless of whether a “single, garden variety mother board” or “Two ATHLON Pc's” were in use by Team 2004-16, the author concluded there was a significant increase in processing power.

- Teams 2004-17 and 2005-18

Team 2004-17 stated: “The Challenge Vehicle will contain up to 9 regular desktop, IBM, Pentium 4, 3.0Ghz PC computers and an IBM laptop.” ([142], p. 5).

Team 2005-18 stated: “[The challenge vehicle's] software systems run on six Dell PowerEdge servers and two quad-core IBM Opteron-based servers...” ([197], p. 7).

Team 2005-18 later stated: “The computing platform consists of six Dell PowerEdge 750 servers with 3 GHz, Pentium 4 processors and a single IBM eServer 326 with dual 2.2 GHz dual-core AMD 64 processors.” ([54], p. 781).

Although Team 2004-17 did not report the number of computers in use by the team, but stated the challenge vehicle will contain “*up to* 9 regular desktop” (*emphasis added*) computers, the author concluded there was an increase in processing power.

- Teams 2004-18 and 2005-20

Team 2004-18 stated: “Three computers have been implemented [*sic*] One computer handles the environment sensing, while the second computer handles the map matching and path logic, and the third computer handles vehicle control and system feedback. Two of the computers are 1.6 GHzGETAC [*sic*] Laptops with custom power, data acquisition cards, and filters. The control computer consists of a 1.3 GHz processor running a real-time operating system, as well as a motor controller and digital and analog interface cards. This computer is a PXI (PCI extensions for Instrumentation) form factor." ([48], pp. 2 - 3).

Team 2005-20 stated: "The computational hardware consists of seven computers including a National Instruments PXI, a National Instruments CompactRIO, four MINI ITX Pentium 4 computers, and a single Pentium 4 extreme edition 3.73 GHz computer that uses hyperthread technology for the stereo camera." ([56], p. 4).

The author concluded there was a significant increase in processing power.

- Teams 2004-23 and 2005-21

Team 2004-23 reported six "Pentium 4 machines" were in use by the team ([159], p. 3).

Team 2005-21 did not report the computing hardware and equipment in use by the team via the team technical proposal ([160]).

Team 2005-21 later stated: "The autonomous system consists of computers, communication network, sensors, vehicle control interface, and the supporting mounting and protection structures. The autonomous system utilized in the 2004 DGC was completely removed and upgraded for the 2005 DGC." ([57], p. 694).

The author concluded there was an increase in processing power.

- Teams 2004-25 and 2005-22

Team 2004-25 stated: "The computing systems for the Challenge Vehicle consist of four sensor interface computers, a global mapping computer, a local mapping/path-planning computer, and a system status/motion control computer." ([49], p. 4) and "The Challenge Vehicle uses three National Instruments Compact Field Point (cFP) 2010 units and a CVS-1454 Compact Vision System to capture and preprocess local sensor data." ([49], p. 6). Team 2004-25 reported one "PXI – 8176 Controller", one "PXI 8186 Controller", and one "PXI-8174 Controller" were in use by the team.

Team 2005-22 stated: "Computational power on [the challenge vehicle] is distributed across three National Instruments PXI-8176 controllers." ([58], p. 2).

Team 2005-22 later stated ([59], p. 711):

> Both vehicles are equipped with National Instruments PXI-8176 controllers. These controllers are high-performance compact personal computers containing Pentium processors with up to 1 GB of random access

memory. The controllers can run at speeds ranging from 1.2 to 2.6 GHz...

The three computers on [the challenge vehicle] each perform a specific task: Vision, INS/Path Planning, and Motion Control.

The author concluded there was an increase in processing power.

Teams 2004-25 and 2005-22 reported sufficient technical detail to determine the quantity, manufacturer, and model number of computing hardware and equipment in use by the team.

IX.C. Results

Of teams participating in both the 2004 and 2005 GCE:

- Two of 12 teams (17 percent) reported sufficient technical detail to determine the quantity, manufacturer, and model number of computing hardware and equipment in use by the team.
- There was an increase or significant increase in processing power available to the challenge vehicle controlling intelligence for eight of 12 teams (67 percent).
- There was no change in processing power available to one of 12 teams (eight percent).
- There was a decrease or significant decrease in processing power available to one of 12 teams (eight percent).
- Insufficient technical detail was reported to determine if there was an increase in processing power available to the challenge vehicle controlling intelligence for two of 12 teams (17 percent).

IX.D. Conclusions

Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average. Teams which participated in both the 2004 and 2005 GCE completed 48.6 miles of the 2005 GCE course, on average. Teams which participated in the 2005 GCE but not the 2004 GCE completed 47.9 miles of the 2005 GCE course, on average. See paragraph X.D.1.

As a result, although there was an increase or significant increase in processing power available to the challenge vehicle controlling intelligence for 67 percent of teams which participated in both the 2004 and 2005 GCE, the author was unable to conclude teams which participated in both the 2004 and 2005 GCE completed more miles of the

2005 GCE course as a result of an increase in processing power than teams which participated in the 2005 GCE but not the 2004 GCE. In addition, teams which participated in the 2005 GCE but not the 2004 GCE provide no basis for comparison, and insufficient technical detail was reported to determine the quantity, manufacturer, and model number of computing hardware and equipment in use by the vast majority of teams which participated in the 2004 QID or GCE or 2005 GCE.

However, the fact remains that teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average, and teams which participated in the 2004 GCE completed 1.95 miles of the 2004 GCE course, on average. The author concluded corporate and academic sponsorship allowed teams which participated in the 2005 GCE but not the 2004 GCE to effectively “buy in”, by providing access to resources such as labor, high-quality sensors, and computing equipment, and COTS technologies such as integrated challenge vehicle controls and COTS components used to integrate navigation sensors. See paragraph X.D.2. The author proposes this may have enabled these teams to participate in the 2005 GCE on a more even basis with teams which participated in both the 2004 and 2005 GCE, 67 percent of which increased or significantly increased the processing power available to the challenge vehicle controlling intelligence.

As a result, the author concluded an increase in processing power available to the challenge vehicle controlling intelligence was a key factor.

Ironically, following the unsuccessful conclusion of the 2004 GCE, DARPA stated: “Work in this area continues to address increasingly difficult route planning and terrain navigation challenges, but under the assumption Moore’s law would enable higher vehicle speeds in the future.” ([3], p. 2). Insufficient technical detail was reported to conclude the increase in available processing power between the 2004 and 2005 GCE observed by the author was a direct consequence of Moore's Law, but the increase in processing power available to the challenge vehicle controlling intelligence contributed to the higher vehicle speeds predicted. The author asserts the effect was indistinguishable from an increase in processing power due to Moore's Law.

CHAPTER X. PRIOR EXPERIENCE AND CORPORATE OR ACADEMIC SPONSORSHIP

X.A. Discussion

Based on the author's conclusion that some teams were able to more effectively visualize the interaction of the challenge vehicle with the environment, the author proposed the ability to effectively visualize the interaction of the challenge vehicle with the environment was influenced by experience, sponsorship, or test and evaluation. See paragraph VIII.D.4.

Based on a review of performance during the 2004 GCE:

- Three of nine teams which completed more than zero miles of the 2004 GCE course reported prior experience in the field of autonomous vehicle development and significant (either moderate or extensive, see paragraph X.B., below) corporate or academic sponsorship: Teams 2004-04, 2004-10, and 2004-23.

- Four of the remaining six teams which completed more than zero miles of the 2004 GCE course reported significant corporate or academic sponsorship: Teams 2004-13, 2004-14, 2004-17, and 2004-18.

- The two remaining teams which completed more than zero miles of the 2004 GCE course reported neither prior experience in the field of autonomous vehicle development nor significant corporate or academic sponsorship: Teams 2004-06 and 2004-07.

X.B. Analysis

The author performed a review of published records to evaluate the effect of prior experience and corporate or academic sponsorship. Because the author concluded it would not be possible to estimate the cost of team challenge vehicles from published records (see paragraph V.E.), the author reviewed the published record to determine the primary group identity and level of corporate and/or academic sponsorship for each team which participated in the 2004 QID and GCE or 2005 GCE. Compared to teams which participated in the 2005 GCE, fewer teams which participated in the 2004 QID or GCE reported sponsors via their technical proposals.

Some teams reported sponsors via the team technical proposal or team website. Examples are included throughout this section, and references to the sources of this information are also included. However, to determine the primary group identity and level of corporate and/or academic sponsorship for each team, the author reviewed the Archived Grand Challenge 2004 and 2005 websites ([17] and [19]) and team websites to identify the sponsors were reported by the teams. References to the sources of this information are not cited in Tables LXVI, LXVII, and LXVIII, but may be confirmed by review of the Archived Grand Challenge 2004 and 2005 websites ([17] and [19]) and team websites.

The author established the following categories of primary group identity:

- Individual. Members of the team do not predominately represent a corporation or academic institution, although they may have a collective identity as a Limited Liability Company (LLC) or similar business structure. Individual members of the team may represent small businesses, individually-owned companies, or consultancies.

- Corporate. Members of the team predominately represent a corporation.

- Academic. Members of the team predominately represent an academic institution such as a university or high school.

The author established the following levels of corporate or academic sponsorship:

- Limited. Equipment donations had a typical value of less than $5,000. Sponsors providing limited support were typically corporations such as AMD, Amphitech, Applanix, C&C Technologies, Crossbow, Delphi, Intel, NavCom, NovAtel, OmniSTAR, and SICK, among others. In general, teams with limited sponsorship were self-funded, or represented small businesses formed for the purpose of participating in the 2004 or 2005 GCE.

- Moderate. Individual sponsor equipment donations had a typical value between $5,000 and $25,000. Sponsors providing moderate support were typically medium to large corporations such as AM General, Caterpillar, Ford, GM, Honda, Honeywell, Oshkosh, and Rockwell Automation. Some teams with moderate sponsorship formed partnerships with small to medium businesses or academic institutions with no history of robotics research.

- Extensive. Individual sponsor equipment donations had a typical value in excess of $25,000. Sponsors providing extensive support were typically large corporations or defense contractors such as Boeing, Northrop Grumman, and SAIC. Some teams with extensive sponsorship formed partnerships with medium to large businesses, including defense contractors, or academic institutions with a history of robotics research and prior experience in the development of autonomous vehicles.

Individual sponsors may have made multiple donations or donations may have been received from multiple individual sponsors. In addition, sponsors may have offered the free use of equipment through loans, “free lease” arrangements, or “like kind” agreements. For this reason, the author focused on evaluating the number and relative sizes of the sponsors reported by the teams. This analysis was, to an extent, subjective. However, even the limited information available provides some insight.

As a result, teams receiving overall limited sponsorship may have had several limited sponsors described above; teams receiving overall moderate sponsorship may have had a corporate or academic primary group identity, one or more moderate sponsors, or multiple limited sponsors described above; and teams receiving overall extensive sponsorship may have had a corporate or academic primary group identity, one or more extensive sponsors, or multiple moderate and limited sponsors. For example:

- Team 2004-02

Team 2004-02 stated: "Fifteen teams report that they raced in the 2004 DARPA Grand Challenge. Only seven of those team were actually eligible to win the $1 Million prize. [Team 2004-02] was the only self-funded 'Completely Accepted' team to be eligible for the US Senate funded prize at the start of the 2004 DGC race." ([86]).

- Team 2004-18

Team 2004-18 stated: "[Team 2004-18] is sponsored by ENSCO Inc, a privately owned engineering company that specializes in signal processing and data acquisition." and "[Team 2004-18] is employed and sponsored by ENSCO, Inc., which provides engineering, science and advanced technology solutions for the defense, security, transportation, environment, aerospace, and intelligent automation industries." ([48], p. 1).

- Team 2005-01

Team 2005-01 stated: "[Team 2005-01] is a self sponsored autonomous racing team battling large universities, Department of Defense contractors, and large for profit organizations. The team spends five cents or less for every dollar spent by well funded competitors. The team's major sponsor has been the Kehaly family of Westlake Village, California." ([86]). Although Team 2005-01 reported "no sponsors for 2005" on December 11, 2004, the team later reported "working relationships" with Northrop Grumman and Amphitech ([86]) on June 3, 2005.

- Team 2005-05

Team 2005-05 stated: "We would like to thank our sponsors: Mobileye LTD; BEI Technologies, Inc.; Intel Corporation; Federal Signal Corporation; OmniSTAR USA; Kenyon Labs LLC; Prime Resource, Inc.; National Instruments; and Sick, Inc." ([34], p. 13).

- Team 2005-07

Team 2005-07 stated: “Sponsors are: NC State University, IBM, SAS, Red Hat, Ascot Technologies, BDMICRO, Comtrol, Council & Sons Repair Service, Crossbow, Frantz Automotive, Lord Corporation, PC MedEvac, SICK, and Smith Anderson.” ([233]), and “Sponsors: Ascot Technologies, Inc., BDMICRO, Crossbow Technology, Inc., Council & Son Repair Service, Gemini Automotive Care, NC State University, PC MedEvac, and SICK, have provided valuable resources to help [Team 2005-07] reach this important milestone.” ([118])

- Team 2005-08

Team 2005-08 stated: “The core team draws on sponsorship from Ford, Honeywell, Delphi, and PercepTek...” ([173], p. 3).

- Team 2005-09

Team 2005-09 stated: “[Team 2005-09] is sponsored by the MITRE Corporation. MITRE is a collection of Federally Funded Research and Development Centers that support the DoD, FAA, IRS and other federal agencies. MITRE sponsors [Team 2005-09] entirely on discretionary funds and chooses this investment in a belief that many of The MITRE Corporation’s work programs would benefit from an investigation in the technologies that contribute to the DARPA Grand Challenge.” and “While the MITRE Corporation is the primary sponsor, additional companies that provided equipment and services include: ACTTechnico, Concurrent Technologies, Hybricon, Electronic Mobility Controls, Corp.., [*sic*] SuperLift Suspensions, Interco Tire, MSC Software, Top-Soil Precision Ag., OmniStar, PCB Piezotronics, Inc., and Tidewater Communications.” ([175], p. 2).

- Team 2005-10

Team 2005-10 stated: “The support that we received from our more than two dozen sponsors was astounding.” ([176], p. 8). Team 2005-10 reported the following sponsors: “Alpine Powder Coating”, “Automation Direct”, “Automotive Customizers”, “Barney Brothers Off Road”, “Big 'O' Tires”, “CoorsTek”, “Copley Controls”, “Crossbow”, “DVT Sensors”, “Earth LCD”, “Entivity”, “Foxhaven Video”, “Fuoco Motors”, “Galil Controls”, “General Technics”, “Genesis Engineered Solutions”, “Kearfott Navigation”, “Navcom”, “Optech”, “Platinum Signs”, “PNI”, “SICK”, “Tee Time USA”, and “Visual Expressions” ([176], p. 1).

- Team 2005-12

Team 2005-12 stated: “[The Team 2005-12 challenge vehicle] was fortunate to receive product donations from several companies. Rick Spina ’85 helped obtain a salvaged vehicle from General Motors. Trimble Navigation and ALK Technologies donated GPS receivers. Otherwise, all student summer salaries, graduate student support and equipment was purchased using University endowment funds from the CSX Transportation Research Fund, the Lion Transportation Senior Thesis Fund, and the Kornhauser-Gervasio Graduate Fellowship. The team is also indebted to the generosity of the parents of the undergraduate researchers and Eric Huber." ([185], p. 8).

- Team 2005-15

Teams 2004-13 and 2004-14 were co-participants during the 2004 GCE. See paragraphs V.C.13. and V.C.14. Team 2004-13 participated in the 2005 GCE as Team 2005-15, and the Team 2004-13 challenge vehicle continued to the 2005 GCE. The Team 2004-14 challenge vehicle did not continue to the 2005 GCE.

Team 2005-15 stated ([53], pp. 2 - 3):

> Our fundraising approach is to invite companies and individuals, including many of our volunteers, to invest... Key investors are Rockwell Scientific and ATV Corporation... Amgen, a Thousand Oaks based biotechnology company, has provided computing hardware for [the Team 2005-15 challenge vehicle] and several Amgen employees are team members. Another key partner is the Engineering School of Auburn University who has developed the vehicle closed loop control system... Finally, we have also teamed with ARC Seibersdorf who has provided their stereovision system for feature detection.
>
> Support for our mapping task and waypoint file creation comes from volunteers employed by Vestra, Inc, ESRI and the City of Thousand Oaks.

Team 2005-15 later stated: "[Team 2005-15] formed to compete in the initial DARPA Grand Challenge in 2004. The core technical team was initially comprised mainly of engineers at Rockwell Scientific Corporation (RSC) and received a large portion of its funding from RSC." ([133], p. 580).

- Team 2005-16

Team 2005-16 stated: "[Team 2005-16] is sponsored through four *Primary Supporters*: Volkswagen of America's Electronic Research Lab, Mohr Davidow Ventures, Android, and Red Bull... [Team 2005-16] has also received support from Intel Research, Honeywell, Tyzx, Inc., and Coverty, Inc. Generous financial contributions were made by the David Cheriton [*sic*], the Johnson Family, and Vint Cerf." ([195], p. 3).

- Team 2005-17

Team 2005-17 stated: “We are thankful to the following companies and individuals for their support of the project: C&C Technologies, Lafayette, LA; Ray Majors and family, Melville, LA; MedExpress Ambulance Service, Alexandria, LA; Oxford Technology Solutions and Brendel Associates; SOLA Communications, Lafayette, LA; Lafayette Motors, Lafayette, LA; BEGNAUD Manufacturing, Lafayette, LA; Louisiana Department of Transportation; Recreative Industries, Buffalo, NY.; FireFly Digital, Lafayette; and Pixus Printing, Lafayette.” ([140], p. 11).

- Team 2005-20

Team 2005-20 stated: “The team is sponsored by ENSCO, Inc., which provides engineering, science and advanced technology solutions for the defense, security, transportation, environment, aerospace, and intelligent automation industries.” ([56], p. 2).

X.C. Results

Tabulated results are presented by Tables LXVI and LXVII. A comparison of sponsorship of teams which participated in both the 2004 and 2005 GCE is presented by Table LXVIII.

X.C.1. Experience

- Three teams which participated in the 2004 GCE reported prior experience in the development of autonomous vehicles: Teams 2004-04, 2004-10, and 2004-23.

  The Team 2004-04 sponsoring university stated: “The Center for Intelligent Machines and Robotics was founded in the 1970's... to be a leading center for interdisciplinary basic and applied research related to the many aspects of robotics.” ([234]).

  The Team 2004-10 sponsoring university stated: “The Robotics Institute at Carnegie Mellon University was established in 1979 to conduct basic and applied research in robotics technologies relevant to industrial and societal tasks.” ([235]).

  Team 2004-23 reported participating in the “1996 Ground Robotics competition”, “Demo’97” where “OSU autonomous cars were driven 70 mph and performed autonomous lane change and passing”, and “Demo’99” where “OSU cars performed GPS and map based driving” ([159]).

  Several other teams reported participation in events similar to the Grand Challenge but of such limited scope that the author did not consider the experience relevant for the purposes of this analysis. For example, Team 2004-25 stated: “...[the Team 2004-25 sponsoring university] won 1st and 2nd place in the

Autonomous Challenge at the 2003 Intelligent Ground Vehicle Competition.", but also stated: "...the speeds are slower (limited to 5 mph)" ([49], p. 13). Figures 14 and 15 ("Test Vehicle from the Intelligent Ground Vehicle Competition") of the team technical proposal ([49], p. 14) depict a three-wheeled vehicle slightly larger than, but not otherwise dissimilar to, the Pioneer series of robots popular in robotics research.

- Twelve teams participated in both the 2004 and 2005 GCE, which itself forms the basis for a claim of prior experience. See Table LXVIII. Teams 2004-04, 2004-10, and 2004-23 participated in the 2005 GCE as Teams 2005-02, 2005-04, 2005-13, and 2005-21, respectively[25].

  Several teams which participated in both the 2004 and 2005 GCE reported lessons learned from the 2004 GCE in their technical proposals for the 2005 GCE. For example, Team 2005-05 participated in the 2004 GCE as Team 2004-07. Team 2005-05 stated: "Reviewing the outcome of the 2004 Grand Challenge..." ([34], p. 2) and reported the rationale for several decisions made as a result of their experience during the 2004 GCE.

  However, the average number of miles of the 2005 GCE completed was not significantly different for teams which participated in the 2005 GCE but not the 2004 GCE and teams which participated in both the 2004 and 2005 GCE. See paragraph X.D.

- Two teams which participated in the 2005 GCE but not the 2004 GCE reported experience prior to the 2004 GCE: Teams 2005-14 and 2005-16.

X.C.2. Corporate sponsorship

- Three of 25 teams (12 percent) which participated in the 2004 GCE did not report corporate sponsorship was received by the team: Teams 2004-12, 2004-22, and 2004-24.

- All teams which participated in the 2005 GCE reported corporate sponsorship was received by the team.

- Between 2004 and 2005, a minor shift in levels of corporate sponsorship was reported: the number of teams receiving overall limited sponsorship decreased from 2004 to 2005 from 11 of 22 teams (50 percent) to eight of 23 teams (35 percent), while the number of teams receiving overall moderate sponsorship increased from nine of 22 teams (41 percent) to 12 of 23 teams (52 percent). The number of teams receiving extensive sponsorship increased slightly from two of 22 teams (9 percent) to three of 23 teams (13 percent). The author does not consider this increase to be significant because it is due entirely to Team 2005-14. Teams 2005-13 and 2005-14 were co-participants in the 2005 GCE.

X.C.3. Academic sponsorship

- Nine of 25 teams (36 percent) which participated in the 2004 GCE reported academic sponsorship.

- Fourteen of 23 teams (61 percent) which participated in the 2005 GCE reported academic sponsorship.

- Between 2004 and 2005, a significant shift in levels of academic sponsorship was reported: the number of teams receiving overall limited sponsorship decreased from 2004 to 2005 from four of nine teams (44 percent) to two of 14 teams (14 percent), the number of teams receiving overall moderate sponsorship increased from three of nine teams (33 percent) to seven of 14 teams (50 percent), and the number of teams receiving overall extensive sponsorship increased from two of nine teams (22 percent) to five of 14 teams (36 percent).

X.D. Conclusions

X.D.1. The effect of experience

Two teams which participated in the 2004 GCE but had no prior experience, limited sponsorship, and a primary group identity of “Individual” distinguished themselves by achieving the third- and fourth-greatest distances traveled: Teams 2004-06 and 2004-07, with 6.0 and 5.2 miles completed respectively. However, this performance was exceeded by teams which participated in the 2005 GCE but also had no prior experience, limited sponsorship, and a primary group identity of “Individual”: Teams 2005-10 and 2005-11, with 23.0 and 7.2 miles completed respectively. The author considers this demonstrates the performance achieved by Teams 2004-06 and 2004-07 during the 2004 GCE was achievable by teams with similar levels of experience and sponsorship, and was not extraordinary, however extraordinary it may have seemed at the time of the 2004 GCE.

On average:

- Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course.

- Teams which participated in both the 2004 and 2005 GCE completed 48.6 miles of the 2005 GCE course.

- Teams which participated in the 2005 GCE but not the 2004 GCE completed 47.9 miles of the 2005 GCE course.

Because teams which participated in the 2005 GCE but not the 2004 GCE completed as many miles of the 2005 GCE course as teams which participated in both the 2004 and 2005 GCE, the author concluded experience gained from participation in the

2004 GCE was not a contributing factor to the increase in the average number of miles of the 2005 GCE course which were completed. Based on the results, the author concluded experience prior to the 2004 GCE was much more important, providing a clear advantage to Teams 2004-04 and 2005-02, 2004-10 and 2005-13, 2005-14, 2005-16, and 2004-23 and 2005-21. With the exception of Teams 2004-04 and 2005-02, these teams completed the 2005 GCE. Teams 2004-10 and 2005-13, 2005-14, and 2005-16 were successful.

To say: "The advantage belongs to experienced teams." provides *a* perspective. However, to say: "Lack of experience is a significant barrier to entry" provides the correct perspective. One of the first deficiencies which must be overcome if inexperienced teams want to compete with more experienced teams is their overall lack of experience. The 2004 and 2005 GCE clearly favored teams with prior experience. For example:

- Four of the five teams which completed the 2005 GCE course had prior experience in the field of robotics: Teams 2005-13, 2005-14, 2005-16, and 2005-21. Teams 2005-13, 2005-14, and 2005-16 were successful.

- Three of the five teams which completed the 2005 GCE course participated in the 2004 GCE, which itself forms the basis for a claim of prior experience: Teams 2005-13, 2005-14, and 2005-21.

- Only one of the four teams which successfully completed the 2005 GCE course had neither prior experience nor participated in the 2004 GCE: Team 2005-06.

- Including 2005 GCE co-participants, one of which participated in the 2004 GCE (Teams 2005-13 and 2005-14 and Teams 2005-22 and 2005-23), 14 of the 23 teams which participated in the 2004 GCE completed more than 7.4 miles of the 2005 GCE course, more than the maximum number of miles completed by any team which participated in the 2004 GCE.

- Including 2005 GCE co-participants, one of which participated in the 2004 GCE (Teams 2005-13 and 2005-14 and Teams 2005-22 and 2005-23), seven of the nine teams which completed more than 25 percent of the 2005 GCE course (32.9 miles) were participants in the 2004 GCE. The exceptions were Teams 2005-06 and 2005-16, both of which successfully completed the 2005 GCE.

The author concluded prior experience was the equivalent of a "force multiplier", which informed team decisions throughout development of a challenge vehicle, allowing teams to bypass unproductive areas of research, guiding team decisions to procure high-quality components and use robust software development methodologies, and highlighting or underscoring the need to perform adequate test and evaluation.

In addition, the basis for team selection was not objective. The evidence supports a conclusion that DARPA selected some teams not on the basis of their ability to develop an autonomous vehicle capable of successfully completing the 2004 or 2005 GCE, but on the basis of a novel technology proposed by the team. This had the effect of "muddying the waters" by advancing teams not capable of competing with other, more experienced teams. See Appendix C, paragraph I.A.5.

For example, DARPA stated: "DARPA used experts in the fields of robotics and sensing technology to evaluate the technologies utilized by the teams seeking to participate in the Grand Challenge and to recognize relevant technological highlights and innovative ideas of potential interest to DoD. The independent technical evaluation team identified the following technology from Grand Challenge 2004 noteworthy..." ([3], p. 10). The list of "technological highlights and innovative ideas" includes several "wrong problems" variously solved by teams participating in the 2004 QID or GCE including "Custom hardware solution for low-cost, real-time stereo algorithm with reflexive planning", "Dynamically balancing motorcycles", and "Rotating ladar for foveal sensing". See paragraph XIV.A.

X.D.2. The effect of sponsorship

Although the author was unable to determine an estimate for the total cost of team challenge vehicles, available evidence supports a conclusion that sponsorship was more a predictor of success than any factor other than experience.

Significant sponsorship increased the number of available options, broadening the potential scope of team solutions to the fundamental problem. Teams with significant sponsorship were able to procure high-quality computing hardware and sensors, reduce complexity by procuring components to eliminate the development of sub-systems such as challenge vehicle controls or INS, and devote additional resources to software development and performance of adequate test and evaluation. Significant sponsorship also caused some teams to lose focus and divert resources to problems other than the fundamental problem.

Limited or no sponsorship resulted in lack of resources such as labor, high-quality sensors, and computing equipment, and limited team use of COTS technologies such as integrated challenge vehicle controls and COTS components used to integrate navigation sensors which had a very real and very direct impact on some teams. For example:

- Team 2004-08

Team 2004-08 was selected to participate in the 2004 QID, but was unable to participate due to limited sponsorship. Team 2004-08 participated in the 2005 GCE as Team 2005-07. Team 2005-07 stated: "[Team 2004-07] is a finalist for the second year in a row. However, last year they were unable to compete due to lack of . This year they were able to develop a number of sponsors who made participation possible and whose logos cover the vehicle... Sponsors are: NC State University, IBM, SAS, Red Hat, Ascot

Technologies, BDMICRO, Comtrol, Council & Sons Repair Service, Crossbow, Frantz Automotive, Lord Corporation, PC MedEvac, SICK, and Smith Anderson." ([233]).

- Team 2004-15

Team 2004-15 was selected to participate in the 2004 QID, but was unable to participate due to limited sponsorship. Team 2004-15 stated: "Although the team has worked diligently and sacrificed much in our effort to have [the challenge vehicle] ready for the March Grand Challenge, it is not to be. We made great strides and were on the right track as evidenced by our inclusion in the first group invited to the QID. Unfortunately, we fell victim to everyone's problem of 'not enough time' and 'not enough money'." ([136]).

- Team 2005-11

Team 2005-11 was selected to participate in the 2005 GCE, and completed 7.2 miles of the 2005 GCE course. Team 2005-11 had limited sponsorship and stated: "...procuring equipment, skilled labor, and sufficient funding also provided formidable challenges for the team." ([182], p. 9).

Although no team which participated in the 2004 GCE completed more than 7.4 miles of the 2004 GCE course, only two teams which participated in the 2005 GCE completed *less than* 7.4 miles of the 2005 GCE. The author considers the increase in sponsorship a contributing factor to the increase in the average number of miles of 2005 GCE course completed, but does not consider the evidence supports a conclusion that sponsorship alone is responsible for the increase in the number of miles of the 2005 GCE course completed.

Based on a comparison of sponsorship of teams which participated in both the 2004 and 2005 GCE (see Table LXVIII), the author concluded there was no significant change in levels of sponsorship, although there was a significant change in the number of miles of the 2005 GCE course completed. Only two teams which participated in both the 2004 and 2005 GCE reported an increase in levels of sponsorship from 2004 to 2005, both of which reported partnership with an academic sponsor: Teams 2004-07 and 2005-05, and 2004-13 and 2005-15.

The author concluded the overall increase in levels of corporate and academic sponsorship cannot account for the increase in average number of miles of the 2005 GCE course completed because the level of sponsorship for teams which participated in both the 2004 and 2005 GCE did not generally increase and teams which participated in the 2005 GCE but not the 2004 GCE completed as many miles of the 2005 GCE course as teams which participated in both the 2004 and 2005 GCE. See paragraph X.D.1. The author also concluded corporate and academic sponsorship allowed teams which participated in the 2005 GCE but not the 2004 GCE to effectively “buy in” by providing access to resources such as labor, high-quality sensors, and computing equipment, and COTS technologies such as integrated challenge vehicle controls and COTS components used to integrate navigation sensors.

In addition to reducing the difficulty of the 2005 GCE course compared to the 2004 GCE course, the author proposes an increase in the number of high-quality sensors in use by the teams, use of a COTS component and Kalman filter to integrate navigation sensors, and performance of adequate test and evaluation was ultimately responsible for the increase in the average number of miles of the 2005 GCE course completed. These issues are explored in more detail throughout this technical report.

X.D.3. Overall conclusions

Prior to the 2005 GCE, in response to a question about the use of government-reimbursed Independent Research and Development (“IR&D”) funding, DARPA stated: “...the funding restriction exists to give all equal opportunity at winning...” ([236], p. 3). However, the evidence does not support a conclusion that all teams had an “equal opportunity at winning”, despite the funding restrictions established by DARPA.

Overall, the author concluded prior experience and significant corporate or academic sponsorship were key factors. Lack of experience was a significant barrier to entry. Sponsorship was more a predictor of success than any factor other than experience. As one of the more extreme examples, Team 2005-07 stated: “[Team 2005-07] is a finalist for the second year in a row. However, last year they were unable to compete due to lack of funding. This year they were able to develop a number of sponsors who made participation possible...” ([233]), and “While invited to the QID for the 2004 Grand Challenge we were unable to compete due to earlier financial constraints. We have continued to develop our technologies and sponsorships and we are now in a position to compete in this year's challenge...” ([118]).

As a result, the author defined the phrase “potentially disruptive team” to identify teams with no prior experience in the field of autonomous vehicle development and neither extensive corporate nor academic sponsorship which implemented key factors. See Chapter XV. No team with prior experience and extensive corporate or academic sponsorship was considered potentially disruptive, consistent with the author's interest. Therefore, these key factors are a negative selector, and were not evaluated for potentially disruptive teams in later sections of this technical report.

CHAPTER XI. PRE-MAPPING

XI.A. Discussion

Many teams which participated in the 2004 QID or GCE or 2005 GCE reported pre-mapping was in use by the team. “Pre-mapping” is defined herein as the addition of metadata as an “overlay” to existing map data which allowed team members to constrain the decisions of the challenge vehicle controlling intelligence. The combination or fusion of map data from multiple maps into a single map is not considered to be pre-mapping, although it was a necessary prerequisite for pre-mapping as defined to by the author when multiple maps were in use by a team. Team strategies to increase waypoint density are considered path editing, and are discussed in Chapter XII.

XI.B. Analysis

Team 2004-10 completed 7.4 miles of the 2004 GCE course, the greatest number of miles completed by any team. Team 2004-10 reported the team performed extensive pre-mapping in the two hours between receiving the 2004 GCE RDDF and the first Departure Signal. Based on the strength of Team 2004-10's performance during the 2004 GCE, the author reviewed the published record to determine whether pre-mapping provided a competitive advantage to teams which participated in the 2004 QID or GCE or 2005 GCE and which reported pre-mapping was in use. Several teams which participated in the 2004 QID or GCE or 2005 GCE reported pre-mapping was in use by the team. For example:

- Team 2004-07

  In response to 2004 SQ 1.d.1 (see Table XXII), Team 2004-07 stated ([46], p. 6):

  ```
  Prior to the race we will create annotated maps of the
  Southern California/Nevada region based on our own GPS
  measurements and on USGS Digital Raster Graphics with
  1-meter resolution, USGS Digital Elevation Models with
  30-meter resolution, and US Census Bureau Tiger 2000
  Transportation Layers including roads from U.S.
  highways to vehicular trails, for all regions for
  which these files are available from the California
  Spatial Information Library and the W.M. Keck Earth
  Sciences and Mining Research Information Center.

  We will annotate areas and road arcs on these maps
  with subjectively determined cost information and
  store the resulting cost maps in a multiresolution
  data structure...
  ```

- Team 2004-10

Team 2004-10 stated: “An off-board map database contains map features including sand, water, paved roads, unpaved roads, vegetation, rock, dry lake beds, out of bounds, and non-traversable terrain to the extent that they are known. This data comes from integrated USGS and BLM maps and is corrected relative to aerial imagery and road reconnaissance. During the two hour period prior to race, provided waypoints are used to extract relevant portions of this map database, which is transferred to vehicle...” ([77], pp. 3 - 4).

- Team 2004-17

Team 2004-17 stated: “We have obtained 1m resolution images of the entire possible race-course, minus censored data over military bases. The computer alone will not know what to do with the RGB maps, so we will 'paint' terrain types onto the maps. Based on color pixel value the computer will be able to distinguish roads, railroad tracks, overpasses, water, mountains, buildings, dry lakes, vegetation areas, and off-road trails.” ([142], p. 6).

- Team 2004-18

Team 2004-18 stated: “The map data will be processed prior to the race to determine zones that will exceed safe operating parameters of the vehicle.” ([48], p. 3), “Pre-processed data consists of map data, boundaries, hydrology, and elevations.” ([48], p. 4), and “Map data will be acquired from the USGS for the southern California and Nevada regions. These maps will consist of 1:24,000 scale DEMs (Digital Elevation Models) and DLGs (Digital Line Graphs). The accuracy of these maps is 40 ft. These digital maps will be analyzed with commercial and custom developed software to determine zones that the vehicle will not be able to traverse due to steep slopes, deep water, etc. Road, bridge, and stream locations will also be stored for use in path planning and object detection and classification while the vehicle is in motion. All map data will be pre-stored on the vehicle for two purposes: high risk long distance route planning once the GPS waypoints are given to us and predictive information during dynamic operation. For instance, if it is known that a stream is within a certain 40ft region then the software interpreting the sensor data will place a higher likelihood on the determination of finding water in the region and the object will be correctly detected and classified according to known depth from the pre-stored map data.” ([48], p. 4).

- Team 2004-19

Team 2004-19 stated: “The maps will be preprocessed within the 2 hours before the race by members of [Team 2004-19] to eliminate areas which are out of bounds (as defined by the RDDF). Further areas will be eliminated as possible route segments at the discretion of [Team 2004-19]. This is to prevent the vehicle from entering an area of treacherous terrain if possible.” ([151], p. 2).

- Team 2004-23

Team 2004-23 stated: “There will be three types of maps. The first is the basic map of the area from the USGS data library, supplied by the OSU Mapping Center. This is being manually 'weighted' to assign hospitability-weights based on photographic images and other known information and create the Hospitability Map.” ([159], p. 7).

- Teams 2005-13 and 2005-14

Teams 2005-13 and 2005-14 stated: “An off-board route planning system incorporates elevation topology, satellite imagery and drive-by topography data. The map data is sparse relative to the possible GC routes. The planning process designates contexts like paved road, dirt trail or underpass. The race planners refine a preplanned route and set intended speeds compliant to the race data definition file. Just prior to race start [the challenge vehicle] receives a path definition file (PDF) consisting of [waypoints], coordinates, speeds and contexts defined for every meter along the race route.” ([11], p. 7 and [12], p. 7).

- Team 2005-21

Team 2005-21 reported a complex description of a three-stage “Pre-Mission Route Planner” and stated: “In the third stage on race day, each split route will be handed over to a human editor for review and possible editing. The editor will then assess his/her assigned split route and look for potential problems with the help of the in-house developed visualization/editing software. The vertical profile at the vicinity of each waypoint being examined is shown to alert him/her of potential speed problems. Maximum vehicle speed at each waypoint can be specified... In case of doubt over the terrain contour from sometimes-ambiguous geo image, the editor can then switch to a 3D exocentric view mode from the map view mode, to determine whether significant terrain drop or rise occur at the side of the route.” ([160], p. 12).

XI.C. Results

- Nine of 48 teams which participated in the 2004 QID or GCE or 2005 GCE reported pre-mapping was in use by the team: Teams 2004-07, 2004-10, 2004-17, 2004-18, 2004-19, 2004-23, 2005-13, 2005-14, and 2005-21.

- Ten of 48 teams which participated in the 2004 QID or GCE or 2005 GCE explicitly stated no external map data was in use by the team: Teams 2004-11, 2004-12, 2004-24, 2005-03, 2005-09, 2005-10, 2005-12, 2005-20, 2005-22, and 2005-23.

- Eleven of 48 teams did not report external map data was in use, but did not explicitly state no external map data was in use by the team: Teams 2004-04, 2004-05, 2004-06, 2005-02, 2005-04, 2005-06, 2005-08, 2005-15, 2005-16, 2005-17, and 2005-18.

- Most[26] other teams reported external map data was in use by the team, but did not report pre-mapping was in use.

In addition, of the 12 teams which participated in both the 2004 and 2005 GCE:

- Two teams reported pre-mapping was in use during both the 2004 and 2005 GCE: Teams 2004-10 and 2005-13 and 2004-23 and 2005-21. Team 2005-13 successfully completed the 2005 GCE. Team 2005-21 completed the 2005 GCE course, but was not successful.

- One team reported external map data was in use during the 2004 and 2005 GCE, but did not report pre-mapping was in use: Team 2004-02 and 2005-01.

- Seven teams reported external map data was in use during the 2004 GCE, but explicitly stated external map data was not in use, or did not report external map data was in use, during the 2005 GCE: Teams 2004-07 and 2005-05, 2004-08 and 2005-07, 2004-13 and 2005-15, 2004-16 and 2005-17, 2004-17 and 2005-18, 2004-18 and 2005-20, and 2004-25 and 2005-22.

- Insufficient technical detail was reported by Teams 2004-04 and 2005-02 and 2004-06 and 2005-03 to determine if external map data was in use during the 2004 GCE or if there was a change in strategy between the 2004 and 2005 GCE.

Two of the teams which reported external map data was not in use by the team successfully completed the 2005 GCE: Teams 2005-06 and 2005-16.

Team 2005-06 later stated: "The rules did not prevent normalization of DARPA's data before they were fed to the vehicles, neither did they prevent elevation map databases, however, [the challenge vehicle] did not make use of any information other than its sensor readings and DARPA's waypoint data given to it in raw form." ([28], p. 510).

Team 2005-16 did not report external map data was in use by either the team technical proposal ([195]) or results published via the Journal of Field Robotics ([25]).

XI.D. Conclusions

Although two of the four teams which successfully completed the 2005 GCE (Teams 2005-13 and 2005-14) reported pre-mapping was in use, two of the four teams did not report pre-mapping was in use. As a result, the author concluded it was possible to successfully complete the 2005 GCE without the use of pre-mapping, and that pre-mapping was not a key factor.

Teams 2005-13 and 2005-14 stated: "Much of the technical approach described in this paper was excessive given the final form of the Grand Challenge. The groomed roads and carefully detailed route provided by the organizers greatly reduced two of the competitive advantages (namely the H1 & HMMWV chassis and the preplanning system) applied by the team." ([24], p. 505).

The author considers this supports a conclusion that the pre-mapping in use by Teams 2005-13 and 2005-14 did not provide a competitive advantage to the teams, but that insufficient evidence was available to conclude pre-mapping was a negative selector.

However, the author concluded pre-mapping may address certain vulnerabilities reported by teams participating in the 2004 QID or GCE or 2005 GCE: terrain features indicative of the presence of water and significant changes in elevation.

XI.D.1. Terrain features indicative of the presence of water

Teams 2004-05 and 2004-20 reported the implementation of certain sensors or types of sensors to enable the challenge vehicle to detect and avoid water obstacles, such as "depth finders", "conductivity sensors", and "water sensors". See Table XXV. No team participating in the 2005 GCE reported similar sensors were in use. See Table XXVII. Team 2004-18 specifically reported using pre-mapping to identify areas where the challenge vehicle controlling intelligence might encounter "deep water", although Team 2004-18 did not report implementing sensors to detect and avoid water obstacles. See paragraph XI.B.

The 2004 and 2005 GCE courses were located in the Mojave Desert. There are few permanent water features in the area of the Mojave Desert on which the 2004 and 2005 GCE courses were located. As a result, the author concluded team implementation of these sensors increased complexity and was unlikely to have had an effect on success.

However, the temporary presence of water in the Mojave is accompanied by washouts, dry lake beds, and gullies, of which the challenge vehicle controlling intelligence should be aware and which had a very real impact on team success during the 2005 GCE. Following the 2005 GCE Team 2005-06 stated: "...the director of DARPA said later that if we hadn't had a bug where we slowed down in the dry lakebeds, we would have either beaten [Team 2005-16] or been very, very close to [Team 2005-16's] car. The bug meant we went from 30 miles an hour to two miles an hour on all the dry lakebeds. We'd never tested in an area 100 feet wide like that. We call it the $2 million bug." ([31]).

The author notes the 2004 and 2005 GCE RDDF define several areas with extreme lateral boundary offset. See paragraph II.C.7.d. Although the author cannot be certain, these areas were probably the dry lake beds reported by Team 2005-06. As a result, although the author acknowledges pre-mapping may have offered a solution to this problem, the author asserts pre-mapping would not have addressed the root cause of the problem. The root cause of the problem reported by Team 2005-06 was inadequate test and evaluation. If Team 2005-06 had tested in areas with extreme lateral boundary offset, as indicated by the 2004 GCE RDDF to which it had access prior to the 2005 GCE, it may have encountered the "$2 million bug" and subsequently won the 2005 GCE.

XI.D.2. Significant changes in elevation

Several teams reported the use of ultrasonic or other sensors to provide the challenge vehicle controlling intelligence with the ability to detect rapid changes in elevation. For example:

- Team 2004-20

Team 2004-20 stated: "In addition, there are narrow-angle sonars pointing down ahead of each leading wheel and behind each trailing wheel. These are used to check supporting terrain during low-speed operation." ([107], p. 5).

- Team 2005-01

Team 2005-01 stated: "Cliffs are a serious issue that [Team 2005-01] has encountered, for cliffs generally imply wide open space, which is typically a safe place to drive. [Team 2005-01] will meet this challenge by adjusting its LADAR sensors over the side of the vehicle, to detect and avoid the cliffs." ([10], p. 13).

- Team 2005-04

Team 2005-04 stated: "Two additional ultrasonic rangefinders are mounted high on the front of the vehicle and angled downward, in an attempt to detect sharp dropoffs on either side of the vehicle." ([169], p. 9).

Other teams reported the use of pre-mapping or external map data to eliminate areas with significant changes in elevation from consideration. For example:

- Team 2004-07

Team 2004-07 reported pre-mapping was in use by the team. See paragraph XI.B. In response to 2004 SQ 1.g.3 (see Table XXII), Team 2004-07 stated: "Challenge Route boundaries are treated in the same way as cliffs or any other known impassable obstacle that may not be detectable by onboard sensors." ([46], p. 8).

- Team 2004-19

Team 2004-19 reported pre-mapping was in use by the team to eliminate areas of "treacherous terrain" from consideration. See paragraph XI.B.

- Team 2004-25

Team 2004-25 stated: "Impassable routes such as lakes, cliffs, and areas outside the allowable boundaries will also be removed from the database of possible solutions." ([49], p. 8).

- Team 2005-19

Team 2005-19 stated: "[The challenge vehicle] also makes use of digital elevation models (DEMs) provided by Digital Globe to initialize its maps. The DEMs have errors less than 10m, and can be used to detect roads and large negative obstacles like cliffs. At the beginning of the race, this map data is used as low confidence sensor data to plan an initial path from the start line to the finish." ([55], p. 6).

- Team 2005-21

Team 2005-21 reported pre-mapping was in use by the team to eliminate areas with significant changes in elevation from consideration. See paragraph XI.B.

Although no challenge vehicle was destroyed during the 2004 or 2005 GCE, the author concluded the decision to use pre-mapping to eliminate areas with significant changes in elevation from consideration by the challenge vehicle controlling intelligence was nonetheless prudent due to the high cost of team challenge vehicles, and considers this validates the decisions by some teams to perform pre-mapping for this purpose.

XI.D.3. External map data

Seven of the 12 teams which participated in both the 2004 and 2005 GCE reported external map data was in use during the 2004 GCE, but explicitly stated external map data was not in use, or did not report external map data was in use, during the 2005 GCE. On average, these teams completed 48.6 miles of the 2005 GCE course, approximately 25 times the average distance completed by teams during the 2004 GCE and approximately six and one-half times the greatest distance traveled by Team 2004-10 during the 2004 GCE of 7.4 miles.

The author does not consider the increase in the average number of miles of the 2005 GCE course which were completed to be due to the decrease in the number of teams which explicitly stated external map data was not in use, or did not report external map data was in use, during the 2005 GCE. However, the author concluded the use of external map data during the 2004 GCE may have required teams to implement overly-complex solutions to the problem of autonomous navigation, and may, in fact, have been a "wrong problem" solved by some teams which diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge. See paragraph XIV.A.4.

CHAPTER XII. PATH EDITING

XII.A. Discussion

Many teams which participated in the 2004 QID or GCE or 2005 GCE reported path editing was in use by the team. "Path editing" is defined herein as manually or algorithmically increasing waypoint density of the path defined by the 2004 QID or GCE or 2005 GCE RDDF.

XII.B. Analysis

Several teams which participated in the 2004 QID or GCE or 2005 GCE reported path editing was in use by the team. For example:

- Team 2004-03

Team 2004-03 stated: "The only two databases that the vehicle will have pre-stored are the provided waypoint (RDDF) and our augmented waypoint set (ARDDF). The ARDDF will be generated using a custom application that allows pre-race offline processing of satellite imagery to increase the density of waypoints to provide a tighter route for the vehicle to follow." ([92], p. 4).

- Teams 2004-13 and 2004-14

Teams 2004-13 and 2004-14 stated: "Using the DARPA supplied waypoint list distributed two hours prior to the start of the race, we will analyze the route... The result of this analysis will contain micro-waypoints (additional waypoints between DARPA-provided waypoints)..." ([232], pp. 2 - 3) and ([132], p. 3).

- Team 2004-18

Team 2004-18 stated: "Reactive Route Planning will be accomplished dynamically from all available localization and obstacle data by placing intermediate waypoints between DARPA defined route waypoints that the Challenge vehicle must also pass through." ([48], p. 3).

- Team 2004-25

Team 2004-25 stated: "In the two hours prior to the race, we will develop an optimal global path for the entire route. This will create a curved path within the course boundaries." ([49], p. 8).

- Team 2005-04

Team 2005-04 stated: "Before the race, when the waypoint file is supplied, we have developed software to... Add virtual waypoints... Shift location of waypoints (presumably within the given boundaries)..." ([169], p. 7).

- Team 2005-10

Team 2005-10 stated: "Virtual waypoints are computed on-the-fly to supplement the DARPA waypoints. Waypoints in curves are fitted to a spline to better define the course." ([176], p. 2) and "The path planning algorithm attempts to maintain the vehicle's front differential directly above the proper path at all times... This algorithm computes 'virtual waypoints' between the DARPA supplied waypoints. On long straight portions of road, it adds these virtual waypoints for local guidance when the DARPA waypoint may be over a mile away. In curves, the algorithm fits a spline to the given waypoints and adds additional virtual waypoints to smooth the path." ([176], p. 5).

- Teams 2005-13 and 2005-14

Teams 2005-13 and 2005-14 reported algorithmically increasing waypoint density in the context of collision avoidance: "Collision avoidance modifies the preplanned route to swerve around a sensed obstacle represented as terrain with very high cost. The path planner generates the swerve maneuver by modifying the location of 1 meter spaced Waypoints." ([11], p. 12 and [12], p. 12). However, Teams 2005-13 and 2005-14 later stated: "Path editing is a process that transforms a set of coarse waypoints and speed limits into a preplanned path with 1 m spaced waypoints." ([24], p. 492).

- Team 2005-15

Team 2005-15 stated: "The very first step after obtaining the DARPA RDDF file is to improve the given route based on existing map data. Such data exists in the form of published maps and has been acquired by predriving certain roads prior to the course area being placed off limits. For the Grand Challenge Event, during the two hours between obtaining the RDDF file and the actual vehicle start, a reference path is computed which includes the DARPA waypoints, but also creates a more refined path at a higher resolution. This reference path is the basis for the vehicle following the given route." ([53], pp. 8 - 9).

- Team 2005-16

Team 2005-16 stated: "To attain a suitable trajectory and associated maximum velocity, the RDDF file is processed by a smoother. The smoother adds additional via points [*sic*] and ensures that the resulting trajectory possesses relatively smooth curvature. The preprocessing then also generates velocities so that while executing a turn, the robot never exceeds a velocity that might jeopardize the vehicle's ability to avoid sudden obstacles. This calculation is based on a physical model of the actual vehicle." ([195], p. 10).

- Team 2005-20

Team 2005-20 stated: "The real time computer does the fundamental global position point following with a 'best estimated path (BEP)' that is calculated beforehand using HANSEL. This program currently interpolates between the large GPS increments provided in the RDDF file. This algorithm's purpose is to generate points at increments that the GPS follower could follow even without a path planner active." ([56], p. 6).

XII.C. Results

DARPA increased waypoint density for the 2005 GCE, defined forced deceleration lanes, and eliminated course segments in excess of 305 m (1000 ft). See paragraph II.D. With the exception of introducing deceleration lanes which forced challenge vehicles to decelerate to significantly lower speeds before a significant change in bearing or other terrain features, the author was unable to determine why DARPA increased waypoint density and eliminated course segments in excess of 305 m (1000 ft) if team strategies to manually or algorithmically increase waypoint density were in common use. For example, each waypoint defined by the 2004 or 2005 GCE RDDF was not accompanied by a change in allowed speed limit and waypoints did not represent a "route" in the traditional sense to a human driver, i.e.: "Go one block, turn left, then go two blocks, and turn right. The shopping center is on the right."

XII.D. Conclusions

At least one team successfully completed the 2005 GCE by smoothing the path without increasing waypoint density: Team 2005-06.

Team 2005-06 stated: "The path planning systems are responsible for ensuring that any path they generate is drivable by the vehicle. To accomplish this, the path planning systems use cubic b-splines to interpolate a path between waypoints. These smoothed paths allow the vehicle to make much more accurate sharp turns. In testing, [Team 2005-06] has successfully navigated several 180 degree hairpin turns with extremely low radii." ([172], p. 10). Team 2005-06 later stated: "The rules did not prevent normalization of DARPA's data before they were fed to the vehicles, neither did they prevent elevation map databases, however, [the challenge vehicle] did not make use of any information other than its sensor readings and DARPA's waypoint data given to it in raw form." ([28], p. 510).

A similar strategy was in use by several other teams which did not report path editing was in use by the team and which did not successfully complete the 2005 GCE, for example: Teams 2005-08, 2005-18, and 2005-19. As a result, the author concluded it was possible to successfully complete the 2005 GCE without increasing waypoint density, and that path editing was not a key factor, but that insufficient technical detail was available to conclude path editing was a negative selector.

The strategy employed by the author to limit the speed of a vehicle in simulation is based on the maximum velocity allowed by vehicle and course geometry, which was determined by analysis of the 2004 and 2005 RDDF, and is not dependent on increased waypoint density. Review of published records revealed this approach was simplistic: although it results in a smooth path from one waypoint to the next, it does not take into account factors such as surface condition, the effect of slope, or the need to alter heading to avoid an obstacle.

However, review of the maximum allowed turn radius calculated by the RDDF analysis application using the 2005 GCE RDDF (see Chapter III.) revealed:

- There was no rollover risk to challenge vehicles during the 2005 GCE. The minimum safety factor in the 2005 GCE course design was 9.8. See paragraph III.D.1.d. A challenge vehicle would have been able to complete the 2005 GCE in 9.45 hours at a maximum course-wide speed limit of 15 mph. See paragraph II.C.7.b. A challenge vehicle would have been able to complete the 2005 GCE in 6.81 hours at a maximum course-wide speed limit of 25 mph, in less time than Team 2005-16. See Table XIII. There was significantly decreased risk of side slip due to surface condition at a reduced speed of 15 or 25 mph in a turn with a safety factor of 9.8.

- No additional waypoints defined by the 2005 RDDF were identified at which the effect of slope would have resulted in a challenge vehicle being at risk of rollover on a slope of five, ten, 20, or 30 degrees. See paragraph III.D.1.a.

In addition, DARPA did not place obstacles along the 2005 GCE course to test challenge vehicle obstacle avoidance capabilities. See Chapter I.

As a result, although the author's approach was simplistic, the author considers it more than adequate for conditions encountered during the 2005 GCE, and asserts this provides some insight into the success of Team 2005-06's path planning strategy.

CHAPTER XIII. FAILURE ANALYSIS

XIII.A. Discussion

The most conclusive evidence that the fundamental problem of the Grand Challenge was not software engineering or artificial intelligence but system integration, is *failure analysis*. To the author's knowledge, no comprehensive failure analysis was performed. DARPA did not perform or publish a comprehensive failure analysis, and stated, when questioned by the author ([237]):

> `DARPA did not publish any reports on Grand Challenge 2004 results. Our goal was, and remains, sparking interest and encouraging innovation in autonomous vehicle technology. It is up to the entrants in Grand Challenge to determine why no vehicle finished the course. We are confident that the $2 million prize for Grand Challenge 2005 will be adequate incentive for many teams to do just that. Grand Challenge 2004 teams are perhaps the best source of information regarding vehicle performance.`

DARPA later amended their reply ([238]):

> `Our October 22 response to your question failed to mention the final report from Grand Challenge 2004 ... which might be of interest to you. It is available in the "Highlights" section at the bottom of DARPA's homepage...`

Although DARPA reported results following the 2004 GCE, insufficient technical detail was reported to determine the cause of failure ([30] and [3], pp. 8 - 9), or the information reported by DARPA did not agree with information reported by the teams. For example:

- Team 2004-01

Team 2004-01 passed on their turn on the first day of the 2004 QID ([78]), and terminated within the starting chute area on the last day of the 2004 QID ([79]). Team 2004-01 was not selected to participate in the 2004 GCE ([80]). DARPA stated only that Team 2004-01 "terminated within the starting chute area" ([79]). However, in private communication with the author the Team 2004-01 team leader attributed the cause of the problem to an unknown system integration failure caused by "severe lack of time" ([239]).

- Team 2004-24

Team 2004-24 was selected as a semifinalist to participate in the 2005 NQE. On September 30, 2005, DARPA stated that Team 2004-24 "did not pass their technical inspection" and "were not permitted to conduct a run" ([240]). However, Team 2004-24 did not report failing a technical inspection. At 2108 on September 30, 2005, Team 2004-24 stated: "[The challenge vehicle] had a good day today, breezing through the dynamic inspection after finding a final irritating bug that kept us from starting the dynamic run earlier in the day." ([241]). Team 2004-24 reported the team made four attempts to complete the 2005 NQE, including an "easier course", but was not selected to participate in the 2005 GCE ([242]).

- Team 2004-25

DARPA attributed the failure of Team 2004-25 to exit the starting chute as ([30]):

```
[Team 2004-25] - Vehicle brakes locked up in the start
area.  Vehicle was removed from the course.
```

and ([3], p. 8):

```
[Team 2004-25] – The vehicle brakes locked up in the
start area; the vehicle was removed from the course.
```

However, in private communication with the author the Team 2004-25 team leader attributed the cause of the problem to "human error" ([243]).

As a result, the author is not confident sufficient technical detail was reported by DARPA to determine the cause of failures encountered by teams participating in the 2004 GCE, and concluded the published record did not report sufficient technical detail to determine the cause of failure for most teams which participated in the 2004 or 2005 GCE. Several teams reported the results of formal or informal failure analysis via the Journal of Field Robotics. The author considers these records generally reliable.

XIII.B. Analysis

The author reviewed the results of formal or informal failure analysis reported via the Journal of Field Robotics to determine the causes of failure before, during, and after the 2005 GCE. To evaluate the assertion that the fundamental problem of the Grand Challenge was not software engineering or artificial intelligence but system integration, the author divided the failures into categories depending on their *type:* "system integration", "controlling intelligence", or "other".

The author then determined if the failures were *preventable* through the use of effective simulation. The most common approach used by teams participating in the 2004 and 2005 GCE may be described as "mixed" or "composite", where a client-server architecture was used to join disparate elements in a distributed architecture. Each of these elements can be reproduced through the use of high-fidelity simulation. Therefore, the use of *effective* simulation would have allowed a team to simulate failure of these elements by introducing noise or errors, and test and evaluate the ability of the controlling intelligence to adapt to, and respond to, failure.

The author classified all failures of the controlling intelligence as preventable because the controlling intelligence was, in general, entirely dependent on external input which could be simulated with high fidelity. However, not all system integration failures were preventable. Teams participating in the 2005 GCE were held to a high standard: system integration failures were considered preventable if they could have been identified through the use of effective simulation, even if this would have required the team to implement a method for performing adequate test and evaluation in simulation.

The DOD's interest in autonomous ground vehicle technology is to enable the controlling intelligence to replace a human driver. As a result, the author first established the expectation that the driving ability of the challenge vehicle's controlling intelligence should equal or exceed that of a human driver. Based on this equivalency, the author reasoned that system integration failures resulting in the same or substantially similar outcome for both the controlling intelligence and a human driver were not preventable, and would not have been identified through the use of effective simulation. Also, the author considers failures not preventable if the failure could not be identified without adequate test and evaluation of the challenge vehicle in the field.

For example, undiagnosed engine problems are not predictable, because unexpected mechanical malfunctions may occur with either a controlling intelligence or human driver driving a vehicle. Components wear and malfunction unpredictably. As a result, undiagnosed engine trouble was classified as unpreventable.

However, suddenly swerving into a wall because of “GPS drift” was predictable. Although reliance on dashboard GPS may cause a human driver with no advance knowledge of the road or terrain to conclude that a road exists where no road exists, no human driver would suddenly swerve into a wall because “GPS drift” caused it to be incorrectly reported as traversable terrain. As a result, this problem was classified as preventable.

XIII.B.1. Team 2005-02

Team 2005-02 selected a purpose-built platform for their challenge vehicle. See Table XVI. During testing prior to the 2005 GCE, the platform selected by Team 2005-02 failed. Team 2005-02 stated: “One of the rear shocks snapped and the engine and frame dropped onto the rear drive shaft and odometer gear. The sudden stop also caused the front sensor cage struts to snap and the sensor cage collapsed forward. The causes of the failures were determined and the system was redesigned and rebuilt in approximately one week.” ([50], p. 618).

Team 2005-02 failed to complete the 2005 GCE due to “a 20-foot position error [which] caused a corresponding shift of the boundary smart sensor that eliminated the actual sensed road as an option to the planner.” ([50], p. 622).

The author considers the platform selection failure an unpreventable other failure, and the GPS drift failure a preventable system integration failure.

XIII.B.2. Team 2005-04

Team 2005-04 stated: “In the first set of robotic operations, [the challenge vehicle] tried five times back-and-forth operations before it overcame an obstacle. In the second set of robotic operations, [the challenge vehicle] was terminated. However, neither DARPA report nor [the challenge vehicle's] race log indicated that [the challenge vehicle] had had any collisions or gone off the road in the GC05 race. Also, [the challenge vehicle] was still totally driveable and stayed in the middle of the road when it was terminated. We guess it was because of the slowness in [the challenge vehicle's] gear shifting. Since it took up to 1 min for [the challenge vehicle] to shift its gear position in some situations, which might be intolerably slow, the second set of robotic operations might present the illusion that [the challenge vehicle] came to a halt and thus caused the termination.” ([51], p 741). Team 2005-04 later stated: “We were not provided with official reasons of the termination.” ([51], p 741).

The author was unable to determine if a failure occurred, or if Team 2005-04 was able to determine the cause of failure, if a failure occurred. As a result, the author did not include Team 2005-04 in the summary results presented later in this section.

XIII.B.3. Team 2005-05

Team 2005-05 stated: “[The challenge vehicle] crashed on three significant occasions: Twice during NQE trials and once during the GCE.” ([170], p. 550). Team 2005-05 described the causes of the two failures that occurred during the 2005 NQE as follows:

- “...one of the vertical ladars had been repositioned and miscalibrated (due to a missing decimal point)” ([170], p. 550).
- A path planner “...failed to properly validate all the possible candidate trajectories and ended up selecting a degenerate trajectory containing two sharp 180º turns” ([170], p. 551). As a result, the challenge vehicle drove into a concrete barrier.

Team 2005-05 failed to complete the 2005 GCE due to “static memory over-allocation” and stated: “[The challenge vehicle] had made experimental autonomous runs of 10 miles or so, but had never made a continuous overland journey on the scale of the GCE. Furthermore, an endurance trial which consisted of driving for long periods around a track would probably not have uncovered this bug.” ([170], p. 551).

The author considers the path planner failure a failure of the controlling intelligence, but the other two failures to be preventable system integration failures.

XIII.B.4. Team 2005-06

Team 2005-06 successfully completed the 2005 GCE. Team 2005-06 stated: "Several issues were discovered after analyzing the vehicle during a postrace inspection." ([28], p. 524). Team 2005-06 described the failures that occurred during the 2005 GCE as follows ([28], pp. 524 - 525):

- "The vehicle's steering was severely out of alignment."
- "The ABS was displaying intermittent failures that caused the brakes to behave in an erratic fashion."
- "The logging system crashed after 28 miles."
- "...an error in the path planning algorithms ... caused them to time out when faced with sections of the route with extremely wide lateral boundaries."

The author considers the steering and braking failures other failures, and the logging system failure a preventable system integration failure. When evaluating the causes of the steering and braking failures, Team 2005-06 stated they were assumed to be the result of rough terrain. The author concluded these failures were not preventable.

Team 2005-06 indirectly attributed their failure to place first or second during the 2005 GCE on extreme lateral boundary offset. Team 2005-06 stated: "...the director of DARPA said later that if we hadn't had a bug where we slowed down in the dry lakebeds, we would have either beaten [Team 2005-16] or been very, very close to [the Team 2005-16 challenge vehicle]. The bug meant we went from 30 miles an hour to two miles an hour on all the dry lakebeds. We'd never tested in an area 100 feet wide like that." ([31]).

The 2004 RDDF defines 12 segments with lateral boundary offset exceeding 50 ft. See paragraph II.C.7.d. As a result, the author concluded Team 2005-06 should have expected to encounter areas of extreme lateral boundary offset and considers the error in the path planning algorithms a preventable system integration error.

XIII.B.5. Team 2005-09

Team 2005-09 described the cause of multiple failures during the 2005 NQE in the "hand-off from planning and to reactive modes" as: "GPS loss" ([52], p. 832). The author considers this a preventable system integration failure.

Team 2005-09 reported test and evaluation using "a ball cap covered with tin foil over the GPS unit, effectively killing its signal" to induce "GPS loss" to diagnose this problem ([52], p. 832). The author considers this supports a conclusion that this was a preventable system integration failure.

Team 2005-09 failed to complete the 2005 GCE, and stated the challenge vehicle detected occasional dust clouds as transient obstacles, which ultimately caused the challenge vehicle to veer off course where it was unable to continue because "the lasers could not differentiate between weeds and large rocks" ([52], p. 835). The author considers this a preventable system integration failure.

XIII.B.6. Team 2005-12

Team 2005-12 failed to complete the 2005 GCE due to "a bug in the obstacle tracking code, as obstacles were never entirely cleared from the list of tracked obstacles when passed. Tracking the position of thousands of irrelevant obstacles overwhelmed the processor, and starved critical code." ([183], p. 752). The author considers this a preventable system integration failure.

In addition, Team 2005-12 described several failures that occurred while attempting to evaluate the challenge vehicle's performance after the failure due to the bug in the obstacle tracking code was corrected ([183], p. 753):

- "a communications failure between the GPS unit and the guidance computer".
- The "vehicle blew out its left front tire at the base of the pass on the descent, following a collision with a small sharp rock" because the challenge vehicle's stereo camera pair "could not detect small but crucial features of this size". As a result, the "front wheels were also jarred out of alignment".
- Team 2005-12 also reported "three hardware failures would have ended a fully autonomous attempt of the course: A communications cable came loose, the steering position encoder became jammed with sand, and the vehicle's spare tire, installed to replace the old left front tire, was eventually destroyed by the terrain".

Team 2005-12 reported insufficient technical detail to evaluate the cause of the communications failure reported. The author considers the failure of the stereo camera pair to reliably detect an obstacle which disabled the challenge vehicle, communications cable failure, and steering position encoder failure preventable system integration failures. The author considers the failure of the challenge vehicle's spare tire an unpreventable other failure.

XIII.B.7. Teams 2005-13 and 2005-14

Although Teams 2005-13 and 2005-14 successfully completed the 2005 GCE, Team 2005-14 reported a failure due to an undiagnosed engine problem ([24], pp. 501 - 502) and a gimbal failure ([24], p. 502). The gimbal housed the challenge vehicle's Riegl LMS-Q140i.

The author considers the failure due to an undiagnosed engine problem an unpreventable other failure, and the gimbal failure a preventable system integration failure.

XIII.B.8. Team 2005-15

Team 2005-15 described the cause of a failure that occurred during the 2005 NQE as follows: “The GPS receiver incorrectly reported its measurements−valid to within 10 cm. Instead, the position measurement was off by 10 m to the north and east, and the velocities were reported as pure zeros causing the localization algorithm to crash. The addition of a few simple lines of code ignored these false messages...” ([133], p. 595). The author considers the GPS receiver failure a preventable system integration failure.

Team 2005-15 failed to complete the 2005 GCE and stated: “Although the vehicle was capable of operating at higher speeds, the obstacle detection system could not process the data reliably beyond 11 m/s. ... After an analysis of the recorded data, the cause of failure is fairly certain. Shortly before [the challenge vehicle] went off road, it lost all LIDAR data. Soon thereafter, it lost all vehicle state data. The LIDAR and the internal sensors were connected via USB hubs to the processing computers. Speculation is that one of the following faults occurred and ended [the challenge vehicle's] day: USB hubs lost power−terminating the connection between the computer and sensors, or the USB hubs overheated and ceased to function.” ([133], p. 595).

The author considers the USB hub failure an unpreventable system integration failure, even though the effect was indistinguishable from complete loss of sensors.

XIII.B.9. Team 2005-16

Team 2005-16 stated: “The primary measure of system capability was 'MDBCF'−mean distance between catastrophic failures. A catastrophic failure was defined as a condition under which a human driver had to intervene. Common failures involved software problems... occasional failures were caused by the hardware, e.g., the vehicle power system. In December 2004, the MDBCF was approximately 1 mile. It increased to 20 miles in July 2005. The last 418 miles before the National Qualification Event were free of failures; this included a single 200-mile run over a cyclic testing course. At that time, the system development was suspended, [the challenge vehicle's] lateral navigation accuracy was approximately 30 cm. The vehicle had logged more than 1,200 autonomous miles.” ([25], pp. 685 - 686).

Team 2005-16 successfully completed the 2005 GCE, placing first with a time of 06:53:58 hours. Team 2005-16 reported insufficient technical detail to evaluate the cause of the failures reported by the team. As a result, the author did not include Team 2005-16 in the summary results presented later in this section. However the author considers the aggressive test and evaluation reported by Team 2005-16 to have been a factor contributing to their success and to support a conclusion that system integration was the real Grand Challenge.

XIII.B.10. Team 2005-17

Team 2005-17 described the causes of the failures that occurred during the 2005 NQE as follows ([196], pp. 574 - 575). The challenge vehicle:

- "climbed the hay bails [*sic*] when approaching the tunnel due to a rounding error in the path planner". Team 2005-17 had previously identified this as a potential cause of failure.

- "suddenly stopped after going through the tunnel due to a GPS/INS-related failure" caused by "loss of GPS signal in the tunnel".

- "did not compete in Run 3 because of a mechanical failure" caused by a "broken transmission".

- "ran into the last car on the final stretch in Run 6" which was not detected by the challenge vehicle's LIDAR sensors because "the second car was in the blind spot of the top lidar".

The author considers the failure caused by a broken transmission to be an unpreventable other failure. The author considers the failures caused by rounding error, loss of GPS signal, and a blind spot in the challenge vehicle's LIDAR sensors to be preventable system integration failures.

Team 2005-17 failed to complete the 2005 GCE due to a problem related to the failure caused by the broken transmission noted above, and stated: "After transmission failure, [Team 2005-17] did not calibrate the actuators [*sic*] correctly. Its '1' was mapped to a position that the transmission could not physically reach. When the vehicle was put into pause mode, to engage the brakes the levers had to be moved to '1.' However, this position could not be reached and the motor controller continued to attempt to move it. In the process, for 45 min, the motor was fed its peak current, a current it can withstand only for short duration. That caused the motors on the actuators to burn out." ([196], p. 576).

If the motor had burned out due to routine use and wear, the author would consider the failure due to actuator calibration an unpreventable other failure, but because the controlling intelligence could not distinguish between the actual position of the actuator and the target position of the actuator and consequently burned out the motor, the author considers this a preventable system integration failure, however difficult it would be to simulate in practice.

The author acknowledges it was not an expected failure mode of the vehicle, and that it is unreasonable to expect a team to willfully sabotage its own entry to determine the impact of re-assembling the vehicle incorrectly after component failure. However, the author asserts an installation or repair procedure would have prevented this problem.

XIII.B.11. Team 2005-18

Team 2005-18 failed to complete the 2005 GCE and described the causes of several failures that occurred during the 2005 GCE as follows ([54], pp. 807 - 808):

- "...[the challenge vehicle's] ultimate demise was rooted in its incorrect state estimates (due to poor GPS signals)".
- "midrange LADAR sensor failures" caused by entering "an error mode from which they cannot recover".
- "the lack of a system-level response to such failures".
- "high speeds assigned to long-range sensor data, even in the face of state uncertainty."

The author considers the lack of system-level response to failures encountered by Team 2005-18 during the 2005 GCE and high speeds assigned to long-range sensor data to be failures of the controlling intelligence, but the incorrect state estimation due to "poor GPS signals" and midrange LIDAR sensor failures to be preventable system integration failures.

XIII.B.12. Team 2005-19

Team 2005-19 failed to complete the 2005 GCE and described the causes of two failures that occurred during the 2005 GCE as follows ([198], p 649):

- A "GPS receiver experienced a jump of approximately 2 m, and thereafter it reported an apparent error of more than 1 m" due to "re-acquisition of the OmniSTAR HP signal, which [the challenge vehicle] had lost approximately 175 s earlier".
- The "attitude estimator's pitch estimate to pitch derived from GPS velocity" caused the challenge vehicle to "localize LIDAR measurements incorrectly".

The author considers both failures preventable system integration failures.

XIII.B.13. Team 2005-21

Team 2005-21 completed the 2005 GCE course, but was not successful. Team 2005-21 did not report failures encountered by the team via the Journal of Field Robotics. As a result, the author did not include Team 2005-21 in the summary results presented later in this section.

XIII.B.14. Teams 2005-22 and 2005-23

Teams 2005-22 and 2005-23 described the cause of a failure that occurred during test and evaluation prior to the 2005 GCE: "A common experience for [Teams 2005-22 and 2005-23] GPS and inertial-based positioning systems is the 'GPS pop'... This occurs when, after running on inertial-only positioning, the GPS/ INS regains the GPS signal. The perceived position of the vehicle instantaneously jumps from the INS-computed location to the GPS-based position." ([59], pp. 723 - 724).

Teams 2005-22 and 2005-23 failed to complete the 2005 GCE and stated: "Both vehicles failed due to mechanical problems, rather than poor navigation decisions. [The Team 2005-22 challenge vehicle] drive engine stalled when it briefly slowed to an idle, and [the Team 2005-23 challenge vehicle's] on-board generator shut down due to a suspected false low-oil reading." ([59], p. 726).

The author considers the "GPS pop" failure a preventable system integration failure. Teams 2005-22 and 2005-23 reported insufficient technical detail to evaluate the cause of the mechanical failures reported by the teams. Although Teams 2005-22 and 2005-23 reported what occurred, the teams did not report sufficient technical detail to determine if the failures were preventable. As a result, the author did not include the mechanical failures reported by Teams 2005-22 and 2005-23 in the summary results presented later in this section.

XIII.C. Results

Tabulated results are presented in Table LXIX, and summarized below:

- Three of 32 failures reported (9 percent) were failures of the controlling intelligence,

- Twenty-three of 32 failures reported (72 percent) were system integration failures, and

- Six of 32 failures reported (19 percent) were other failures.

- Twenty-three of 32 failures reported (72 percent) were preventable.

XIII.D. Conclusions

The author concluded the majority of failures reported by teams before, during, and after the 2005 GCE were system integration failures which were preventable through the use of effective simulation. As a result, the author considers adequate test and evaluation a key factor.

CHAPTER XIV. SYSTEM INTEGRATION WAS THE FUNDAMENTAL PROBLEM OF THE GRAND CHALLENGE

Throughout this chapter, system integration is described as "the fundamental problem of the Grand Challenge" or "the fundamental problem"[27].

The most conclusive evidence that the fundamental problem of the Grand Challenge was not software engineering or artificial intelligence but system integration, is *failure analysis*. See Chapter XIII. However, there were a number of other strategies common to the teams which support a conclusion that system integration was the fundamental problem of the Grand Challenge:

XIV.A. Identify the fundamental problem of the Grand Challenge

DARPA established the Grand Challenge to "promote innovative technical approaches that will enable the autonomous operation of unmanned ground combat vehicles". See Chapter I. However, DARPA did not award prize money on the basis of innovation in the field of autonomous ground vehicle technologies. DARPA awarded prize money to the first team to complete the 2005 GCE course. As a result, the actual goal of the Grand Challenge was concealed by the format of the Grand Challenge as a race.

The author considers the difference between the problem statement reported by DARPA and the fundamental problem of the Grand Challenge to be a contributing factor to the failure of some teams to accurately identify the problem and to solve what was essentially a "wrong problem", for example, the pre-mapping performed by Teams 2005-13 and 2005-14:

In a discussion of lessons learned from the Grand Challenge, Teams 2005-13 and 2005-14 stated: "Know the problem. Much of the technical approach described in this paper was excessive given the final form of the Grand Challenge. The groomed roads and carefully detailed route provided by the organizers greatly reduced two of the competitive advantages namely the H1 & HMMWV chassis and the preplanning system applied by the team. Furthermore, the team put an excess of wear-and-tear on the vehicles during testing operating on more rugged terrain than that encountered during the challenge. Had the final race conditions been known ahead of time, it would have been possible to shed a significant amount of technical complexity." ([24], p. 505).

The author considers solving a wrong problem diverted team resources which may have been used to more effectively solve the fundamental problem, or introduced unnecessary complexity by making the fundamental problem more difficult to solve.

Wrong problems variously solved by teams participating in the 2004 QID or GCE or 2005 GCE included:

XIV.A.1. Purpose-built vehicles

XIV.A.1.a. 2004

Six teams which participated in the 2004 QID selected purpose-built vehicles as challenge vehicle platform: Teams 2004-01, 2004-05, 2004-11, 2004-12, 2004-19, and 2004-24. See Table XIV. Five of the six teams did not complete the QID and were not selected to participate in the 2004 GCE: Teams 2004-01, 2004-05, 2004-11, 2004-12, and 2004-19. Team 2004-24 was selected to participate in the 2004 GCE, but withdrew prior to start ([30] and [3], p. 9).

XIV.A.1.b. 2005

Two teams which participated in the 2005 GCE selected purpose-built vehicles as challenge vehicle platform: Teams 2005-02 and 2005-20. See Table XIV. Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average. Team 2005-02 completed 13.6 miles of the 2005 GCE course, less than the average.

Team 2005-20 completed 81.2 miles of the 2005 GCE course, the only team in either the 2004 or 2005 GCE to select a purpose-built vehicle as challenge vehicle platform and complete more than the average number of miles completed in either event.

Team 2005-20 stated: “[Team 2005-20] is a volunteer group of highly qualified ... engineers that specialize in the development of innovative technologies.” Team 2005-20 reported the team was sponsored by a corporation “...which provides engineering, science and advanced technology solutions for the defense, security, transportation, environment, aerospace, and intelligent automation industries.” ([56], p. 2).

In addition, Team 2005-20 stated: “The main goal of selecting a vehicle was to choose a vehicle that could handle the rough desert terrain with good handling characteristics, and acceptable acceleration performance while supplying a stable platform for the obstacle detection sensor array. This approach eliminates the need for complex gimbals and/or shock suppression suspensions for the sensor array. The major disadvantage of this approach is that the sensors look in a fixed direction requiring multiple sensors to cover the same zone that a single sensor could handle if it was gimbaled and pointed at the appropriate heading. The team researched several commercial trucks, military vehicles, and desert race vehicles before deciding on a custom-made chassis meeting all of our derived requirements.” ([56], p. 3) and “The time spent in chassis specification and selection has paid off in safe reliable operation of [the challenge vehicle] on a variety of surfaces and at speeds and turning radiuses not achievable by either our previous Grand Challenge vehicle..., or by conventional SUV or pickup trucks.” ([56], p. 15). The author concluded team experience and corporate sponsorship contributed to Team 2005-20's completion of 81.2 miles of the 2005 GCE course using a purpose-built vehicle as challenge vehicle platform.

However, Team 2005-20 also stated: "A concerted effort was put into the selection of the suspension components and tires to minimize unsprung weight and therefore minimize chassis motion during tire impact. The suspension links are lightweight and the wheel and tire combinations are the largest and lightest available on the market today." and "Runflat or foam filled technologies were rejected owing to the additional unsprung weight of 60-100 lbs per tire." ([56], pp. 3 - 4). Ironically, Team 2005-20's selection of lightweight components may have been the cause of the problem which prevented the team from completing the 2005 GCE. Team 2005-20 failed to complete the 2005 GCE due to a tire blowout, after the team challenge vehicle "started to exhibit some unusual behaviors" ([244]), possibly after leaving the course due to a bent frame.

XIV.A.1.c. Conclusions

Overall, the author concluded design and construction of a purpose-built vehicle represented a major development effort which diverted resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

The author considers the decrease in the number of purpose-built vehicles selected as challenge vehicle platform by teams which participated in the Grand Challenge from the 2004 QID to the 2004 GCE supports this conclusion. In addition, several teams explained the rationale behind their decision to select a commercially-available SUV or truck as challenge vehicle platform was influenced by similar concerns. For example:

- Team 2005-05

Team 2005-05 stated: "Reviewing the outcome of the 2004 Grand Challenge, we believe that generally speaking … vehicles based on commercial platforms did better than entirely custom-made vehicles. We felt this vindicated our choice of platform." ([34], p. 2).

- Team 2005-09

Team 2005-09 stated: "The decision was made early to purchase a commercial vehicle rather than develop a custom platform. This has allowed the focus to be on issues more relevant to potential [Team 2005-09] sponsors including vehicle control, localization, navigation, and sensing/responding to the environment." ([175], p. 2).

- Team 2005-10

Team 2005-10 stated: "The rational [*sic*] for this choice was that we didn't want to spend time designing and building a vehicle. We wanted to spend time on the sensory and navigation systems, so we bought a commercial vehicle that was as close as possible to what was needed and modified it in the ways described above." ([176], p. 2).

XIV.A.2. Proprietary sensors

Several teams which participated in the 2004 QID or GCE or 2005 GCE reported proprietary sensors were in use by the team. For example:

- Team 2004-04

Team 2004-04 stated: “One sensor is mounted on a rotating mechanism that enables it to scan multiple lines to produce a 3 dimensional data representation of the terrain.” ([44], pp. 8 - 9). Team 2004-04 participated in the 2005 GCE as Team 2005-02. Team 2005-02 also proposed using one rotating LIDAR sensor, however no rotating LIDAR sensor was in use by Team 2005-02 during the 2005 GCE. See below.

Both Teams 2004-04 and 2005-02 reported one rotating LIDAR sensor was in use via team technical proposals, and the rotating LIDAR sensor therefore represented a continuous development effort on the part of the team over a period of several years. The author concluded the Team 2004-04 rotating LIDAR sensor did not represent a major development effort on the part of the team, but diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

- Team 2004-06

Team 2004-06 developed a proprietary stereo camera pair for use during the 2004 GCE as the only obstacle and path detection sensor. See Table XXV. Team 2004-06 stated: “The vision system represents the major effort of the project.” ([114], p. 2).

In response to 2004 SQ 2.a and 2.b (see Table XXII), Team 2004-06 stated: “The vision system is functional and road testing will begin once the new sensors are operational.” and “Extensive tests are planned.” ([114], p. 3). The Team 2004-06 technical proposal ([114]) was dated February 20, 2004, approximately three weeks prior to the 2004 QID and GCE.

The author concluded the Team 2004-06 proprietary stereo camera pair represented a major development effort on the part of the team, diverting team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

Team 2004-06 participated in the 2005 GCE as Team 2005-03. Team 2005-03 developed a proprietary LIDAR sensor for use during the 2005 GCE. See below.

- Team 2004-22

Team 2004-22 developed a proprietary video system for use during the 2004 GCE as the only obstacle and path detection sensor. See Table XXV. Team 2004-22 reported very little additional identifying information for the components comprising their proprietary solution, and no additional identifying information for the cameras in use by the team. See paragraph V.C.22.c. Team 2004-22 twice referred to a "proprietary annex" which concealed technical detail. See paragraph V.E.2.f.

Despite a lack of sufficient technical detail, based on the capabilities reported by the team the author concluded the Team 2004-22 Video System represented a major development effort on the part of the team, diverting team resources which may have been used to more effectively solve the problem of system integration presented by the Grand Challenge.

- Team 2005-02

Team 2005-02 stated: "Also mounted on the sensor cage are two SICK ladars: one rotating ladar for 3D obstacle detection, the other fixed to scan the ground ahead of the vehicle for terrain slope estimation, tuned for negative obstacle detection." ([167], p. 8). Team 2005-02 later stated: "Also mounted on the sensor cage are two SICK LADARs that scan the ground ahead of the vehicle for terrain slope estimation; one tuned for negative obstacle detection and the other for smooth terrain detection. Also, an additional SICK LADAR aimed parallel to the ground plane is mounted on the front of the vehicle at bumper level for planar obstacle detection." ([50], p. 604).

Team 2005-02 did not report a rotating LIDAR sensor was in use by the team during the 2005 GCE via the Journal of Field Robotics. The author concluded a rotating LIDAR sensor was not in use by Team 2005-02.

However, both Teams 2004-04 and 2005-02 reported one rotating LIDAR sensor was in use via team technical proposals, and the rotating LIDAR sensor therefore represented a continuous development effort on the part of the team over a period of several years. The author concluded the Team 2005-02 rotating LIDAR sensor did not represent a major development effort on the part of the team, but diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average. See paragraph VI.D. Team 2005-02 completed 13.6 miles of the 2005 GCE course, less than the average.

- Team 2005-03

Team 2005-03 developed a proprietary LIDAR sensor for use during the 2005 GCE as the only obstacle and path detection sensor. See Table XXVII. Team 2005-03 stated: "[Team 2005-03] designed and built all components in use for its DGC entry from the ground up dedicated for this purpose." ([33], p. 6).

The author concluded the Team 2005-03 proprietary LIDAR sensor represented a major development effort on the part of the team, diverting team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average. See paragraph VI.D. Team 2005-03 completed 26.2 miles of the 2005 GCE course, less than the average.

Team 2005-03 was the only team which participated in both the 2004 and 2005 GCE to develop a different proprietary sensor as the only obstacle and path detection sensor in use by the team for each event.

- Team 2005-04

Team 2005-04 developed a proprietary RADAR sensor for use during the 2005 GCE. See Table XXVII. Team 2005-04 stated: “The second radar has a slewing dish antenna and is an in-house development.” ([169], p. 8). The author concluded the Team 2005-04 proprietary RADAR sensor did not represent a major development effort on the part of the team, but diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

Teams which participated in the 2005 GCE completed 48.3 miles of the 2005 GCE course, on average. See paragraph VI.D. Team 2005-04 completed 29.0 miles of the 2005 GCE course, less than the average.

XIV.A.3. Navigation sensor integration

The author reviewed the published record to determine whether a Kalman filter or other sensor fusion strategy was in use by the teams, and whether teams implemented their own Kalman filter or other sensor fusion strategy, or it was a feature of a COTS component in use by the team. See Chapter VII.

The author concluded teams which independently implemented an other sensor fusion strategy diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge to attempt to solve a problem that had been solved by providers of COTS components at the time of the 2004 and 2005 GCE, not a problem of artificial intelligence, and were, in effect, solving a wrong problem. See paragraph VII.D.

XIV.A.4. Pre-mapping

Several teams which participated in the 2004 QID or GCE or 2005 GCE reported pre-mapping was in use by the team, including Team 2004-10, which completed 7.4 miles of the 2004 GCE course, the greatest number of miles completed by any team. Based on the strength of Team 2004-10's performance during the 2004 GCE, the author reviewed the published record to determine whether pre-mapping provided a competitive advantage to teams which participated in the 2004 QID or GCE or 2005 GCE and which reported pre-mapping was in use. See Chapter XI.

The author concluded it was possible to successfully complete the 2005 GCE without the use of pre-mapping, and that pre-mapping was not a key factor. However, the author concluded pre-mapping may address certain vulnerabilities reported by teams participating in the 2004 QID or GCE or 2005 GCE: terrain features indicative of the presence of water and significant changes in elevation. In addition, the author concluded the use of external map data during the 2004 GCE may have required teams to implement overly-complex solutions to the problem of autonomous navigation, and may, in fact, have been a wrong problem solved by some teams which diverted team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge. See paragraph XI.D.

XIV.A.5. Team 2004-03 self-stabilizing motorcycle

Team 2004-03 selected a motorcycle as challenge vehicle platform. See Table XIV. In response to 2004 SQ 2.a (see Table XXII), Team 2004-03 described test and evaluation performed to date to develop a self-stabilizing motorcycle ([92], pp. 6 - 7). Although Team 2004-03 has headings for other tests including "DGPS correction", "GPS waypoint navigation", and "RDDF processing", Team 2004-03 did not report any previous or planned tests in these areas as of the March 1, 2004 revision of their technical proposal, approximately one week prior to the first day of the 2004 QID on March 8, 2004.

The author concluded the self-stabilizing motorcycle described by Team 2004-03 represented a major development effort on the part of the team, diverting team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

XIV.A.6. Team 2004-21 programming language, compact "standard and solar charging system", and "hybrid navigational system"

Team 2004-21 stated ([155], p. 4, *emphasis in original*):

> The microcontrollers will be programmed in their native Forth language and the Pentium class machine(s) will be programmed in "**Hoopla**", a custom programming language with many features not found in other languages...
>
> (**Hoopla** – Hierarchical **O**bject **O**riented **P**rogramming **La**nguage.)
>
> Hoopla is a set of application-specific words (using **Forth** as a base language) that define an environment

> that can quickly react to interrupting conditions with predefined decision tables controlling how the vehicle should react to the interrupting conditions. Hoopla basically turns every sensory condition into an action similar to the way in which biological nervous systems react to stimulus such as a pin-prick or a bruising. Combining what might be called the **"Best of AI"**, Hoopla is best described as (1) a set of sensory objects that combine (2) an Artificial Neural Network with (3) predefined methods that take the form of (4) a decision tree/expert system.

An Internet search using the key words "HOOPLA" or "Hierarchical Object Oriented Programming Language" as the search string revealed several programming languages named "Hoopla" exist, including some with sound-alike names such as "HOPL" or "HOOPLE" and a periodical about object-oriented programming languages named HOOPLA ("Hooray for Object Oriented *Programming Languages*!"). Some of these references pre-date the 2004 GCE by several years, while others are more recent developments. However, none of the programming languages named "Hoopla" conform to the Team 2004-21 description of Hoopla, above.

In addition to the Team 2004-21 programming language, Team 2004-21 also stated: "Extra power will be provided by standard and solar charging system. Our design is more compact and more efficient than anything ever used before. This too is new technology." ([155], p. 3) and "We will be using terrain following technology, this is a hybrid navigational system unlike anything used before, a composite of many systems working together." ([155], p. 6).

The author concluded Hoopla, as described by Team 2004-21, the compact "standard and solar charging system", and the "hybrid navigational system" represented a major development effort on the part of the team, diverting team resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

XIV.B. Reduce complexity

XIV.B.1. Reduce the number of components

XIV.B.1.a. <u>Eliminate unnecessary state sensors</u>

Via 2004 SQ 1.f.1 and 1.f.2 (see Table XXII), DARPA requested teams report: "What sensors does the challenge vehicle use for sensing vehicle state?" and "How does the vehicle monitor performance and use such data to inform decision making?" The author completed a comprehensive review of technical proposals submitted by teams participating in the 2004 QID or GCE to determine if team technical proposals reported sufficient technical detail to identify the quantity, manufacturer, and model number for state sensors in use by the teams.

Via 2005 SQ 2.3.3 (see Table XXIII), DARPA requested teams report: “Describe the internal sensing system and architecture used to sense the vehicle state.” The author did not complete a comprehensive review of 2005 NQE and GCE technical proposals. The author did not attempt to determine if 2005 technical proposals reported enough information to determine the quantity, manufacturer, and model number for state sensors in use by the teams. See paragraph V.B.2.

The author asserts these questions predisposed some teams to implement unnecessary state sensors. For example:

XIV.B.1.a.i. Fuel level monitoring sensors

XIV.B.1.a.i.a. 2004

Three of 25 teams participating in the 2004 QID or GCE reported fuel level monitoring sensors were in use by the team: Teams 2004-01, 2004-08, and 2004-21. No 2004 challenge vehicle had a maximum range of less than the reported 142-mile course length (see Table LXX).

However, DARPA revised the proposed 2004 GCE course length continuously in the months prior to the date team technical proposals were required to be submitted to DARPA. Teams were required to implement a challenge vehicle which could traverse a course of these lengths and describe their implementation via their technical proposals. DARPA stated the proposed 2004 GCE course length would be 300 miles on February 22, 2003, “approximately 250 miles” on June 18, 2003, and “approximately 210 miles” on November 26, 2003. See Appendix C.

Team technical proposals were required to be submitted to DARPA by October 14, 2003, approximately two and one-half months before DARPA published revision “5 January 2004” of the 2004 GCE rules which eliminated the “Checkpoint Area” the author determined was located near the midway point of the proposed 2004 GCE course and after DARPA stated the proposed 2004 GCE course length would be 250 miles.

As a result, the author selected proposed 2004 GCE course length of 250 miles as representative of the expected course length prior to January 5, 2004, and on the date by which teams participating in the 2004 GCE were required to submit a complete technical description of their challenge vehicles to DARPA, including reported range.

Three teams reported a range of less than a proposed 2004 GCE course length of 250 miles: Teams 2004-03, 2004-10, and 2004-16. See Table LXX.

Neither Team 2004-03, 2004-10, nor 2004-16 reported fuel level monitoring sensors were in use by the team, and all thee teams were selected to participate in the

2004 GCE. Team 2004-10 completed 7.4 miles of the 2004 GCE course, the best performance by any team. As a result, the author concluded fuel level monitoring sensors were unnecessary. This does not explain why Teams 2004-03, 2004-10, and 2004-16 did not implement a challenge vehicle capable of traversing a course length of 250 miles. The author proposes a discussion between DARPA, several of the teams with prior experience, and others resulted in the reduction in proposed course length to a length which could be completed within the reported ranges of all challenge vehicles, and that this discussion was the basis for the eventual reduction of the proposed 2004 GCE course length from 250 miles to less than 150 miles.

In contrast, none of the three teams which reported fuel level monitoring sensors were in use by the team performed well in the 2004 QID or were selected to participate in the 2004 GCE:

- Team 2004-01

Team 2004-01 passed on their turn on the first day of the 2004 QID, and terminated within the starting chute area on the last day of the 2004 QID. Team 2004-01 was not selected to participate in the 2004 GCE. See paragraph V.C.1.

- Team 2004-08

Team 2004-08 did not participate in the 2004 QID or GCE due to "lack of funding". See paragraph V.C.8.

- Team 2004-21

Team 2004-21 passed on their turn on the first day of the 2004 QID, terminated their attempt on the third day of the 2004 QID, and officially withdrew on the last day of the 2004 QID. Team 2004-21 was not selected to participate in the 2004 GCE. See paragraph V.C.21.

XIV.B.1.a.i.b. <u>2005</u>

No team which participated in the 2005 GCE reported fuel level monitoring sensors were in use by the team. DARPA did not revise the proposed course length of 175 miles after the 2005 GCE rules were published on October 8, 2004. See Appendix C.

However, no team which participated in the 2004 GCE reported a challenge vehicle range of less than 175 miles. See Table LXX. 175 miles was less than the minimum range reported by Team 2004-10 of approximately 186.5 miles. Team 2004-10 participated in the 2005 GCE as Team 2005-13. The author proposes this may explain why the 2005 GCE rules established a proposed 2005 GCE course length of "no longer than 175 miles" ([2], p. 4), after DARPA decreased the proposed 2004 GCE course length from 300 miles to "approximately 250 miles" and then "approximately 210 miles"[28].

XIV.B.1.a.ii. Temperature monitoring sensors

XIV.B.1.a.ii.a. 2004

Nine of 25 teams participating in the 2004 QID or GCE reported temperature monitoring sensors were in use by the team: Teams 2004-01 (“water temperature”), 2004-05 (“cooling water temperature”), 2004-15 (“air conditioning information”), 2004-18 (“temperature sensors to monitor engine and other critical components”), 2004-20 (“temperature”), 2004-21 (“temperature”), 2004-22 (“temperature sensors” for “engine, oil, and outside temperatures”), 2004-24 (“water temperature” for the Challenge vehicle's generators), and 2004-25 (“temperature inside all electronic enclosures”). In addition, Team 2004-17 reported OEM OBD-II sensors were in use by the team to monitor “engine temperature”. See Table XXIV. With the exception of Teams 2004-15, 2004-24, and 2004-25 the teams reported temperature sensors were in use to monitor the state of the challenge vehicle's engine.

Six of the nine teams which reported temperature monitoring sensors were in use by the team were not selected to participate in the 2004 GCE: Teams 2004-01, 2004-05, 2004-15, 2004-20, 2004-21, and 2004-22. See paragraphs V.C.1., V.C.5., V.C.15., V.C.20., V.C.21., and V.C.22.

Three of the nine teams which reported temperature monitoring sensors were in use by the team were selected to participate in the 2004 GCE: Teams 2004-18, 2004-24, and 2004-25. Team 2004-24 withdrew prior to start, Team 2004-25 completed zero miles of the 2004 GCE course, and Team 2004-18 completed 0.20 miles of the 2004 GCE course ([30] and [3], p. 8). Team 2004-18 was the only team which participated in the 2004 GCE and reported temperature monitoring sensors were in use by the team to have completed more than zero miles of the 2004 GCE course.

XIV.B.1.a.ii.b. 2005

Six teams which participated in the 2005 GCE reported temperature monitoring sensors were in use by the team, two pairs of which were co-participants:

- Team 2005-08

Team 2005-08 reported a “Temperature Monitor” via Figure 2 (“Hardware Configuration”) of the team technical proposal ([173], p. 7). Team 2005-08 stated: “The computing hardware is located in a common environmental enclosure in the bed of the F250.” and “The environmental enclosure is cooled using a stock Ford Excursion auxiliary air conditioning unit mounted in the truck bed.” ([173], p. 5). Team 2005-08 did not participate in the 2004 QID or GCE, and completed 14.0 miles of the 2005 GCE course.

- Teams 2005-13 and 2005-14

Teams 2005-13 and 2005-14 stated: “[The challenge vehicle's] state sensing monitors and measures equipment temperature, actuator position, velocity and acceleration. State is sensed via optical encoders, potentiometers, rotational variable differential transformers (RVDT), thermocouples, current and voltage sensors.” ([11], p. 10 and [12], p. 10). Team 2005-13 participated in the 2004 QID and GCE as Team 2004-10. Teams 2005-13 and 2005-14 successfully completed the 2005 GCE course. However, Teams 2005-13 and 2005-14 had prior experience and extensive corporate and academic sponsorship.

- Team 2005-19

Team 2005-19 stated: “The [challenge vehicle controlling intelligence] also monitors vehicle health, and has the capability of adjusting vehicle behavior based on engine and generator temperatures, as well as several other vehicle health metrics.” ([55], p. 13). Team 2005-19 did not participate in the 2004 QID or GCE, and completed 8.9 miles of the 2005 GCE course.

- Teams 2005-22 and 2005-23

Teams 2005-22 and 2005-23 stated: “[The challenge vehicle] uses an on-board accelerometer array with [a] temperature sensor located in the electronics enclosure to measure the conditions to which the vehicle electronics are subject. Battery voltage is also logged on the vehicle’s power system... This information does not affect the vehicle’s navigation behavior.” ([58], p. 7 and [164], p. 9). Team 2005-22 participated in the 2004 QID and GCE as Team 2004-25. Teams 2005-22 and 2005-23 completed 43.5 and 39.4 miles of the 2004 GCE course, respectively.

XIV.B.1.a.iii. Results

- 2004

The author is not confident sufficient technical detail was reported by DARPA to determine the cause of failures encountered by teams participating in the 2004 QID or GCE. For example, DARPA reported the Team 2004-17 challenge vehicle “...veered off course, went through a fence, tried to come back on the road, but could not get through the fence again.” and the Team 2004-18 challenge vehicle “...began smoothly, but at mile 0.2, when making its first 90-degree turn, the vehicle flipped.” ([3], p. 8).

Neither of these problems is directly attributable to implementation of fuel level or temperature monitoring sensors, or any other state sensors, and the author considers it unlikely that implementation of unnecessary state sensors was a direct cause of failure to complete the 2004 QID or GCE. The author asserts the complexity observed in some team technical proposals is an indicator of another problem: lack of experience.

Teams 2004-01, 2004-04, 2004-05, 2004-10, 2004-15, 2004-18, 2004-20, and 2004-24 reported large numbers of state sensors (five or more) were in use by the team: engine RPM, "intake manifold pressure", fuel level, various temperature, transmission position, throttle position, steering angle, various suspension, "low oil pressure", driveshaft RPM, various voltage, various current, or otherwise unspecified sensors were in use by the teams.

Four of eight teams which reported large numbers of state sensors were in use by the team participated in the 2004 QID but were not selected to participate in the 2004 GCE: Teams 2004-01 (nine sensors), 2004-05 (nine sensors), 2004-15 (eight sensors), and 2004-20 (five sensors). None of these teams reported prior experience. Teams 2004-01, 2004-05, and 2004-15 reported only limited corporate or academic sponsorship. Team 2004-20 reported moderate corporate sponsorship.

Four of eight teams which reported large numbers of state sensors were in use by the team participated in the 2004 QID and were selected to participate in the 2004 GCE: Teams 2004-04 (five sensors), 2004-10 (five sensors), 2004-18 (five sensors), and 2004-24 (eight sensors). Team 2004-04 reported prior experience, moderate corporate sponsorship, and extensive academic sponsorship, and completed 0.45 miles of the 2004 GCE course. Team 2004-10 reported prior experience and extensive corporate and academic sponsorship and completed 7.4 miles of the 2004 GCE course. Team 2004-18 reported no prior experience and moderate corporate sponsorship and completed 0.2 miles of the 2004 GCE course. Team 2004-24 reported no prior experience and no sponsorship and withdrew prior to start.

- 2005

Based on the failure analysis performed by the author (see Chapter XIII.), there is no evidence fuel level monitoring sensors, temperature monitoring sensors, or any other state sensors directly contributed to the failure of any team which participated in the 2005 GCE to complete the course. There is no evidence the implementation of these sensors contributed to the success of any team which participated in the 2005 GCE.

XIV.B.1.a.iv. Conclusions

The decision to implement unnecessary state sensors reported by some teams prior to the 2004 QID or GCE or 2005 GCE contributed to poor performance by increasing the complexity of the challenge vehicle, requiring teams to divert resources which may have been used to more effectively solve the fundamental problem of the Grand Challenge.

In addition, the author concluded the effect of experience may have allowed teams with prior experience in the field of autonomous vehicle development (e.g., 2004-04, 2004-10, 2005-02, 2005-13, and 2005-14) or prior experience in the 2004 GCE (e.g., Teams 2005-22 and 2005-23) to have implemented these sensors, supporting a conclusion that the lack of experience was a significant barrier to entry. See paragraph X.D.1.

In the extreme cases of teams which reported eight or more state sensors were in use by the team, the published record confirms lack of experience or limited sponsorship prevented teams which were otherwise considered competitive by DARPA from participating in either the 2004 or 2005 GCE, demonstrating that, for some teams, lack of experience or limited sponsorship was an insurmountable obstacle:

- Team 2004-01

Team 2004-01 reported what information the unknown state sensors (see Table XXIV) in use by the team provided, but the team did not report how the team intended to combine state sensor output to produce useful information for the challenge vehicle controlling intelligence.

Team 2004-01 stated: “We realize there is probably so much we don't know so we try to keep everything as brutally simple as possible. We are trying to avoid dependence on overly sophisticated systems which may be more prone to failure and less able to adapt to an unexpected set of conditions.” ([81]).

Team 2004-01 passed on their turn on the first day of the 2004 QID, and terminated within the starting chute area on the last day of the 2004 QID. Team 2004-01 was not selected to participate in the 2004 GCE. See paragraph V.C.1. DARPA stated only that Team 2004-01 “terminated within the starting chute area” ([79]). However, in private communication with the author the Team 2004-01 team leader attributed the cause of the problem to an unknown system integration failure caused by “severe lack of time” ([239]).

Team 2004-01 was selected as a semifinalist to participate in the 2005 NQE, but did not complete the 2005 NQE and was not selected to participate in the 2005 GCE ([242]).

- Team 2004-05

2004-05 reported what information the unknown state sensors (see Table XXIV) in use by the team provided, but the team did not report how the team intended to combine state sensor output to produce useful information for the challenge vehicle controlling intelligence.

The Team 2004-05 team website was no longer available. However, their “Team Information” on the Archived Grand Challenge 2005 website ([19]) stated, in part: “We are a group of volunteers that have 'day jobs' and know we can make a difference by being part of this history making event. Our numbers continue to grow as people learn of our goals. All are welcome regardless of the amount of time available to participate or specialty. It is exciting to be around so much energy and intellectual capital."

Team 2004-05 was delayed awaiting parts for the challenge vehicle until the third day of the 2004 QID, and officially withdrew on the last day of the 2004 QID. See paragraph V.C.5.

Team 2004-05 was selected as a semifinalist to participate in the 2005 NQE, but did not complete the 2005 NQE and was not selected to participate in the 2005 GCE ([242]).

- Team 2004-15

2004-15 reported what information the unknown state sensors (see Table XXIV) in use by the team provided, but the team did not report how the team intended to combine state sensor output to produce useful information for the challenge vehicle controlling intelligence.

Team 2004-15 stated: "Although the team has worked diligently and sacrificed much in our effort to have [the challenge vehicle] ready for the March Grand Challenge, it is not to be. We made great strides and were on the right track as evidenced by our inclusion in the first group invited to the QID. Unfortunately, we fell victim to everyone's problem of 'not enough time' and 'not enough money'." ([136]).

Although Team 2004-15 applied to participate in the 2005 GCE, the team was not selected as a semifinalist to participate in the 2005 NQE ([242]).

Overall, the author concluded the performance of teams which implemented unnecessary state sensors confirms the effects of experience and sponsorship, and asserts this effect was *lasting*. Teams which were unable to overcome lack of experience or limited sponsorship were not competitive with teams which had prior experience or significant corporate or academic sponsorship.

Teams with prior experience or extensive corporate or academic sponsorship were able to use their experience, in particular, and sponsorship as the equivalent of a "force multiplier". The advantage this gave these teams was so significant that the author questions whether it was appropriate for DARPA to allow most of the teams which participated in the 2004 or 2005 GCE to participate without first ensuring those teams were able to identify the fundamental problem and devote sufficient resources to the development of a challenge vehicle which would be competitive with those of teams with prior experience and significant sponsorship.

XIV.B.1.b. Leverage the capabilities of the challenge vehicle platform

XIV.B.1.b.i. Electrical power generation strategies

In general, team strategies to provide electrical power to the challenge vehicle's computing hardware and sensors fall into four categories: exclusive use of the challenge vehicle alternator, challenge vehicle alternator and batteries, exclusive use of an external generator, or external generator and batteries. The author performed a comprehensive review of team technical proposals to determine what strategy was in use by teams which participated in the 2004 or 2005 GCE. Teams which only participated in the 2004 QID were excluded from this review.

Some teams reported one or more alternators or one or more generators were in use by the team. The author did not distinguish between teams using one or more alternators or one or more generators, except to note that it increased redundancy. See paragraph XIV.C. In addition, teams alternately referred to the use of challenge vehicle batteries (i.e., for the challenge vehicle's starter motor) and batteries which were part of the power generation system. When evaluating the use of batteries, the author considered only additional batteries installed as part of the challenge vehicle's power system to be "batteries", even if the team referred specifically to the use of challenge vehicle batteries to provide electrical power. In addition, several teams reported the use of an Uninterruptible Power Supply (UPS). For the purposes of this analysis, the author considers a UPS to be a battery.

Tabulated results are presented by Tables LXXI and LXXII. The results do not support a conclusion that any particular electrical power generation strategy was "best". However, the published record supports conclusions that some strategies were more effective than others:

- There was a net migration from the use of generators to the use of challenge vehicle alternators to generate electrical power. Seven of 15 (47 percent) teams which participated in the 2004 GCE reported an alternator or alternator and batteries were in use by the team, compared to 12 of 21 (57 percent) teams which participated in the 2005 GCE.

- Five of ten (50 percent) teams which participated in the 2004 GCE and did not select a commercially-available ATV as challenge vehicle platform reported an alternator or alternator and batteries were in use by the team, compared to 11 of 17 (65 percent) of teams which participated in the 2005 GCE.

- The use of an external generator or external generator and batteries was a common strategy among teams which participated in the 2004 GCE regardless of challenge vehicle platform. Teams which reported an external generator or external generator and batteries were in use variously selected a commercially-available SUV, commercially-available truck, commercially-available ATV, military service vehicle, or purpose-built vehicle as challenge vehicle platform.

- The use of an external generator or external generator and batteries was *not* a common strategy among teams which participated in the 2005 GCE. In general, teams which reported an external generator or external generator and batteries were in use selected a commercially-available ATV as challenge vehicle platform, with the exception of the following teams: Teams 2005-13, 2005-14, 2005-18, and 2005-19.

- No team which participated in the 2005 GCE and reported an external generator or external generator and batteries were in use and which selected a commercially-available ATV as challenge vehicle platform completed more than 48.3 miles of the 2005 GCE course, the average number of miles completed.

- The use of an external generator or external generator and batteries may have been a consequence of selection of a commercially-available ATV as challenge vehicle platform, but an alternate strategy was in use by Team 2005-11. Team 2005-11 stated: "...the OEM 12-volt generator is augmented with an additional 65 amp, 24 volt alternator and high capacity batteries." ([182], p. 5). Team 2005-11 had no prior experience and completed 7.2 miles of the 2005 GCE course.

- Teams 2005-13 and 2005-19 selected a military service vehicle as challenge vehicle platform. The use of an external generator or external generator and batteries may have been a consequence of selection of a military service vehicle as challenge vehicle platform[29]. Team 2005-13 had prior experience and successfully completed the 2005 GCE. Team 2005-19 had no prior experience and completed 8.9 miles of the 2005 GCE course.

- Seven teams completed more than 48.3 miles of the 2005 GCE course, the average number of miles completed: Teams 2005-01, 2005-06, 2005-13, 2005-14, 2005-16, 2005-20, and 2005-21. With the exception of Teams 2005-06, 2005-13, and 2005-14, an alternator or alternator and batteries were in use by all teams which completed more than the average number of miles of the 2005 GCE course.

- Team 2005-06 was the only team with no prior experience which successfully completed the 2005 GCE. The electrical power generation strategy in use by Team 2005-06 was unique. Team 2005-06 selected a 2005 Ford Escape Hybrid as challenge vehicle platform. See Table XVI.

  Team 2005-06 stated: "...the hybrid's electrical system, which is powered by a 330-volt battery, provides over 1300 watts of power to the equipment mounted in the vehicle. This alleviates [Team 2005-06] from having to use a generator to provide power for the computer equipment." ([172], p. 3); "Rather than use a generator, [Team 2005-06] chose to use the Escape Hybrid's integrated electrical system to provide 12 volts of power for all of its computer and navigation equipment. The Escape Hybrid provides 110 amps of power at 12 volts, which is more than adequate to power all of [Team 2005-06's] equipment." ([172], p. 5); and "The Grand Challenge could require a vehicle to be paused for extended periods of time. This could cause problems for many vehicles due to excess fuel consumption during the pause. Most vehicles will not want to shut down their navigation systems during a pause, so an extended pause could tax both their generator's fuel supply and the vehicle's own fuel supply. The Escape Hybrid will run off electrical power during pauses and will only start the gas engine when necessary to recharge the battery. This will help ensure that [Team 2005-06's] vehicle will not need to shut down any systems, yet still have the fuel necessary to finish the Grand Challenge." ([172], p. 3).

As a result, by careful selection of the platform for their challenge vehicle, Team 2005-06 was able to leverage the capabilities of the challenge vehicle platform to provide power for computing hardware and navigation sensors[30].

Overall, the author considers the results of the review support the following key factors:

- Identify the fundamental problem of the Grand Challenge. Selection of challenge vehicle platform may have unintended consequences.

- Leverage the capabilities of the challenge vehicle platform. Use the challenge vehicle alternator or alternator and batteries to provide electrical power to the challenge vehicle's computing hardware and sensors, if possible.

- Reduce complexity. Do not implement an electrical power generation strategy through exclusive use of an external generator or external generator and batteries, unless necessary.

In addition, the author considers the results of the review confirm the effects of experience and sponsorship.

XIV.B.1.b.ii. Computing hardware cooling strategies

Several teams reported the challenge vehicle air conditioning system or dedicated, air-conditioned enclosures were in use to cool computing hardware, or selected components able to withstand high temperatures. For example:

- Team 2004-09

Team 2004-09 stated: "Vehicle air conditioning will provide the required cooling to ensure that the ambient conditions of the processing equipment are within published tolerance.” ([47], p. 3). Team 2004-09 selected a commercially-available SUV as challenge vehicle platform. See Table XV. As a result, Team 2004-09 was able to leverage the vehicle's air conditioning system. Team 2004-09 had no prior experience, moderate corporate sponsorship, and limited academic sponsorship. See Table LXVI. Team 2004-09 was selected to participate in the 2004 GCE, but completed zero miles of the 2004 GCE course.

- Team 2004-10

Team 2004-10 stated: “E-box cooling system was designed and implemented, based on analyzed and measured thermal characteristic data.” ([77], p. 6). Team 2004-10 selected a military service vehicle as challenge vehicle platform. See Table XV. As a result, Team 2004-10 was not able to leverage the vehicle's air conditioning system. Team 2004-10 had prior experience and extensive corporate and academic sponsorship. See Table LXVI. Team 2004-10 completed 7.4 miles of the 2004 GCE course, the best performance by any team.

- Team 2004-25

Team 2004-25 reported “cooling fans” were in use by the team via Table 1 (“Estimated Peak Power Consumption”) of the team technical proposal ([49], p. 4) and stated: “...we expect to monitor... the temperature inside all electronic enclosures.” ([49], p. 11). Team 2004-25 selected a commercially-available ATV as challenge vehicle platform. See Table XV. As a result, Team 2004-25 was not able to leverage the vehicle's air conditioning system. Team 2004-25 had no prior experience and moderate corporate and academic sponsorship. See Table LXVI. Team 2004-25 was selected to participate in the 2004 GCE, but completed zero miles of the 2004 GCE course.

- Team 2005-06

Team 2005-06 stated: “In order to ensure that the best computing hardware was chosen, [Team 2005-06] investigated the leading computing hardware used by several different industries. The marine industry offered a ready made system that included protection from excessive shock, high temperatures, and other environmental issues. [The system]... hosts all of the main computing functions, such as sensor communication, vehicle controls, and artificial intelligence.” ([172], p. 7).

Team 2005-06 later stated ([28], p. 512):

> After initial testing during a hot summer day, we noticed that the computing equipment was overheating and then malfunctioning due to the high temperatures in the cabin of the car. This revealed an issue between having proper fuel efficiency and having an acceptable cabin temperature. If the air conditioner

> was kept on its highest setting, the equipment did not overheat, but the resulting fuel economy was projected to be too low to finish the expected 175 mile race (projections were based on the fuel economy of the 2005 Ford Escape 4 cylinder model). This lowered fuel economy was due to the fact that if the air conditioning system on a Ford Escape Hybrid is set to its maximum setting, then the compressor must run constantly, which causes the gasoline engine to also run constantly. This defeats the whole fuel efficient design of the hybrid's engine as explained previously.
>
> As a result of this problem, we created a simple on/off mechanism for the air conditioning system that was suited to the cooling needs of the equipment rather than the passenger's comfort. The device consisted of a temperature sensor, a BASIC stamp, and a servomotor. We mounted the servo to the air conditioning system's control knob so that the servo could turn the air conditioner on and off. The BASIC stamp is a simple programmable microcontroller with eight bidirectional input and output lines and a limited amount of memory which can hold a small program. We programmed the BASIC stamp to monitor the temperature of the cabin near the equipment. If the temperature dropped below a certain threshold, the air conditioner was turned off. If the temperature rose above a certain temperature, the air conditioning system was turned to its maximum setting. This simple system solved our temperature problems while not adversely affecting our fuel efficiency, yet still only interfacing with the vehicle at its highest level.

As a result, Team 2005-06 selected components able to withstand high temperatures and was able to leverage the vehicle's air conditioning system. Team 2005-06 had no prior experience and moderate corporate sponsorship. See Table LXVII. Team 2005-06 successfully completed the 2005 GCE.

- Team 2005-08

Team 2005-08 stated: "The computing hardware is located in a common environmental enclosure in the bed of the F250." and "The environmental enclosure is cooled using a stock Ford Excursion auxiliary air conditioning unit mounted in the truck bed." ([173], p. 5). Team 2005-08 selected a commercially-available truck as challenge vehicle platform. See Table XVI. Because Team 2005-08 located computing hardware in an "environmental enclosure" in the bed of the challenge vehicle, Team 2005-08 was not able to leverage the vehicle's air conditioning system. Team 2005-08 had no prior experience and moderate corporate sponsorship. See Table LXVII. Team 2005-08 completed 14.0 miles of the 2005 GCE course.

- Team 2005-09

Team 2005-09 stated: "We desired a vehicle that would be street legal with sufficient off-road capabilities as well as a protected interior that would keep the components cooled and not exposed to the elements... The SportTrac ... has sufficiently cooled interior space for our computing equipment." ([175], p. 2). Team 2005-09 selected a commercially-available SUV as challenge vehicle platform. See Table XVI. As a result, Team 2005-09 was able to leverage the vehicle's air conditioning system. Team 2005-09 had no prior experience and moderate corporate sponsorship. See Table LXVII. Team 2005-09 completed 0.7 miles of the 2005 GCE course.

- Team 2005-10

Team 2005-10 stated: "Standard equipment includes... air conditioning... The rational [*sic*] for this choice was that we didn't want to spend time designing and building a vehicle. We wanted to spend time on the sensory and navigation systems, so we bought a commercial vehicle that was as close as possible to what was needed and modified it in the ways described above." ([176], p. 2). Team 2005-10 selected a commercially-available SUV as challenge vehicle platform. See Table XVI. As a result, Team 2005-10 was able to leverage the vehicle's air conditioning system. Team 2005-10 had no prior experience and limited corporate sponsorship. See Table LXVII. Team 2005-10 completed 23.0 miles of the 2005 GCE course.

- Team 2005-13

Team 2005-13 stated: "A custom aluminum body and a cooled, shock-isolated electronics bay replaced the crew compartment body panels, doors, seats and windshield." ([11], p. 2). Teams 2005-13 and 2005-14 were co-participants during the 2005 GCE. Team 2005-14 did not report the cooling solution in use by the team. Team 2005-13 selected a military service vehicle as challenge vehicle platform. See Table XVI. As a result, Team 2005-10 was not able to leverage the vehicle's air conditioning system. Team 2005-13 had prior experience and extensive corporate and academic sponsorship. See Table LXVII. Team 2005-13 successfully completed the 2005 GCE.

- Team 2005-15

Team 2005-15 stated: "We use two 750 MHz Pentium-4 embedded systems built as a PC104+ stack. These two computers do not require active cooling." ([53], p. 6). Team 2005-15 selected a commercially-available ATV as challenge vehicle platform. See

Table XVI. As a result, Team 2005-15 was not able to leverage the vehicle's air conditioning system. Team 2005-15 had no prior experience and moderate corporate and academic sponsorship. See Table LXVII. Team 2005-15 completed 15.9 miles of the 2005 GCE course.

- Team 2005-16

Team 2005-16 stated: “The computing system is located in the vehicle’s trunk, as shown in Fig. 2. Special air ducts direct air flow from the vehicle’s AC system into the trunk for cooling.” ([195], p. 4). Team 2005-16 selected a commercially-available SUV as challenge vehicle platform. See Table XVI. As a result, Team 2005-16 was able to leverage the vehicle's air conditioning system. Team 2005-16 had prior experience and extensive corporate and academic sponsorship. See Table LXVII. Team 2005-16 successfully completed the 2005 GCE.

- Team 2005-20

Team 2005-20 stated: “This experience has led to redesign of some components of the vehicle, improved cooling for computers, and knowledge of critical spare parts to have on hand.” ([56], p. 14). Team 2005-20 selected a purpose-built vehicle as challenge vehicle platform. See Table XVI. As a result, Team 2005-20 was not able to leverage the vehicle's air conditioning system. Team 2005-20 had no prior experience and moderate corporate sponsorship. See Table LXVII. Team 2005-20 completed 81.2 miles of the 2005 GCE course. Although Team 2005-20 did not describe the method by which computing hardware was cooled, the team described “improved cooling for computers” as a result of their test and evaluation program.

- Team 2005-21

Team 2005-21 stated: “...all the computers are housed in a closed container which is cooled with a closed-loop, filtered, air-conditioning system.” ([160], p. 3). Team 2005-21 selected a military service vehicle as challenge vehicle platform. See Table XVI. As a result, Team 2005-21 was not able to leverage the vehicle's air conditioning system. Team 2005-21 had prior experience and extensive corporate sponsorship. See Table LXVII. Team 2005-21 completed the 2005 GCE, but was not successful.

Overall, the author considers the cited examples support the following key factors:

- Identify the fundamental problem of the Grand Challenge. Select a challenge vehicle platform with capabilities that may be leveraged.

- Leverage the capabilities of the challenge vehicle platform. Use the challenge vehicle air conditioning system to cool computing hardware, if possible.

- Leverage existing COTS components. Use components which do not require the team to implement a cooling strategy, if necessary.

- Perform adequate test and evaluation. Adequate test and evaluation may identify weaknesses in team implementation of a cooling strategy.

In addition, the author considers the cited examples confirm the effects of experience and sponsorship.

XIV.B.1.b.iii. Suspension

Several teams reported the challenge vehicle suspension was in use to reduce the impact of off-road terrain on computing hardware and sensors[31], frequently in combination with an additional level of shock isolation. For example:

- Team 2005-06

Team 2005-06 stated: “...the Escape Hybrid is a very narrow four wheel drive vehicle with a very smooth suspension... The smooth suspension also ensures that the rough terrain will have less impact on the equipment mounted in the vehicle.” ([172], p. 3).

- Team 2005-13

Team 2005-13 stated: “The chassis suspension utilizes custom coil-over struts with nitrogen reservoirs... [The challenge vehicle's] electronics enclosure is suspended with 12 shock isolators, each of which is a coil over strut shock absorber... These two levels of suspension serve (1) to protect [the challenge vehicle's] sensitive electronics and computing hardware and (2) to smooth sensor trajectories.” ([11], pp. 2 - 3).

- Team 2005-14

Team 2005-14 stated: “The chassis suspension utilizes custom coil-over struts with nitrogen reservoirs and a central tire inflation system... [The challenge vehicle's] electronics enclosure sits on a semi-active modified Stewart Platform. Each shock isolator of the Stewart platform is a coil-over strut with a magnetorheological fluid damper... These two levels of suspension serve to protect [the challenge vehicle's] sensitive electronics and computing hardware.” ([12], pp. 2 - 3).

- Team 2005-20

Team 2005-20 stated: “The main goal of selecting a vehicle was to choose a vehicle that could handle the rough desert terrain... while supplying a stable platform for the obstacle detection sensor array. This approach eliminates the need for complex gimbals and/or shock suppression suspensions for the sensor array.” ([56], p. 3) and “The suspension response is benign enough to eliminate the need for active control of sensors, saving development time and considerable cost.” ([56], p. 15).

Teams 2005-06, 2005-13, and 2005-14 successfully completed the 2005 GCE. Team 2005-20 completed 81.2 miles of the 2005 GCE course, more than the average number of miles completed. Overall, the author considers the prevalence of this strategy among teams which successfully completed the 2005 GCE and Team 2005-20 supports the following key factors:

- Identify the fundamental problem of the Grand Challenge. Select a challenge vehicle platform with capabilities that may be leveraged.

- Leverage the capabilities of the challenge vehicle platform. Use the challenge vehicle suspension to reduce the impact of off-road terrain on computing hardware and sensors.

In addition, the author considers the prevalence of this strategy confirms the effects of experience and sponsorship.

XIV.B.1.c. Reduce the number of obstacle and path detection sensors in use by eliminating other sensors

The author reviewed the published record in an attempt to quantify the number of major obstacle and path detection sensors in use by the teams, in particular sensors which were considered high-quality. See Chapter VI.

The author concluded there was a decrease in the number of teams using other cameras, other LIDAR, and other RADAR from 2004 to 2005 and a decrease in the number of sensors in use by teams which participated in the 2004 and 2005 GCE. The author considers the reduction in the number of sensors in use due to the elimination of other sensors an example of reducing complexity. See paragraph VI.D.1.

XIV.B.2. Leverage existing COTS components

XIV.B.2.a. Challenge vehicle controls

All teams referred to actuation of challenge vehicle steering, throttle, brake, and transmission controls. In general, teams either independently implemented challenge vehicle controls or integrated COTS controls.

Due to the effect of experience, the author does not consider the integration of COTS challenge vehicle controls by teams with prior experience to have been a key factor for those teams. The author considers it likely teams with prior experience also had experience independently implementing challenge vehicle controls and were able to accomplish this with minimal impact on development of the challenge vehicle, for various reasons. Teams with prior experience included Teams 2004-04 and 2005-02, 2004-10 and 2005-13, 2005-14, 2005-16, and 2004-23 and 2005-21.

Although some teams with significant sponsorship also independently implemented challenge vehicle controls, this was generally required by team selection of challenge vehicle platform. For example:

- Eleven teams participating in the 2004 QID or GCE reported moderate or extensive corporate or academic sponsorship. See Table LXVI. Eight of 11 teams selected a commercially-available ATV, military service vehicle, or purpose-built vehicle as challenge vehicle platform. See Table XV. The author considers it likely integrated COTS controls for these vehicles did not exist, requiring teams to independently implement challenge vehicle controls. Of the remaining three teams: Team 2004-04 selected a commercially-available SUV but had prior experience; Team 2004-09 selected a commercially-available SUV and integrated COTS controls; and Team 2004-17 selected a commercially-available SUV and independently implemented controls.

- Seventeen teams participating in the 2005 GCE reported moderate or extensive corporate or academic sponsorship. See Table LXVII. Ten of 17 teams selected a commercially-available ATV, military service vehicle, or purpose-built vehicle as challenge vehicle platform. See Table XVI. The author considers it likely integrated COTS controls for these vehicles did not exist, necessitating team development of a challenge vehicle control solution.

  Of the remaining seven teams:

  Teams 2005-06, 2005-14, and 2005-16 successfully completed the 2005 GCE, with Team 2005-16 placing first. Team 2005-06 selected a commercially-available SUV and integrated COTS controls; Team 2005-14 selected a commercially-available SUV, had prior experience, and independently implemented controls; and Team 2005-16 selected a commercially-available SUV, had prior experience, and integrated COTS controls.

Teams 2005-08, 2005-12, 2005-18 completed 14.0, 9.5, and 8.0 miles of the 2005 GCE course, respectively. Team 2005-08 selected a commercially-available truck and independently implemented controls; Team 2005-12 selected a commercially-available truck and independently implemented controls; and Team 2005-18 selected a Ford E-350 Van and independently implemented controls. None of these teams had prior experience.

The author is not attempting to imply causation, i.e., that independently implementing controls *caused* Teams 2005-08, 2005-12, and 2005-18 to complete less than the average number of miles of the 2005 GCE course completed, or that integrated COTS controls *caused* Teams 2005-06 and 2005-16 to successfully complete the 2005 GCE. However, the author considers the performance of Teams 2005-06, 2005-08, 2005-12, 2005-14, 2005-16, and 2005-18 to support a conclusion that teams which implemented key factors were more successful.

Team 2005-09 completed 0.7 miles of the 2005 GCE course, the least number of miles of any team which participated in the 2005 GCE. Team 2005-09 selected a commercially-available SUV and integrated COTS controls. Team 2005-09 had no prior experience. Team 2005-09 attributed the cause of their failure to complete the 2005 GCE to errors in obstacle detection. See paragraph XIII.B.5. However, the author concluded the ultimate cause may have been a lack of available resources, specifically time in which to perform adequate test and evaluation of the team challenge vehicle. See paragraph XIV.D.1.

The author considers the use of COTS components a key factor in teams with no prior experience because it reduced complexity and allowed the teams to focus on the fundamental problem in the limited time available to develop a challenge vehicle. The author proposes some teams with no prior experience which independently implemented challenge vehicle controls completed less miles of the 2004 or 2005 GCE course because limited sponsorship restricted the ability of the teams to effectively make use of COTS components, or because teams, correctly or not, determined that independently implementing challenge vehicle controls offered advantages or could be accomplished at minimal cost in terms of team resources.

In addition, the use of COTS components eliminated the need to control the challenge vehicle using actuators, linkages, and other physical components which were a potential cause of failure, and leveraged test and evaluation performed by the manufacturer to ensure the reliability of the component, eliminating the need to divert team resources to perform adequate test and evaluation for the components.

The author made no effort to determine which of the potential rationales, or indeed what other rationale, may have resulted in team decisions to independently implement challenge vehicle controls.

Team descriptions of integrated COTS controls are included herein. The author concluded all other teams independently implemented challenge vehicle controls. Those descriptions were frequently detailed, and are not included herein. In cases where it was unclear, the author attempted to provide enough justification to support his conclusion.

Overall, integrated COTS controls were in use by four teams which participated in the 2004 or 2005 GCE: Teams 2004-09, 2005-06, 2005-09, and 2005-16. Teams 2004-09 and 2005-09 were teams with moderate corporate sponsorship, but no prior experience. Teams 2005-06 and 2005-16 successfully completed the 2005 GCE, with Team 2005-16 placing first. Team 2005-06 had no prior experience and moderate corporate sponsorship. Team 2005-16 had prior experience, moderate corporate sponsorship, and extensive academic sponsorship. None of these teams participated in both the 2004 and 2005 GCE.

The author considers team selection of commercially-available ATV, military service vehicle, or purpose-built vehicle as challenge vehicle platform, and the resulting lack of availability of integrated COTS controls to be a potential limitation of those platforms. Also, the author proposes selection of commercially-available ATV by some teams may have been influenced by lack of sponsorship or resource allocation decisions, and questions whether it was appropriate for DARPA to allow teams with limited sponsorship to participate in the Grand Challenge, or to encourage participation by teams that could not field a vehicle capable of replacing a manned ground vehicle.

- Team 2004-02

Team 2004-02 stated: “The steering wheel is actuated by means of a DC electric servo motor system...”; “[The Electronic Mobility Controls (EMC) Electric Gas Brake (EGB-IIF) unit] is commercial off-the-shelf, installed according to manufacturer’s specifications.”; and “The shifting is controlled by means of a linear actuator.” ([9], p. 4). Although the EMC Electric Gas Brake in use by Team 2004-02 was a COTS component, the author concluded Team 2004-02 independently implemented challenge vehicle controls.

- Team 2004-09

Team 2004-09 stated: “Automation of the vehicle will be accomplished with a subsystem developed by Electronic Mobility Controls LLC...” and “The control of vehicle functions, such as acceleration, braking, and steering, will be performed by a driving control system based on the Advanced Electronic Vehicle Interface Technology (AEVIT) system from Electronic Mobility Controls (EMC) LLC, which modifies the steering wheel, brake and accelerator pedals with commercially available controls.” ([38], p. 2).

- Team 2005-01

Team 2005-01 stated: “The steering wheel is actuated by means of a DC electric servo motor system...”; “[The Electronic Mobility Controls (EMC) Electric Gas Brake (EGB-IIF) unit] is commercial off-the-shelf, installed according to manufacturer’s specifications.”; and “The shifting is controlled by means of a linear actuator.” ([10], pp. 10 - 11). Although the EMC Electric Gas Brake in use by Team 2005-01 was a COTS component, the author concluded Team 2005-01 independently implemented challenge vehicle controls.

- Team 2005-02

Team 2005-02 stated: “The automation of the vehicle, to include power system design and actuation, was headed by personnel of Eigenpoint, Inc.” ([167], p. 3). Team 2005-02 reported the team was a collaboration of several groups, including Eigenpoint. Although Eigenpoint claimed to have over a decade of experience in “robotic and automation systems”, and (as of 2004) to be “applying our knowledge towards developing our own products”, the “Products” page of the Eigenpoint website was (as of 2010) “under construction” ([246]). As a result, the author concluded Eigenpoint did not offer COTS challenge vehicle controls at the time of the 2005 GCE, and that Team 2005-02 independently implemented challenge vehicle controls.

- Team 2005-04

Team 2005-04 stated: “Drive by wire capability was added to the vehicle so that computer control was possible for throttle, brake, steering control, and transmission gear.” ([169], p. 3), but did not affirmatively state integrated COTS controls were in use by the team. In addition, Team 2005-04 selected a commercially-available ATV as challenge vehicle platform. See Table XVI. The author concluded Team 2005-04 independently implemented challenge vehicle controls.

- Team 2005-06

Team 2005-06 stated: “[Team 2005-06] installed an AEVIT 'drive-by-wire' system from Electronic Mobility Controls (EMC) to physically control the car. The AEVIT system uses redundant servos and motors to turn the steering wheel, switch gears, apply throttle, and apply brake. A primary reason that this system was chosen was because it has a proven safety record in the automobile industry due to its use of redundant hardware. One of [Team 2005-06's] primary goals in all of their designs is redundancy, and the AEVIT system satisfies this goal... This level of reliability in the physical vehicle controls has allowed the team's efforts to be spent on other critical projects rather than wasting time solving vehicle control problems." ([172], p. 4).

- Team 2005-09

Team 2005-09 stated: "Immediately after purchase, [the challenge vehicle] was modified by EMC (Electronic Mobility Controls Corp) to provide a drive-by-wire capability. This included modifications to both the transmission and steering column... By using EMC, the [challenge vehicle] has a robust drive-by-wire capability that leverages years of investment and experience." ([175], p. 3).

Team 2005-09 also stated team selection of challenge vehicle platform was influenced by the availability of integrated COTS controls: "Another consideration that influenced our decision is that Ford vehicles are well understood by Electronic Mobility Controls Corp (EMC), the vendor that provided our drive-by-wire capability." ([175], p. 2). The author proposes this may also have influenced Team 2005-06 selection of a Ford Escape Hybrid as challenge vehicle platform.

- Team 2005-10

Team 2005-10 stated: "The process of designing and assembling the drive-by-wire systems... was rather straightforward." ([176], p. 6). Team 2005-10 did not report the results of formal or informal failure analysis via the Journal of Field Robotics. As a result, the author did not include Team 2005-10 in the summary results presented in paragraph XIII.C. However, Team 2005-10 later stated: "...around mile marker 23, the servo motor that we installed a year ago to actuate the throttle suddenly failed, and the on board computer had no way to control the throttle." ([247]). The author considers this supports an assertion that the use of COTS components leverages test and evaluation performed by the manufacturer to ensure the reliability of the component. No team which used integrated COTS controls reported a similar failure.

- Team 2005-16

Team 2005-16 selected a 2004 Volkswagen Touareg R5 as challenge vehicle platform. See Table XVI. Team 2005-16 stated: "The Volkswagen Touareg R5 is natively throttle and brake-by-wire. A custom interface to the throttle and braking system enables [the challenge vehicle's] computers to actuate both of these systems. An additional DC motor attached to the steering column provides the vehicle with a steer-by-wire capability." ([195], p. 4). Team 2005-16 also stated: "The team is comprised of four major groups: The *Vehicle Group* oversees all modifications and component developments related to the core vehicle. This includes the drive-by-wire systems... The group is led by researchers from Volkswagen of America's Electronic Research Lab." ([195], p. 3). Because the steer-by-wire capability was added by the OEM, the author concluded Team 2005-16 integrated COTS controls were essentially OEM controls for the vehicle selected as challenge vehicle platform.

The author considers the use of OEM controls the best possible outcome for teams participating in the 2004 or 2005 GCE. OEM controls were in use by Team 2005-16 only.

XIV.B.2.b. Navigation sensor integration

Several teams independently implemented an other sensor fusion strategy. See Chapter VII. Teams which did not implement their own navigation sensor integration solution were able to leverage an existing COTS component. Overall, the author concluded the use of a COTS component to integrate navigation sensors was an example of reducing complexity by leveraging existing COTS components.

XIV.B.2.c. High-quality sensors

The author reviewed the published record in an attempt to quantify the number of major obstacle and path detection sensors in use by the teams, in particular sensors which were considered high-quality. See Chapter VI.

The author concluded there was an increase in the number of high-quality obstacle and path detection sensors in use. The author considers the increase in the number of high-quality obstacle and path detection sensors in use an example of reducing complexity by leveraging existing COTS components. See paragraph VI.D.1.

XIV.B.3. Object classification or identification

Several teams which participated in the 2004 QID or GCE explicitly stated the challenge vehicle controlling intelligence did not classify or identify objects: Teams 2004-06, 2004-09, 2004-12, and 2004-23. However, teams which participated in the 2004 QID or GCE or 2005 GCE and which reported the challenge vehicle controlling intelligence classified or identified objects reported objects were classified on the basis of characteristics such as: "passable" or "impassable"; "temporary" or "permanent"; "hard", "medium", or "soft"; "size"; and "location". For example, Team 2004-21 stated: "For the moment, we do not plan on having the system classify sensed objects other than as an obstruction." ([155], p. 5). In general, objects were not classified as "gate", "fence", or "guardrail".

The author considers this evidence supports an assertion the teams were making an active effort to reduce complexity by providing the controlling intelligence with the minimal information needed for obstacle avoidance. However, an inability to effectively classify obstacles as “passable” was directly implicated in the failure of several teams to complete the 2004 or 2005 GCE, including several teams which explicitly stated the challenge vehicle controlling intelligence did not classify or identify objects. For example:

- DARPA reported the Team 2004-06 challenge vehicle “was paused to allow a wrecker to get through, and, upon resuming motion, vehicle was hung up on a football-sized rock.” ([30]). The author considers this an example of the challenge vehicle controlling intelligence incorrectly classifying an obstacle as “passable”.

- DARPA reported the Team 2004-23 challenge vehicle repeatedly “sensed some bushes near the road, backed up and corrected itself. At mile 1.2, it was not able to proceed further.” ([30]). The author considers this an example of the challenge vehicle controlling intelligence incorrectly classifying an obstacle as “impassable”.

- Team 2005-09 failed to complete the 2005 GCE, and stated the challenge vehicle detected occasional dust clouds as transient obstacles, which ultimately caused the challenge vehicle to veer off course where it was unable to continue because “the lasers could not differentiate between weeds and large rocks”. See paragraph XIII.B.5. The author considers this an example of the challenge vehicle controlling intelligence incorrectly classifying an obstacle as “impassable”.

XIV.B.4. Miscellaneous observations

In addition to the specific observations documented above, which were of particular interest to the author, the author noted the following miscellaneous observations, which support a conclusion that teams were making an active effort to reduce complexity, in some cases based on experience gained from participation in the 2004 GCE.

- Team 2004-11

Team 2004-11 stated: “There are no other 'typical' engine status sensors on the vehicle, as they would have little use. In a real-world application this would not be the case, but within the limits of this event it is advantageous to keep things as simple as possible.” ([127], pp. 6 - 7).

However, Team 2004-11's decision to “keep things as simple as possible” may have been counterproductive. Following a DARPA site visit prior to the 2005 NQE, Team 2004-11 stated: “Our entry never made it into the semi-finals of qualifying for the '05 event, even though we did turn out a few good autonomous runs during our Site Visit Qualifying. Our demise may have been the fact that we had no obstacle avoidance systems running that day. In an attempt to keep things simple, it was decided to run only sonar that day, since at the time our other sensors only came on line at speeds higher than 15 mph. Early that morning while doing practice runs for the Site Visit, the sonar processor dumped its program, rendering the three sensors useless. With no programming board on site, and no time to run and get one, we ended up 'flying blind' for the day." ([126]).

- Team 2004-18

Team 2004-18 stated: "The design utilizes standard off-the-shelf sensors and hardware." ([48], p. 1).

- Team 2004-21

Team 2004-21 repeatedly expressed a desire to "keep things simple": "We prefer to keep things as simple as possible." ([155], p. 5), "We want to keep things simple.." ([155], p. 6) and "This makes our design simple..." ([155], p. 8).

However, Team 2004-21's desire to "keep things simple" was at odds with the team's identification of the fundamental problem of the Grand Challenge. Team 2004-21 reported implementing a programming language, a compact standard and solar charging system, and a "hybrid navigation system unlike anything used before". See paragraph XIV.A.6.

- Team 2005-04

Team 2005-04 stated: "Lessons learned with the [Team 2004-23] experience were taken to heart and a simpler, cleaner configuration and interprocessor data communication mechanism was created." ([169], p. 5).

- Teams 2005-13 and 2005-14

Teams 2005-13 and 2005-14 stated: "In meeting the Grand Challenge, two principles emerged as the keys to robustness and success: Keep the components simple..." ([24], p. 468).

- Team 2005-15

Team 2005-15 stated: "The emphasis in designing our system architecture was on simplicity and modularity: failure of one component was not to affect the functionality of the main components." ([53], p. 5).

- Team 2005-16

Team 2005-16 stated: "[Team 2005-16] leverages proven commercial off-the-shelf vehicles..." ([195], p. 2).

XIV.C. Reliability and redundancy

Several teams selected reliable components, including a more recent model year vehicle for challenge vehicle platform, increased redundancy in key components where possible, and took proactive measures to ensure reliability, such as shock isolation. This was limited, to a certain extent, by the effects of experience and sponsorship and resource allocation decisions. For example:

XIV.C.1. Select reliable components

- Team 2004-04

Team 2004-04 stated: "[The Team 2004-04 challenge vehicle] also benefits greatly from the unique partnership with Autonomous Solutions, Inc. (ASI) and their similar background in autonomous systems development... The software components (Primitive Driver, Path Planner, Path Manager, Planning Element Knowledge Store, Reactive Planner) and vehicle conversion that ASI is in charge of have been implemented, tested, and proven to be safe and reliable on numerous vehicles currently in use around the world." ([44], p. 11).

- Team 2004-08

Team 2004-08 stated: "We chose the 1330 series because of its 'sealed and pressurized environmental enclosure [which] provides maximum protection against rain, snow, dust, ...' This device is also designed to withstand high shock and vibration." ([76], p. 4).

- Team 2004-09

Team 2004-09 stated: "...mission-critical operating system, software, and parameters may be stored on highly reliable solid-state media that is relatively immune to high temperatures or other shock conditions." ([47], p. 3).

- Team 2004-11

Team 2004-11 stated: "We decided to do away with the long-range radar after we found it to be hard to focus and unreliable in the returns it provided. We opted instead for a fixed long-range laser rangefinder which is much more reliable, and precise." ([127], p. 4) and "As we mentioned earlier, after numerous tests and attempts to calibrate the radar for our application, we opted for a more reliable laser rangefinder to take its place." ([127], p. 8).

Team 2004-11 also stated: "We have tested the sonar set and found it to be reliable and functional for detecting objects at the 50-foot range." ([127], p. 8).

- Team 2004-17

Team 2004-17 stated: “We used an off-the-shelf system (AutoTap) to read data from the On-Board Diagnostic (OBD) system that is part of all 1996 and later vehicles. We found the data from OBD-II to be less than reliable.” ([142], p. 11).

- Team 2005-01

Team 2005-01 stated: “Five Dell Servers have proven reliability while working in the field.” and “[The challenge vehicle's] Artificial Intelligence software is written in Linux [*sic*], which is know for its reliability...” ([10], p. 5).

- Team 2005-03

Team 2005-03 stated: “DSP chips have been in use for decades controlling mission-critical systems for commercial and government applications so the reliability should be excellent.” ([33], p. 4) and “All computer processing and vehicle navigation is based on highly reliable DSP chips with proven field reliability in thousands of products worldwide.” ([33], p. 12). Team 2005-03 also stated: “This vehicle was chosen for its reliability...” ([33], p. 4).

- Team 2005-05

Team 2005-05 stated: “For the 2005 Grand Challenge, we decided to ... prepare a similar second vehicle for use in the Grand Challenge Event. [The challenge vehicle] is based on a 2005 Dodge Ram 2500. We chose a new model year truck, as opposed to another 1994 model like [the Team 2004-07 challenge vehicle], in order to get better mechanical reliability.” ([34], p. 2).

- Team 2005-06

Integrated COTS controls were in use by Team 2005-06. See paragraph XIV.B.2.a. Team 2005-06 stated: “This level of reliability in the physical vehicle controls has allowed the team’s efforts to be spent on other critical projects rather than wasting time solving vehicle control problems.” ([172], p. 4).

- Team 2005-09

Team 2005-09 stated: “Additionally, a set of four off-road Super Swamper tires was also added to increase reliability in rugged terrain.” ([175], p. 3).

- Team 2005-17

Team 2005-17 stated: “The student crafted cage using aluminum rods purchased from a local hardware store has been replaced by a student-designed but professionally manufactured aluminum structure. A hand rigged case that served as a rack is now replaced by a MIL-spec rack manufactured by Hardigg.” ([140], p. 2).

- Team 2005-21

Team 2005-21 stated: “The hardware was selected specifically for the DARPA Challenge race conditions with consideration for withstanding the hot desert conditions and the ruggedness required for off-road high and low frequency vibration.” ([160], p. 3).

XIV.C.2. Increase redundancy in key components

Several teams described strategies for increasing the redundancy of key components. The author notes that teams variously identified “key components”. Common examples include redundant challenge vehicle alternators, GPS sensors, challenge vehicle brakes, and computing hardware.

Several teams reported a sensor or type of sensor was “redundant” in the sense that it provided obstacle and path detection information in the event another sensor failed, for example Teams 2005-08 and 2005-15. The author considers this to be an example of functional redundancy, not component redundancy. Although several teams reported functional redundancy, those descriptions are not included herein.

- Team 2004-01

Team 2004-01 stated: “Braking will be accomplished using standard automotive 4 wheel hydraulic brakes actuated by a double redundant pneumatic system.” ([8], p. 1).

Team 2004-01 also stated: “Redundant hard drives provide storage for data.” ([8], p. 2).

- Team 2004-02

Team 2004-02 stated: “Two (2) independent alternators operating redundantly will charge the batteries.” ([9], p. 4).

- Team 2004-07

In describing a “Redundant Pneumatic Braking System” Team 2004-07 stated: “There will be two independent pneumatic braking systems.” ([46], p. 2).

- Team 2005-01

Team 2005-01 stated: “Two (2) independent alternators operating redundantly will charge the batteries.” ([10], p. 4).

- Team 2005-02

Team 2005-02 stated: “The power system consists of two independent 140 A 28 V alternator systems... Each alternator drives a 2400 W continuous, 4800 W peak inverter and is backed up by four deep-cell batteries. Each alternator feeds one of two automatic transfer switches (ATS). The output of one ATS drives the computers and electronics, while the other drives the actuators and a 3/4 ton (~ 1 kW cooling) air conditioner. Should either the alternator or battery system fail, the entire load automatically switches to the other alternator or battery system. The total system power requirement is approximately 2200 W, so the power system is totally redundant.” ([50], p. 604).

- Team 2005-03

Team 2005-03 stated: “Dual GPS receivers are used, both to establish direction at rest and to provide redundancy.” and “The third gyro in the 6-axis system is used as a redundant backup for the FOG gyro.” ([33], p. 7).

- Team 2005-05

Team 2005-05 stated: “For the 2005 Grand Challenge, we decided to ... prepare a similar second vehicle for use in the Grand Challenge Event. ...we wanted a second vehicle for redundancy (we were aware that several teams suffered serious vehicle accidents in the days leading up to the 2004 Grand Challenge)...” ([34], pp. 2 - 3).

Team 2005-05 also stated: “For development purposes, [the challenge vehicles] are run by laptop computers... Any of the laptops can be inserted into either of [the challenge vehicles] and be used as the controlling computer. ...the system is highly redundant, so that if the laptop driving the vehicle were accidentally destroyed by an electrical short (as happened immediately prior to our DARPA Grand Challenge Site Visit) it could immediately be replaced by any of the other team members’ laptops. The alternative approach of keeping a privileged computer or set of computers permanently mounted in the vehicles would, we think, reduce redundancy...” ([34], p. 3).

- Team 2005-06

Team 2005-06 stated: “[Team 2005-06] installed an AEVIT 'drive-by-wire' system from Electronic Mobility Controls (EMC) to physically control the car. The AEVIT system uses redundant servos and motors to turn the steering wheel, switch gears, apply throttle, and apply brake. A primary reason that this system was chosen was because it has a proven safety record in the automobile industry due to its use of redundant hardware. One of [Team 2005-06's] primary goals in all of their designs is redundancy, and the AEVIT system satisfies this goal." ([172], p. 4).

Team 2005-06 stated: "...[Team 2005-06] chose to use several 1.42 Gigahertz Apple Mac Mini computers to host the path-planning software. These Mac Minis perform all of the path calculations in a redundant cluster. This ensures that the path planning software does not become a single point of failure." ([172], p. 7).

Team 2005-06 stated: "[Team 2005-06] considers the GPS its most important piece of hardware. As a result of this, it has installed two Oxford RT3000 GPS units on its vehicle. Rather than try to integrate the data from both units at the same time, [Team 2005-06] instead chose to use the two units in a primary/secondary role. Both units are always active, but if one unit stops sending data for some reason, the other unit immediately takes over and becomes the primary unit. This configuration ensures that [Team 2005-06] will have accurate GPS information at all times." ([172], p. 9).

- Team 2005-11

Team 2005-11 stated: "Hardware and software have been designed to minimize the impact of temporary failed components. However, limited redundancy in components means that permanent outages of sensors will have a detrimental effect on [the challenge vehicle's] performance." ([182], p. 7).

- Team 2005-17

Team 2005-17 stated: "A single, garden variety mother board is replaced by two Dell Power Edge 750 computers and two mini-ITX boards." and "The single Honda EU2000 generator now shares a berth with another identical generator." ([140], p. 2).

- Team 2005-20

Team 2005-20 stated: "The second GPS unit also provides redundancy in case of failure of the primary GPS or at times when the primary GPS antenna is experiencing high levels of blockage." ([56], p. 9).

XIV.C.3. Take proactive measures to ensure reliability

Several teams reported proactive measures other than test and evaluation in use by the team to ensure reliability, such as shock isolation or sensor stabilization. For example:

- Team 2004-03

Team 2004-03 stated: "The cameras are mounted on a gimbaled gyro-stabilized sensor mount directly above the front wheel." ([92], p. 5).

- Team 2004-04

Team 2004-04 stated: “The solid-state flash cards are used to increase vehicle ruggedness by eliminating the poor shock and vibration tolerance of ordinary hard drives.” ([44], p. 3).

- Team 2004-07

Team 2004-07 stated: “On the roof is another forward Sony DFW-VL500, passively stabilized by a Kenyon Labs KS-8 gyrostabilizer.” ([46], p. 7).

- Team 2004-09

Team 2004-09 stated: “A passive platform will be designed utilizing materials developed to minimize mechanical shock to the processors and sensor mounts.”, “...the mission-critical operating system, software, and parameters may be stored on highly reliable solid-state media that is relatively immune to high temperatures or other shock conditions.”, “Shock mounts and an isolation platform will be used to enhance the survivability of these components.”, and “Except as noted, all units are general-purpose processor boards, running Linux, in an air-cooled shock-mounted rack.” ([47], p. 3). Team 2004-09 also stated: “The video camera and laser will be shock-mounted on the dashboard of the vehicle.” and “We will use a rapid shutter speed of 1/8000 sec. to minimize blurring. We will mount the camera and other sensors on a platform designed to absorb shock.” ([47], p. 7).

- Team 2004-10

Team 2004-10 stated: “E-box shock isolation system was designed and implemented, based on analyzed and measured dynamic inertial data.” ([77], p. 6). In addition, Team 2004-10 reported several sensors were stabilized ([77], p. 4).

- Teams 2004-13 and 2004-14

Teams 2004-13 and 2004-14 stated: “The RADAR will be used to supplement the obstacle detection capability of the LADAR system in situations where visibility is limited by dust, fog, or rain. It will also be relied upon when the LADAR system is 'dazzled' by the sun.” ([232], p. 3 and [132], p. 4).

Teams 2004-13 and 2004-14 also stated: “There will be several ultrasonic units located around the vehicle with a fixed pointing direction for each one. Use of these sensors will assure that the vehicle can sense nearby objects, even when bright sunlight or obscurants such as fog or dust temporarily disable or confuse the optical sensors.” ([232], p. 4 and [132], p. 4).

- Team 2004-17

In response to 2004 SQ 2.a (see Table XXII), Team 2004-17 described extensive component test and evaluation of the challenge vehicle platform and sensors in use by the team. However, Team 2004-17 also reported the results of reliability testing performed by the team. When describing a "Hard drive survivability" test, Team 2004-17 stated: "The purpose of this test was to determine what hard drive mounting methods, if any, would protect them from damage while driving off-road. Computers with spinning hard drives were installed in the back of the stock 1996 Chevy Tahoe. 6 hard drives were tested. Two were installed via a standard mount, two were encased in foam rubber, one was suspended by an 8-point spring mount, and one was mounted on rubber washers. The only disk to fail outright was the spring-mounted drive." ([142], p. 11). When describing "system tests" which were "performed in the field", Team 2004-17 stated: "some generator issues were identified and resolved" and "More generator issues were discovered and resolved. Computing integration issues (software bugs, processor speeds) were discovered and resolved." ([142], pp. 10 - 11).

- Team 2004-24

Team 2004-24 stated: "...[the challenge vehicle] contains is [*sic*] a boom and platform that houses the most shock sensitive equipment." ([161], p. 5).

- Team 2005-04

Team 2005-04 stated: "The remaining electronics were mounted in a shock-mounted metal enclosure... for protection from... terrain induced vibrations affixed to the cargo bed of the vehicle." ([169], p. 3).

- Team 2005-06

Team 2005-06 leveraged the challenge vehicle suspension to provide shock isolation for computing hardware and sensors. See paragraph XIV.B.1.b.iii. In addition, Team 2005-06 stated: "In order to ensure that the best computing hardware was chosen, [Team 2005-06] investigated the leading computing hardware used by several different industries. The marine industry offered a ready made system that included protection from excessive shock... This system... hosts all of the main computing functions, such as sensor communication, vehicle controls, and artificial intelligence." ([172], p. 7).

- Team 2005-08

Team 2005-08 stated: "The environmental enclosure is supported on each corner using Lord Heavy Duty Plateform shock isolation mounts." ([173], p. 5).

- Team 2005-10

Team 2005-10 stated: “To date, the only component that has failed as the result of this testing was the vibration mounts for the lower SICK LIDAR. These were replaced with a more robust design.” ([176], p. 6).

- Team 2005-11

Team 2005-11 stated: “Attached to [the challenge vehicle's] chassis frame is a stressed skin aluminum body which houses the batteries, computer and control electronics. The central portion of this aluminum body is shock mounted... to protect sensitive components from damage.” ([182], pp. 5 - 6).

- Team 2005-12

Team 2005-12 stated: “The software framework was designed with the goals of flexibility, productivity, and reliability in mind. The system is composed of a number of standalone components that interact with each other through direct communication as well as event-based signaling. In addition to significantly reducing complexity, this component-based and event-based architecture makes system monitoring very easy, as a great deal of system reliability is achieved simply through the addition of another 'watchdog' component, whose sole job is to monitor the functioning of the other system components.” ([185], pp. 4 - 5).

- Team 2005-13

Team 2005-13 leveraged the challenge vehicle suspension to provide shock isolation for computing hardware and sensors. See paragraph XIV.B.1.b.iii. In addition, Team 2005-13 stated: “A custom aluminum body and a cooled, shock- isolated electronics bay replaced the crew compartment body panels, doors, seats and windshield.” ([11], p. 2). Team 2005-13 also stated: “An actuated three-axis gimbal... stabilizes the long range single line LIDAR...” ([11], p. 7).

- Team 2005-14

Team 2005-14 leveraged the challenge vehicle suspension to provide shock isolation for computing hardware and sensors. See paragraph XIV.B.1.b.iii. In addition, Team 2005-14 stated: “[The challenge vehicle's] electronics enclosure sits on a semi-active modified Stewart Platform.” ([12], p. 3). Team 2005-14 also stated: “An actuated three-axis gimbal... stabilizes the long range single line LIDAR...” ([12], p. 7).

- Team 2005-15

Team 2005-15 stated: “The key to the Grand Challenge was not necessarily the incredibly accurate sensing technology or immense amounts of computing power. [The challenge vehicle] was able to detect and avoid the same obstacles as teams with twice the number of sensors and considerably more than twice the computing power. With intelligent yet efficient algorithms and a few key sensors, these hurdles could be overcome. The failure that finally disabled [the challenge vehicle] was a simple hardware connection malfunction. More time needed to be spent by the team to harden the vehicle. [The challenge vehicle's] concept was validated by its showing in the Grand Challenge; with more time, the realization of its potential would also have been reached." ([133], p. 596).

- Team 2005-17

In describing a proprietary terrain modeling and obstacle detection algorithm, Team 2005-17 stated: "A special property of the algorithm... is that it does not require that the sensors be stabilized to reduce the shocks and vibrations they experience. This reduces the cost of developing the system since we do not need to use a gimble [*sic*] to stabilize the sensors." ([140], p. 9).

- Team 2005-18

Team 2005-18 stated: "The servers themselves are housed in a shock-isolated, climate-controlled box fitted with mil-spec connectors." ([197], p. 7).

- Team 2005-19

Team 2005-19 stated: "The rough desert terrain can easily damage sensitive electronics required to operate a vehicle autonomously for extended periods of time. To prevent damage, the computers are stored in a pair of opposite-facing rack mounts situated across the back seat of [the challenge vehicle]... The rack mount is vibration isolated from the floor of the vehicle by a six spring/damper suspension system. The suspension system is designed to constrain all six degrees of freedom of the computer rack and to keep displacement and force transmission low at the frequencies experienced by normal driving..." ([55], pp. 7 - 8).

- Team 2005-20

Team 2005-20 leveraged the challenge vehicle suspension to provide shock isolation for computing hardware and sensors. See paragraph XIV.B.1.b.iii. However, Team 2005-20 reported "small variations in the car's pose can result in very large errors in the positions of distant obstacles, even if inertial data is considered." ([56], pp. 6 - 7).

In addition to the examples cited above, several teams variously referred to shock-mounted, shock-resistant, vibration-resistant[32], or stabilized computing hardware or sensors: Teams 2004-02, 2004-03, 2004-04, 2004-07, 2004-10, 2004-16, 2004-22, 2004-25, 2005-01, 2005-02, 2005-03, 2005-09, 2005-13, 2005-14, 2005-16, 2005-18, 2005-21, 2005-22, 2005-23.

XIV.C.4. Miscellaneous observations

In addition to the specific observations documented above, which were of particular interest to the author, the author noted the following miscellaneous observations, which support a conclusion that teams were making an active effort to increase reliability and redundancy, in some cases based on experience gained from participation in the 2004 GCE.

- Team 2005-03

Team 2005-03 stated: "We have applied what we learned in the first race to harden our vehicle in the areas of tires, wiring, mounting hardware, and field-testing." ([33], p. 12).

- Team 2005-19

Team 2005-19 stated: "Although no team came close to finishing the course last year, many lessons were learned from the successes and failures of last year's entrants, and unexpected problems became apparent. In entering the 2005 Grand Challenge, we have the added benefit of being able to observe these deficiencies so that we may ensure that our vehicle will not be defeated by the same design flaws." ([55], p. 2).

Ironically, Team 2005-19 was one of five teams which failed to complete the 2005 GCE due to GPS sensor failure, which was a preventable system integration failure with adequate test and evaluation. See paragraph XIII.B.12.

XIV.D. Test and evaluation

XIV.D.1. Perform adequate test and evaluation

Several teams reported a lack of time prevented them from fully implementing their challenge vehicle[33] or reported details which support a conclusion that the team was unable to complete planned test and evaluation[34]:

- Team 2004-04

Via their response to 2004 SQ 2.b (see Table XXII), Team 2004-04 described an extensive series of planned tests, and stated: "Four different integration tests will be conducted on [the challenge vehicle]." ([44], p. 12). The Team 2004-04 technical proposal was dated February 27, 2004, approximately two weeks prior to the 2004 GCE.

- Team 2004-07

In response to 2004 SQ 1.a.3 (see Table XXII), Team 2004-07 stated: "Once we have achieved reasonable forward driving, we will consider adding a reverse driving capability and submit an addendum to this report if necessary." ([46], p. 3).

- Team 2004-09

Team 2004-09 stated: “Sensors that facilitate moving in reverse with a maximum range of 6 feet ... may be used to assist [the challenge vehicle] should there be a situation where it must back up. However, in consideration of the timeline and final simplicity of our design, these sensors may not be used in the initial version of the vehicle.” ([47], p. 7).

- Team 2004-11

In response to 2004 SQ 1.h.2 (see Table XXII), when describing wireless signals received by the challenge vehicle, Team 2004-11 stated: “We regret that time did not allow us to pursue another idea past a few initial experiments.” ([127], p. 8), but reported no additional information.

- Team 2004-14

Team 2004-14 stated: “...the biggest challenge was to work against the clock. Time was critical, and for a team like us who was working not during the day-time job but during nights and weekends, this proved to be a big issue.” ([248])

- Team 2005-15

Team 2005-15 stated: “[Team 2005-15], along with Seibersdorf Research, managed to build a strong contender for the DARPA Grand Challenge 2005. A team of volunteer engineers with limited resources managed to stay competitive among teams with more time, money, and resources.” ([133], p. 596).

- Team 2005-17

Team 2005-17 stated ([196], pp. 576 - 577):

> Our experience suggests that field testing is one of the most expensive parts of developing an AGV. To field test, one must have a fully operational vehicle, a field for testing it, correct weather conditions, and a significant amount of staff. Unless the procedures for bringing the vehicle to the field are very well-defined, small issues, such as insufficient gas in the generator, can consume significant time.
>
> Having a fully operational vehicle is no small requirement, given that an AGV has linear dependencies between the automotive, the electromechanical components, the electrical, electronics, sensors, and

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the software.  Failure in any one of the components
can hold back the testing.
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In general, teams which participated in the 2004 or 2005 GCE reported “planned” or “previous” (herein “planned”) and "completed" or "past" (herein "completed") test and evaluation in response to 2004 SQ 2.a and 2.b (see Table XXII) and 2005 SQ 2.5.1 and 2.5.2 (see Table XXIII).

Because the sections of team technical proposals which reported planned and completed test and evaluation were extensive, they are not included herein. The reader is directed to the team technical proposals, a complete list of which is available from the Archived Grand Challenge 2004 and 2005 websites ([17] and [19]) or in the “References” section of this technical report.

The author established the following categories of test and evaluation considered to be essential to the development of a challenge vehicle: “component”, “waypoint following and path detection”, and “obstacle detection and avoidance”. The author reviewed planned and completed test and evaluation reported by team technical proposals for key words associated with the categories of testing considered to be essential.

- Component. The author considered descriptions of sensor evaluation, including GPS sensor reception, challenge vehicle handling characteristics, and drive-by-wire implementation to be typical. In addition, because it is unclear if it was necessary or even desirable (see Chapter XII.) to increase waypoint density to successfully complete the 2004 or 2005 GCE, the author considers the development of “path planning” or “route planning” algorithms to be in the category "component", not "navigation".

- Waypoint following and path detection. The author considered the following key words to be typical: “navigation”, “path following”, “path tracking”, “road following”, “road tracking”, “route finding”, “route following”, “waypoint following”, and “waypoint navigation”.

- Obstacle detection and avoidance. The author considered the following key words to be typical: “obstacle detection”, “object detection”, “obstacle avoidance”, and “point cloud”.

The author established the following levels of testing: Incomplete (“I”), Partially completed (“P”), or Significantly completed (“S”).

Test and evaluation reported by the teams was considered incomplete only if the team did not report any planned or completed test and evaluation for that category of testing, significantly completed if the technical proposal reported completed planned test and evaluation for that category of testing, and partially completed otherwise. All three categories were considered significantly completed if the team reported test and evaluation of a fully autonomous challenge vehicle, for example, by number of autonomous miles completed or "endurance test", no matter how many autonomous miles were completed.

The initial attempt by the author to determine whether teams which participated in the 2004 QID or GCE, and which reported completed test and evaluation, performed better or completed more miles than teams which only reported planned test and evaluation was unsuccessful for several reasons:

- Two of 25 teams which participated in the 2004 QID or GCE did not respond to either 2004 SQ 2.a or 2.b (see Table XXII): Teams 2004-15 and 2004-24. Team 2004-04 reported no planned or completed component test and evaluation.

- Twenty-two of 22 teams which participated in the 2004 QID or GCE and which responded to 2004 SQ 2.a and 2.b reported partially or significantly completed component test and evaluation.

- Four of 23 teams reported partially completed waypoint following and path detection test and evaluation: Teams 2004-11, 2004-13, 2004-14, and 2004-20.

- Two of 23 teams reported partially completed obstacle detection and avoidance test and evaluation: Teams 2004-11 and 2004-12. One of 22 teams reported significantly completed obstacle detection and avoidance test and evaluation: Team 2004-10.

- Eight of 25 teams submitted revised technical proposals in the two weeks prior to the 2004 GCE. Twelve of 25 teams submitted revised technical proposals in the 30 days prior to the 2004 GCE.   Some teams which submitted revised technical proposals did not update their technical proposals to record completed test and evaluation.

- Thirteen of 25 teams did not date or otherwise report the revision of their technical proposals. As a result, it was not possible to determine if these teams submitted revised technical proposals reporting test and evaluation completed since a prior revision.

- Few teams reported the results of their participation in the 2004 GCE. The Team 2005-04 technical proposal ([169]) referenced two papers which reported Team 2004-23[25] results following the 2004 GCE. The Team 2005-06 technical proposal ([172]) referenced a paper which reported Team 2004-23 results following the 2004 GCE. In addition, Team 2005-13 published several papers following the 2004 GCE, some of which are referenced herein as published records. However, no team which participated in both the 2004 and 2005 GCE referenced published results in their 2005 technical proposals, including Team 2005-13.

The initial attempt by the author to determine whether teams which participated in the 2005 GCE, and which reported completed test and evaluation, completed more miles than than teams which only reported planned test and evaluation was unsuccessful for several reasons:

- Four of 22[35] teams which participated in the 2005 GCE reported partially or significantly completed component test and evaluation, incomplete waypoint following and path detection, and incomplete obstacle detection and avoidance test and evaluation: Teams 2005-01, 2005-04, 2005-11, and 2005-15.

- Eighteen of 22 teams reported significantly completed component, waypoint following and path detection, and obstacle detection and avoidance test and evaluation.

- Nine of 22 teams submitted revised technical proposals in the sixty days prior to the 2005 GCE.

- Thirteen of 22 teams did not date or otherwise report the revision of their technical proposals. As a result, it was not possible to determine if these teams submitted revised technical proposals reporting test and evaluation completed since a prior revision.

- Sixteen of 23 teams reported the results of their participation in the 2005 GCE via the Journal of Field Robotics. Seven of 23 teams did not, including several teams which participated in both the 2004 and 2005 GCE.

Overall, the category and level of test and evaluation reported by the teams was exceptionally difficult to quantify. An attempt was made to tabulate results, but the author determined the published record was incomplete, insufficient technical detail was reported by most teams, and assessment of category and level of test and evaluation was too subjective for any comparison to have meaning.

In addition, as noted in paragraph V.E.1.b., the technical proposals submitted to DARPA were of indifferent quality, containing a large number of technical mistakes which rendered meanings unclear. For example:

- Team 2005-01

Team 2005-01 participated in the 2004 GCE as Team 2004-02. Team 2005-01's response to 2005 SQ 2.5.1 does not differ significantly from Team 2004-02's response to 2004 SQ 2.a, including repeated errors such as “ODB-II” for OBD-II and “[The challenge vehicle's] GPS system has been tested for accuracy against other COTS GPS system [*sic*].” ([9], p. 12 and [10], p. 13). In addition, Team 2005-01 reported: “The team continues to do cost analysis of the race use of this information." in reference to OBD-II information and "The LADAR unit has been installed..." ([9], p. 12 and [10], p. 13).

The Team 2005-01 technical proposal is dated August 11, 2005, less than 60 days prior to the 2005 GCE, however Team 2005-01 reported a fully autonomous challenge vehicle: "Extensive testing in the field has led to extensive development of these corner cases." ([10], p. 11).

- Teams 2005-13 and 2005-14

Team 2005-14 stated: "[Team 2005-14] has been testing [the challenge vehicle's] systems and subsystems since it became operational in December of 2003." ([12], p. 15). Team 2005-14 also stated: "[The challenge vehicle's] hardware configuration has been frozen since June 1, 2005. [The challenge vehicle] was assembly complete on July 23, 2005." ([12], p. 5) and "[The challenge vehicle] used this maneuver during the 2004 DARPA Grand Challenge after hitting a large rock." ([12], p. 14).

However, although Teams 2005-13 and 2005-14 were co-participants during the 2005 GCE, neither Team 2005-14 nor the 2005-14 challenge vehicle participated in the 2004 GCE.

The author concluded Teams 2005-13 and 2005-14 revised the same base document to create the technical proposals specific to their team challenge vehicles, and that this may be the reason Team 2005-14 referred to events which occurred during the 2004 GCE despite not having participated in the 2004 GCE.

- Teams 2005-22 and 2005-23

Based on the similarity between their technical proposals, the author concluded Teams 2005-22 and 2005-23 revised the same base document to create the technical proposals specific to their challenge vehicles. The Team 2005-22 technical proposal contains many annotated revisions.

In addition, the Team 2005-22 technical proposal is incomplete, lacking detail reported by the Team 2005-23 technical proposal. For example, Team 2005-22 stated: "It also allowed for testing during conditions where it would normally not be possible, such as at night or times when [*sic*]" ([58], p. 13). The corresponding statement in the Team 2005-23 technical proposal was: "It also allowed for testing during conditions where it would normally not be possible, such as at night or during heavy rain." ([164], p. 12).

As a result, it is unclear if the Team 2005-22 technical proposal represents the final published record of the team prior to the 2005 GCE or if the technical proposal was incomplete, or a work in progress, when it was submitted to DARPA.

In addition, the Team 2005-23 technical proposal contains an extensive passage of almost identically-worded text on pages 6 and 12 which describes test and evaluation performed by the team.

As a result, the author concluded no comparison between 2004 and 2005 results was possible and tabulated results are not presented herein.

In addition, the author concluded no comparison between 2004 and 2005 results was desirable because the number of teams which reported significantly completed test and evaluation in all three categories dramatically increased between the 2004 and 2005 GCE. Prior to the 2004 GCE, most teams had partially completed component test and evaluation only. However, prior to the 2005 GCE, most teams had significantly completed all three categories of test and evaluation.

The author concluded the most significant difference between the 2004 and 2005 GCE was the number of teams which reported test and evaluation of a fully autonomous challenge vehicle, and settled on a simpler objective measure: the number of teams which reported a fully autonomous challenge vehicle capable of waypoint following and path detection, and obstacle detection and avoidance ("fully autonomous challenge vehicle"):

- Prior to the 2004 GCE, no teams reported a fully autonomous challenge vehicle.
- Prior to the 2005 GCE, 21 of 22[35] teams reported a fully autonomous challenge vehicle, including several of the teams which reported incomplete waypoint following and path detection, and incomplete obstacle detection and avoidance test and evaluation. The only team which did not report a fully autonomous vehicle was Team 2005-11. The Team 2005-11 technical proposal was dated August 29, 2005, less than sixty days prior to the 2005 GCE. Team 2005-11 completed 7.2 miles of the 2005 GCE.

The author proposes the difference in the number of fully autonomous challenge vehicles between the 2004 and 2005 GCE may provide an explanation for DARPA's comment that "We are confident that the $2 million prize for Grand Challenge 2005 will be adequate incentive for many teams to do just that." when referring to completing the 2005 GCE. See paragraph XIII.A.

The author selected several teams which reported a focus on test and evaluation. Without exception, these teams had prior experience or focused on the fundamental problem. With one exception, all teams which successfully completed the 2005 GCE had prior experience *and* focused on the fundamental problem, although a focus on test and evaluation was a key factor for several potentially disruptive teams.

- Team 2004-02

Team 2004-02 stated: “The testing strategy establishes reliable control of each component separately before the components are integrated.” ([9], p. 12).

Team 2004-02 described an extensive series of planned tests, but no completed tests, and stated: “At this time, the tests below have not been performed, but will be conducted over the next few months.” ([9], p. 12). The Team 2004-02 technical proposal was dated February 29, 2004, approximately two weeks prior to the 2004 GCE.

- Team 2004-05

Via their response to 2004 SQ 2.b (see Table XXII), Team 2004-05 described extensive planned test and evaluation. Team 2004-05 reported an emphasis on formal methods for software development. See paragraph XIV.D.2.

- Team 2004-10

Team 2004-10 stated: “Extensive testing and evaluation was conducted to evolve vehicle sensing and autonomous steering capability.” ([77], p. 5), and continued with a description of various component and obstacle detection and avoidance test and evaluation.

Overall, Team 2004-10 reported the most comprehensive component and obstacle detection and avoidance test and evaluation of any team which participated in the 2004 GCE. In response to 2004 SQ 2.b, Team 2004-10 stated: “Incremental testing regime will continue as program develops and moves towards higher navigational speeds, more complex real-time processing, and increased sensing capability. Vehicle testing programs will include component, subsystem, speed, and desert local.” ([77], p. 6). Team 2004-10 completed 7.4 miles of the 2004 GCE course, the greatest number of miles completed of any team which participated in the 2004 GCE.

Following the 2004 GCE, DARPA alternately stated: “At mile 7.4, on switchbacks in a mountainous section, vehicle went off course, got caught on a berm and rubber on the front wheels caught fire, which was quickly extinguished. Vehicle was command-disabled.” ([30]) and “At mile 7.4, on the switchbacks in a mountainous section, the vehicle veered off course, got caught on a berm, and could not overcome the obstacle.” ([3], p. 8). However, the actual failure was considerably more complex.

Team 2004-10 was one of few teams which participated in the 2004 GCE to publish its results after the 2004 GCE. Team 2004-10 stated ([39], pp. 36 - 38):

> This failure was a result of a variety of weaknesses acting in concert to end [the challenge vehicle's] race. Entering the corner, the onboard navigation system began to filter out laser data. The filtering

> algorithm was triggered as a result of a sharp angle change in the preplanned path which would not have been present if the path used smooth curves. [A Figure] shows that even though the data was disregarded, the classification of the terrain from the laser scan was still reasonable.
>
> Once the laser data was disregarded, the onboard planning system seamlessly switched to following GPS blindly. At this point, [the challenge vehicle] began to cut towards the inside of the curve. [The challenge vehicle's] GPS measurement of the preplanned path had errors pushing it towards the inside of the curve. In addition, the faceted nature of the preplanned path caused it to be even farther towards the inside of the corner. Finally, the pure-pursuit path tracking software can cause [the challenge vehicle] to cut corners. In this case, these three effects combined to push [the challenge vehicle] roughly 1.5 to 2 meters to the left of the road center such that one wheel fell off of the edge. [A Figure] shows a plot of the pre-planned corridor (inner blue circles), pre-race reconnaissance (green) and [the challenge vehicle's] ground track (black). From this data, the path error seems to be due equally to the above mentioned sources.

The author concluded Team 2004-10 did not perform adequate waypoint following and path detection test and evaluation.

- Team 2005-01

Team 2004-02 participated in the 2005 GCE as Team 2005-01. Team 2005-01's response to 2005 SQ 2.5.1 does not differ significantly from Team 2004-02's response to 2004 SQ 2.a, including repeated errors such as “ODB-II” for OBD-II and “[The challenge vehicle's] GPS system has been tested for accuracy against other COTS GPS system [*sic*].” ([9], p. 12 and [10], p. 13). In addition, Team 2005-01 reported: “The team continues to do cost analysis of the race use of this information.” in reference to OBD-II information and “The LADAR unit has been installed...” ([9], p. 12 and [10], p. 13).

The Team 2005-01 technical proposal is dated August 11, 2005, less than 60 days prior to the 2005 GCE, however Team 2005-01 reported a fully autonomous challenge vehicle: “Extensive testing in the field has led to extensive development of these corner cases.” ([10], p. 11).

- Team 2005-06

Team 2005-06 stated: “[Team 2005-06] has approached the 2005 DARPA Grand Challenge from the standpoint of integrators rather than inventors. This design philosophy has driven its decisions in choosing proven technologies such as the AEVIT vehicle control system and the Oxford integrated INS/GPS, rather than trying to develop these types of technologies itself. This has allowed [Team 2005-06] to focus its considerable manpower on the algorithms and innovative ideas necessary to win the 2005 DARPA Grand Challenge.” ([172], p. 2).

Team 2005-06 later stated: “...we would like to think that reaching the finish line after 132 miles of autonomous driving in the desert was not just beginner’s luck but rather the result of our simple design methods, good decisions, and good system integration.” ([28], p. 525).

The author considers this conclusive evidence that prior experience and extensive corporate or academic sponsorship were not required for a team to successfully complete the 2005 GCE. Team 2005-06 was the only potentially disruptive team to successfully complete the 2005 GCE. As a result, the author considers the Team 2005-06 focus on the 2005 GCE as “integrators” to be a distinguishing key factor.

- Team 2005-09

Team 2005-09 stated: “Specific testing and regression testing was performed nearly daily for short focused evaluations.” ([175], p. 6); “[The challenge vehicle] development has been driven by two overarching themes. The first is to do small increments of a develop, simulate, test, and regression cycle. The second is to continuously develop an end-to-end system built with agents of comparable complexity and quality. This approach means at any time the vehicle has all the necessary components to operate and shifts the emphasis from novel ideas to the interaction and integration of agents.” ([175], p. 6); and “The end to end testing of [the challenge vehicle] was performed in stages. Early on we had many short specific tests on a nearly daily basis. Specific tests included a series of vibration and sensor fouling experiments. As the site visit approached we became focused on meeting the specific challenges of the site visit and focused specifically on the waypoint following and trash cans as obstacles. In July we went to the Mojave Desert to test the fully integrated vehicle. We tested for distance, responsiveness to the environment, effects of terrain and overall reliability. This was sufficient to convince us we could compete in the DGC. The final testing phase is emulating the NQE environment and identified NQE evaluation components.” ([175], p. 9).

Team 2005-09 stated: “[Team 2005-09] is sponsored by the MITRE Corporation. MITRE is a collection of Federally Funded Research and Development Centers that support the DoD, FAA, IRS and other federal agencies.” ([175], p. 2). The author proposes Team 2005-09's focus on test and evaluation may have been a result of the team's primary group identity and background in system integration.

Team 2005-09 completed 0.7 miles of the 2005 GCE course, the least number of miles of any team which participated in the 2005 GCE. Team 2005-09 stated the challenge vehicle detected occasional dust clouds as transient obstacles, which ultimately caused the challenge vehicle to veer off course where it was unable to continue because "the lasers could not differentiate between weeds and large rocks" ([52], p. 835). See paragraph XIII.B.5.

However, Team 2005-09 also stated: "A major challenge of the system has been the self imposed requirement that the system be reusable and adaptable to the needs of a variety of our sponsors." ([175], p. 3) and "Given our incredibly short time to prepare, a key challenge for us was to sustain a rapid pace of incremental development while maintaining system coherence. In order to ensure what we learn is of high utility to our sponsors we also had a self imposed challenge of reusability and extensibility of design and code." ([175], p. 9).

As a result, although Team 2005-09 attributed the cause of their failure to complete the 2005 GCE to errors in obstacle detection, the author concluded the ultimate cause may have been a lack of available resources, specifically time in which to perform adequate test and evaluation of the team challenge vehicle.

- Teams 2005-13 and 2005-14

Teams 2005-13 stated: "A vigorous testing program has demonstrated reliable, high-speed navigation including a 7-hour 200-mile endurance run, reliable obstacle avoidance at 35 mph and peak speed of 54 mph." ([11], p. 2), "[Team 2005-13] has been testing [the challenge vehicle's] systems and subsystems since it became operational in December of 2003. [The challenge vehicle] has accumulated over 3000 autonomous test miles." ([11], p. 15), and "In addition to these system tests, [The challenge vehicle] has tested for software endurance via simulation, dust detection, pointing, shock and vibration." ([11], p. 15).

Team 2005-14 stated: "A vigorous testing program has demonstrated reliable, high-speed navigation including a 7-hour 200-mile endurance run, reliable obstacle avoidance at 35 mph and peak speed of 40 mph." ([12], p. 2), "[Team 2005-13] [*sic*] has been testing [Team 2005-14 challenge vehicle's] systems and subsystems since it became operational in December of 2003. [The Team 2005-14 challenge vehicle] has accumulated over 500 autonomous test miles." ([12], p. 15), and "In addition to these system tests, [the Team 2005-14 challenge vehicle] has tested for software endurance via simulation, dust detection, pointing, shock and vibration." ([12], p. 15).

Although Teams 2005-13 and 2005-14 were co-participants during the 2005 GCE, Team 2005-14 did not participate in the 2004 GCE. See paragraph XIV.D.1.

• Team 2005-16

Team 2005-16 stated: “A major emphasis of [Team 2005-16] has been early development of a prototype end-to-end system, to enable extensive testing in authentic desert terrain.” ([195], p. 1), “From the beginning of this project, [Team 2005-16] has placed a strong emphasis on in-field development and testing. Initial tests of a preliminary end-to-end system took place in December 2004. Since this time, [the challenge vehicle] has logged many hundreds of autonomous miles.” ([195], p. 2), and “Testing has played a major role in the development of [the challenge vehicle].” ([195], p. 12). Team 2005-16 described a comprehensive test and evaluation program culminating in endurance testing of a fully autonomous vehicle.

• Team 2005-18

Team 2005-18 stated: “[Team 2005-18] makes use of a spiral development process to guide our efforts as we make progress toward the completion of the DARPA Grand Challenge. Spirals are defined phases in the projects development moving outward from the initial point. Each spiral outward adds a new layer of functionality that future layers can build upon. A given spiral passes through the following phases: define, design, build and test. A spiral process is far more useful for a project like ours that requires multiple components that all depend on one another to be developed in parallel since any given component can always depend on the level of functionality of the other components in the previous spiral.” ([197], pp. 12 - 13).

Team 2005-18 also stated: “Development and testing of individual modules and full system integration is achieved through an extensive test plan.” ([197], p. 13).

• Team 2005-20

Team 2005-20 stated: “[The challenge vehicle] has been thoroughly tested in many different environments. A mockup of last years QID was constructed on a farm (site visit location) to test path following, high speed navigation, and obstacle avoidance. During the development of this system we have endured many failures. Countless hours have been used investigating computer failures/corruptions, network failures, electrical issues, and a few mechanical failures. This experience has led to redesign of some components of the vehicle, improved cooling for computers, and knowledge of critical spare parts to have on hand.” ([56], p. 14).

• Teams 2005-22 and 2005-23

Teams 2005-22 and 2005-23 stated: “[The Team 2005-22 challenge vehicle] was subjected to extensive simulated and live testing in preparation for the 2005 Grand Challenge.” ([58], p. 12) and “[The Team 2005-23 challenge vehicle] underwent extensive simulated and live testing in preparation for the 2005 Grand Challenge.” ([164], p. 6). Both teams reported extensive test and evaluation, including the use of a “vehicle simulator program" to "test conditions and situations that would be difficult, if not impossible, for [the challenge vehicle] to encounter in Blacksburg" ([58], pp. 12 - 13 and [164], p. 6) and which "allowed for testing during conditions where it would normally not be possible, such as at night or during heavy rain" ([58], p. 13 and [164], p. 6). See paragraph XIV.D.1.

XIV.D.2. Use robust software development methodologies

Several teams reported robust software development methodologies were in use by the team. For example:

- Team 2004-04

Team 2004-04 stated: "The Smart Sensor Arbiter component provides a central point for fusing all smart sensor data. The Smart Sensor architecture was defined in such a way that all sensors and the arbiter use the same message interface. The benefits of doing this are two-fold. First it allows the option of having the Smart Sensors share code for the core Smart Sensor functionality. This reduces development time by allowing the core code to be rigorously tested and debugged while each sensor developer works on their sensor data processing." and "The Smart Sensors can also be used individually as input to the Smart Sensor Arbiter allowing the sensors to be tested and debugged with the Reactive Planner component individually." ([44], p. 7).

- Team 2004-05

Team 2004-05 stated: "The software is developed according to well defined formal methods based on the SEI-CMM; with design documents, coding standards, and state and timing charts." ([45], p. 3). Team 2004-05 also stated: "The application and driver software will be verified using formal methods based on UML for Real Time, as well as other methods such as Rate Monotonic Analysis and Dynamic Monotonic Analysis as appropriate. Each software module will have a formal test plan and software test harness that can be executed on the development machines, and there will also be formal integration and performance tests." ([45], p. 7).

- Team 2005-06

Team 2005-06 stated: "Early on in the planning process for the Grand Challenge, [Team 2005-06's] development team decided that they would use the Java programming language to develop as much of the software as possible. This decision was made due to Java's proven track record of stability, rapid development, simple threading capabilities, and portability. Using Java allowed the development team to concentrate on the real issues, rather than having to spend considerable time debugging memory leaks and complex threading issues." ([172], p. 7).

Team 2005-06 also stated: “In order to reduce errors, [Team 2005-06] has chosen to integrate the powerful unit testing framework JUnit throughout its entire development process. By using JUnit, [Team 2005-06] can write tests for independent modules of its code base and then automatically run these tests whenever new code is deployed to the autonomous vehicle. This ensures that as development progresses no bugs are introduced into pieces of code that were previously working.” ([172], p. 8).

- Team 2005-17

Team 2005-17 stated: “Daily builds of the software are tested against a collection of test cases gathered from the real world. Developers perform unit level testing of changes to the software using the combination of the vehicle simulator and visualization tools included in the software suite.” ([140], p. 10).

- Team 2005-18

Team 2005-18 stated: “[Team 2005-18] uses proven open-source tools as a critical part of our code-development. All code is written in C/C++. The source tree is managed with the subversion source control system, allowing for versioning control. Additionally, HTML documentation of the source tree is automatically generated by doxygen. The bugzilla tool from the Mozilla project is used to track the different bugs we inevitably encounter in the team source tree. Bugzilla is also used to manage tasks assigned to different members of the team. The team also maintains a wiki for general documentation. This [*sic*] extent of this documentation ranges from meeting minutes to sub-system documentation and status. The HTML format of the wiki makes our documentation easily accessible to the members. Finally, the team also maintains a web based discussion board for its members to further discuss any new ideas or large issues that come up when its hard to get everyone together for a meeting.” ([197], p. 13).

- Team 2005-20

Team 2005-20 stated ([56], p. 8):

> A variation of Extreme Programming was utilized to develop the majority of the software. A rough architecture was initially sketched out, but the details of the various implementations were left somewhat vague. A core set of classes were developed and ported to all operating systems. Hardware and software architectures were enumerated, as many of the sensors have very specific hardware requirements. A communications layer was developed, and then the individual applications were developed in parallel with simulators and other proprietary testing tools. Code reviews were performed, and large discussions

were held before refactoring certain experimental algorithms. A very large emphasis was placed on using well-known design patterns and STL libraries.

A primary development process for the software was to develop a simulator using the actual real-time PXI controller software. Since the real-time modules are the same ones that run the robot, any conflicts or errors would be immediately evident in the simulation. The simulator estimates where the vehicle position would be based on the commands sent instead of reading its position from a GPS device, but is otherwise identical to the software on the robot. This facilitates testing and optimization of the complex interaction between the path planner and PXI without the need to operate the vehicle.

- Team 2005-21

Team 2005-21 stated ([160], p. 13):

The software was developed and testing in phases utilizing different test methods. These test methods included software peer reviews, simulations on host, lab testing, and testing on the vehicle.

Software peer reviews were held for code that was considered either complex in nature, or a critical interface between two functions. At each software review, members of the team were invited to review the code. Action and questions were formally documented for later investigation and resolution by the coder.

- Teams 2005-22 and 2005-23

Team 2005-22 stated: "The software on [the challenge vehicle] was created using National Instruments' Labview 7.1. This program allows team members with knowledge of control systems but little programming experience to program the vehicles [*sic*] behavior. Certain parts of the programs are written in C; however, these pieces are converted into files that are later used by the larger Labview code. Another large benefit of using Labview is the ease of creating vehicle interfaces within the programs. Any team member can easily create an interface that monitors all vehicle action during autonomous operation. This allows for quick and easy debugging to [*sic*] any problems that appear during testing." ([58], p. 3).

Team 2005-23 stated: "The software on [the challenge vehicle] was created using National Instruments' Labview 7.1. This programming language allows team members with knowledge of control systems but little programming experience to program the vehicles [*sic*] behavior. Certain parts of the programs are written in C; however, these pieces are converted into .dll files that are used by the larger Labview code. Another large benefit of using Labview is the ease of creating vehicle interfaces within the programs. Any team member can easily create an interface that monitors all vehicle action and sensor data during autonomous operation. This allows for quick and easy debugging to [*sic*] any problems that appear during testing." ([164], p. 3).

XIV.D.3. Simulate sensor noise and sensor failure

DARPA cautioned teams might encounter sensor noise or sensor failure. DARPA stated: "Prospective Entrants also are advised that there could be dust, smoke, or other visual obscurants on the Route, and that visual spectrum only sensing may not permit sufficient speed if those situations are encountered (such as when following another vehicle)." ([1] and [6]).

DARPA also cautioned teams should not rely solely on GPS, and that GPS reception was not guaranteed. DARPA stated: "GPS alone will not provide adequate navigation information to a Challenge Vehicle." and "GPS reception at Waypoints is not guaranteed." ([1] and [6]).

Several teams described strategies to simulate or otherwise reproduce sensor noise or sensor failure or reported test and evaluation to determine the effects of sensor noise or sensor failure. For example:

XIV.D.3.a. <u>Noise</u>

- Team 2005-04

Team 2005-04 stated: "Compensation for vibration and other vertical motion is done in software, using the IMU data, specifically generating a 'ground plane' that can be referred to, while doing sensor fusion." ([169], pp. 9 - 10).

- Team 2005-05

Team 2005-05 stated: "We have tested the vehicle in moderate rain. Although the rain did introduce noise into the ladar measurements, our obstacle detection software appeared fairly robust to this noise." ([34], p. 13).

- Team 2005-09

Team 2005-09 stated: "Early on we had many short specific tests on a nearly daily basis. Specific tests included a series of vibration and sensor fouling experiments." ([175], p. 9).

- Teams 2005-13 and 2005-14

Teams 2005-13 and 2005-14 stated: "...[the challenge vehicle] has tested for software endurance via simulation, dust detection, pointing, shock and vibration." ([11], p. 15 and [12], p. 15).

XIV.D.3.b. GPS "jump" and position error

GPS "jump" or "drift" was consistently reported by teams which participated in the 2004 QID or GCE or 2005 GCE. For example, Team 2005-05 stated: "Very often, especially when the vehicle would drive near a wall or approach a tunnel, there would be highly erratic jumps in the GPS measurements due to multipath reflections." ([170], p. 542).

In addition, GPS sensor failure was directly implicated in the failure of five teams to complete the 2005 GCE: Teams 2005-02, 2005-09, 2005-15, 2005-18, and 2005-19.

DARPA, via 2004 SQ 1.g.2 (see Table XXII) and 2005 SQ 2.2.1 (see Table XXIII) requested teams describe how they would handle "GPS outages". In general, teams described how the challenge vehicle controlling intelligence would continue to determine position reliably in the absence of GPS data. A few teams described test and evaluation to determine the effect of GPS outage on the challenge vehicle controlling intelligence. For example:

- Team 2004-05

Team 2004-05 stated: "In the event of a total loss of GPS signals, the system can maintain an accurate location estimate by 'dead reckoning', using the four independent wheel rotation encoders in conjunction with two independent heading determination subsystems, a gyro and an electronic compass sensor." ([45], p. 6).

- Team 2004-07

Team 2004-07 stated: "In the absence of GPS, the vehicle will attempt to proceed by dead reckoning using IMU and odometry data. If the vehicle is on a known trail and following the trail is consistent with remaining on the Challenge Route, the vehicle will follow the trail and use odometry data to infer the distance traveled along it. As the uncertainty of its position grows larger, the vehicle may replan its route to avoid the Challenge Route boundaries, i.e., other things being equal it may try to remain in (what it thinks is) the center of the Challenge Route corridor, even if this is not the shortest route." ([46], p. 8).

- Team 2004-08

Team 2004-08 stated: "In the case of lost GPS signal, we will still receive data from our POS LV regarding current location and other related information. The GPS will automatically update the location in the device when signal is available. As outlined in the table below, without GPS input for a two-minute time span this unit will stil [*sic*] be accurate within 0.60 meters." ([76], p. 6). Team 2004-08 also stated: "...if our vehicle leaves GPS coverage, it will just run off of the INS. When the system loses GPS input for a two-minute time span this unit will stil [*sic*] be accurate within 0.60 meters." ([76], pp. 4 - 5).

- Team 2004-13

Team 2004-13 stated: "In case of short temporary loss of GPS signal, the IMU is able to determine the location of the vehicle, although with an increasing error." ([232], p. 5).

- Team 2004-14

Team 2004-14 stated: "In the absence of GPS data due to communication outages the IND/DGPS [*sic*] system is aided by a 3D-magnetometer and the vehicle's odometer. The Kalman filter of the Navigation system continuously blends the INS/DGPS data with the odometer and magnetic compass. As a result the compass and odometer are constantly calibrated and provide fairly accurate information. During GPS outages the INS uses only odometer and magnetic compass data to aid the inertial data." ([132], p. 6).

- Team 2004-17

Team 2004-17 stated: "We have tested the ability of various materials to block antenna reception. Flat sheets of aluminum and Lucite were unable to block the GPS, as multi-path reflections off of the ground still reached the antenna. Wrapping the antenna in aluminum foil cut off reception (we can selectively cut off satellites and simulate GPS outages)." ([142], p. 12).

- Team 2004-20

Team 2004-20 stated: "We are currently planning to use a Novatel ProPack LBHP GPS with Omnistar corrections, along with a Crossbow AHRS inertial system. This combination should give us location to within 20cm with GPS information available, and in dead-reckoning mode, we expect to have drift rates of perhaps 1 degree per minute in heading." and "The INS system and magnetic compass will take over, but drift is to be expected. If GPS is lost while on a well-defined road, or in an area where there is no alternative path, the road-following and collision-avoidance systems should be sufficient to keep the vehicle on course. Long GPS outages will result in increasing uncertainty as to position and, if this occurs in an area where the course boundaries are narrow, this may result in problems. For safety reasons, speed will be reduced during GPS outages." ([107], p. 7).

- Team 2005-05

Team 2005-05 stated: “The NovAtel Propak-LBPlus GPS has a nominal position accuracy of 20 cm, but under adverse conditions, this accuracy figure can become meaningless. For example, when passing into the shadow of a metal structure, we have witnessed sudden changes in reported position of over 100 meters. We use a Kalman filter which includes the steering properties of the truck in its physical model of the system to reject transient errors of this type. Under typical route conditions we estimate we can maintain a position accuracy of under 30 cm.” ([34], p. 5).

- Team 2005-06

Team 2005-06 stated: “Another extremely effective test involved manually steering the vehicle off course at high speed and then switching back to autonomous mode. This simulated a GPS jump, which can occur rather frequently. After noticing that the navigation system abruptly turned the steering wheel to counteract this jump, the navigation system was updated to eliminate this abrupt movement.” ([172], p. 12).

- Team 2005-10

Team 2005-10 stated: “A MIL-NAV inertial navigation system from Kearfott is computing position at 50 Hz and becomes the primary source of position information when the Navcom reports its data as invalid. It also serves as an error check for the Navcom data.” ([176], p. 3).

- Team 2005-21

Team 2005-21 stated: “During most of the integration and development testing, the antennas for the RT3100s were mounted on the roof of the cab on an aluminum sheet ground plane. For the actual race, the cab was reduced in height and the antennas were mounted on the roll bar just behind the cab. The small patch antennas that were initially used with the RT3100s, were replaced later in the testing phase with GPS-701 antennas from Novatel. It was discovered that the small patch antennas seemed particularly susceptible to interference. In order to obtain a more accurate position solution and eliminate any errors over time, the position solutions from the two RT3100s were averaged together. In the case of a failure of one of the RT3100s, the system will switch to using the remaining RT3100 as the sole GPS source.” ([160], p. 9)

XIV.D.3.c. <u>Other sensor failure</u>

- Team 2005-11

Team 2005-11 stated: “Scenarios were developed to mimic the loss of data as well as terrain obstacles. Multiple simulation runs, particularly obstacle avoidance scenarios, were executed prior to field testing. Both the hardware and software were modified to attempt to remedy shortcomings identified during testing.” ([182], p. 9).

- Team 2005-12

Team 2005-12 stated: "Stereovision has clear advantages over LIDAR in rain as light rain will not affect image quality unless it collects directly on the lens. In addition, water or other obstructions on the lenses produce holes in the depth image that will preclude detection in these areas but will not generate false positives." ([185], pp. 5 - 6).

XIV.D.4. Develop tools to analyze the results of test and evaluation

Several teams reported the development of tools to analyze the results of test and evaluation. For example:

- Team 2005-05

Team 2005-05 stated: "We devoted considerable effort to our visualization/control interface software, called 'Dashboard.' All sensor data is logged while the vehicle is running and can be examined by Dashboard in real time or replayed later. Some interesting features of Dashboard are: 3D visualization in space of the truck's location, heading, and wheel angle, the location of waypoints, ladar reflections, video imagery, inferred obstacles and trail boundaries, the planned route, and current and future planned speed; also the ability to pan, rotate, and zoom to different viewpoints; the ability to measure distances and angles between any points on the screen; and very importantly, the ability to scroll backwards and forwards in time when replaying a 'movie' from logged data. In this way we can find the critical moments of a test run and visualize exactly what the state of the vehicle was at that time, what it sensed, and what decisions it made. This is very useful in debugging." ([34], pp. 4 - 5).

- Team 2005-18

Team 2005-18 stated: "An important feature of all modules is their ability to log raw data and reply [*sic*] the data for offline debugging and testing. This capability is used frequently in testing and allows a detailed analysis of failures and the ability to replay data through the system to verify that modifications solve the intended problem." ([197], p. 13).

- Team 2005-20

Team 2005-20 stated: "In addition, a software program called HANSEL was developed for viewing the GPS data on satellite image maps. This program has evolved into a very significant part of the system diagnostics program. All the time stamped obstacle data, planned path data, and actual traveled path are plotted on the map. This map shows when the vehicle saw the obstacle, when the new path was sent to the controller, and the final result of the vehicle motion all represented in global position and time. Each obstacle is color coded to indicate which sensor saw which obstacle and where it was located relative to the vehicle." ([56], p. 8).

- Team 2005-21

Team 2005-21 stated: “Rockwell also developed a simulation environment that included all of the vehicle dynamics. This simulation was used to test the vehicle control interface, real-time path planner and behavior control. Similar to on the vehicle, a series of waypoint could be executed while avoiding planned obstacles. The 2004 race path was executed several times in this simulation environment to determine if the vehicle could navigate the entire path.” ([160], p. 13).

- Team 2005-22

Team 2005-22 stated: “A second set of software allowed various data recorded from the vehicle to be replayed for analysis. This replay software played back information such as vehicle position and orientation, speed, throttle and brake percentages, and LIDAR scans at the same speed that it was originally recorded. Being able to play back exactly what happened during autonomous runs is valuable to determine exactly how [the challenge vehicle] behaved in the real world.” ([58], p. 13).

- Team 2005-23

Team 2005-23 stated: “A second set of testsoftware [*sic*] allowed various data recorded from the vehicle to be replayed for analysis. This replay software played back information such as vehicle position and orientation, speed, throttle and brake percentages, and LIDAR scans at the same speed that it was originally recorded. Being able to play back exactly what happened during autonomous runs was valuable to see exactly how [the challenge vehicle] behaves in the real world.” ([164], p. 6).

CHAPTER XV. POTENTIALLY DISRUPTIVE TEAMS

XV.A. Definition of “potentially disruptive team”

As used herein, the phrase “potentially disruptive team” refers to a team with no prior experience in the field of autonomous vehicle development and neither extensive corporate nor academic sponsorship which implemented the greatest number of key factors contributing to success. The following teams were not potentially disruptive due to their prior experience and extensive corporate or academic sponsorship: Teams 2004-04, 2004-10, 2004-23, 2005-02, 2005-04, 2005-13, 2005-14, 2005-16, and 2005-21.

Potentially disruptive teams had a great deal in common with teams with prior experience and extensive corporate or academic sponsorship. However, evaluation of the key factors revealed teams with prior experience or extensive corporate or academic sponsorship were able to use the effects of experience, in particular, and sponsorship as the equivalent of a “force multiplier”. The advantage this gave these teams was so significant that the author questions whether it was appropriate for DARPA to allow most of the teams which participated in the 2004 or 2005 GCE to participate without first ensuring those teams were able to identify the fundamental problem and devote sufficient resources to the development of a challenge vehicle which would be competitive with those of teams with prior experience and significant sponsorship.

Throughout this chapter, teams which participated in both the 2004 and 2005 GCE are referred to by their combined team numbers. For example, Team 2004-02 participated in the 2005 GCE as Team 2005-01. Both teams are referred to throughout this chapter as “Team 2004-02 / 2005-01”. This is a departure from practice in all other chapters of this technical report. The author considers this necessary to highlight identification of key factors contributing to success by teams which gained experience through participation in the 2004 QID and GCE. Comments beginning with “The net increase...” are typical.

XV.B. Introduction

In the absence of detailed cost information, it was not possible to relatively rank team challenge vehicles to determine which solution was most cost effective. However, the comprehensive review of technical proposals submitted by teams which participated in the the 2004 QID or GCE or 2005 GCE revealed that teams which performed better or completed more miles of the course used the same or similar strategies, and that teams which did not use these strategies did not perform as well or completed less miles of the course. These strategies are referred to as “key factors contributing to success” or “key factors” herein.

Broadly, a key factor was a strategy common to teams which:

- Successfully completed the 2005 GCE.

- Completed a greater number of miles of the 2004 or 2005 GCE course in comparison to other teams (2004 QID or GCE) or the average number of miles completed (2005 GCE).

- Were selected to participate in the 2004 QID or GCE or 2005 GCE.

Decisions made by or actions taken by DARPA or the teams were directly responsible for some of these key factors, while others were imposed on DARPA and the teams by the format of the Grand Challenge as a race. In general, the author did not attempt to determine the extent to which teams evaluated the problem statement presented by DARPA to determine what key factors the teams were able to control.

However, the author considers the implementation of key factors which teams participating in the 2005 GCE were able to control by teams which completed more than the average number of miles of the 2005 GCE course to support a conclusion teams implementing more of these key factors completed a greater number of miles of the 2005 GCE course than teams implementing fewer of these key factors, and that teams implementing the greatest number of key factors were potentially disruptive.

The following key factors were identified by the author:

XV.C. Key factors

XV.C.1. Key factors contributed by DARPA

Several key factors were contributed by DARPA. Based on a comparison of objective measures calculated from data defined by the 2004 and 2005 GCE RDDF using the RDDF analysis application, the 2005 GCE course was less difficult. DARPA:

- Decreased the course length from 142 miles to 131.6 miles. The maximum corrected time was not reduced to ensure an “average minimum speed of approximately 15 - 20 mph” ([3], p. 2) was achieved for either event.

- Increased the number of waypoints from 2586 to 2934.

- Increased the number of course segments in defined groups as a cumulative percentage of the total number of course segments, the majority of which were distributed across groups with lower course segment speeds.

- Increased the total length of the course in defined groups with lower course segment speeds.

In addition, the evidence supports a conclusion that:

- DARPA provided well-defined berms for the 2005 GCE course to make it easier for challenge vehicles to identify the edges of the path.

- DARPA groomed washouts, eliminating areas that would otherwise have been high risk.

- The location DARPA selected for the 2005 GCE course resulted in a decrease in the number of miles of observed slope greater than 5 degrees from 17.5 miles to less than two miles, which resulted in more effective obstacle detection at long range and provided a sensing advantage to teams which were able to effectively use long-range sensors.

- DARPA engineered the 2005 GCE course to eliminate the extreme course segment lengths and lateral boundary offsets defined by the 2004 GCE RDDF.

- DARPA engineered the 2005 GCE course to decrease the number of significant changes in bearing. As a result, the 2005 GCE course was "smoother" than the 2004 GCE course.

- DARPA engineered the 2005 GCE course to introduce deceleration lanes to force vehicles to decelerate to significantly lower speeds before negotiating areas which were high risk.

XV.C.2. Key factors identified through review of the published record

The author identified the following key factors through the review of the published record documented by this technical report:

- Reduce the number of obstacle and path detection sensors in use by eliminating other sensors. See paragraph VI.D.1.

- Use high-quality sensors which provide a point-map of the environment. See paragraph VI.D.2.

- Use LIDAR sensors with capabilities similar to the SICK LMS 291 product family. See paragraph VI.D.3.

- Use a COTS component to integrate navigation sensors. See paragraph VII.D.1.

- Use a Kalman filter to integrate navigation sensors. See paragraph VII.D.2.

- Effectively visualize the interaction of the challenge vehicle with the environment. See paragraph VIII.D.4.

- Increase processing power available to the challenge vehicle controlling intelligence. See paragraph IX.D.

- Identify the fundamental problem of the Grand Challenge. See paragraph XIV.A.

- Leverage the capabilities of the challenge vehicle platform. See paragraph XIV.B.1.b.
- Leverage existing COTS components. See paragraph XIV.B.2.
- Select reliable components. See paragraph XIV.C.1.
- Increase redundancy in key components. See paragraph XIV.C.2.
- Take proactive measures to ensure reliability. See paragraph XIV.C.3.
- Perform adequate test and evaluation. See paragraph XIV.D.1.
- Use robust software development methodologies. See paragraph XIV.D.2.
- Simulate sensor noise and sensor failure. See paragraph XIV.D.3.
- Develop tools to analyze the results of test and evaluation. See paragraph XIV.D.4.

In addition, potentially disruptive teams generally distinguished themselves in some way by gaining an efficiency, or "doing more with less". For example: Team 2004-07 / 2005-05 reduced complexity to gain an efficiency during the 2005 GCE by providing processing power for the challenge vehicle controlling intelligence using one laptop computer, and Team 2005-06 used two vertically-aligned LIDAR sensors in an oscillating mount to gain an efficiency by increasing the maximum effective range of LIDAR sensors to allow driving at higher speeds. Examples of ways in which potentially disruptive teams distinguished themselves are referred to as "distinguishing key factors" in the paragraphs that follow.

The author is not attempting to assert causality. However, the results support a conclusion the pattern of behaviors required to solve the fundamental problem of the Grand Challenge was typified by potentially disruptive teams.

The perspective of the author is that a syndrome is an appropriate analogy for identification of potentially disruptive teams using the key factors contributing to success. Various definitions of syndrome exist. As used herein, the "syndrome" typified by potentially disruptive teams is defined as a distinctive or characteristic pattern of related behaviors. Key factors were therefore symptoms of the syndrome, and potentially disruptive teams were those teams which displayed the distinctive or characteristic pattern of related behaviors specifically identified as the key factors contributing to success.

Some teams the author identified as potentially disruptive did not implement one or more key factors. Many teams the author *did not* identify as potentially disruptive implemented several key factors, but the evidence does not support a conclusion those teams were potentially disruptive.

XV.D. What prevented potentially disruptive teams from succeeding?

Through evaluation of key factors, the author identified six potentially disruptive teams: Teams 2004-02 / 2005-01, 2004-07 / 2005-05, 2005-06, 2005-12, 2004-16 / 2005-17, and 2004-17 / 2005-18. With the exception of Team 2005-06, no potentially disruptive team successfully completed the 2005 GCE. Team 2005-06 placed fourth during the 2005 GCE, and emerged as the only disruptive team which participated in either the 2004 or 2005 GCE.

For each team the author identified as potentially disruptive, the author reviewed the published record to determine what ultimately caused the team to fail to successfully complete the 2005 GCE.

Overall, the author concluded teams which did not solve a wrong problem and which displayed symptoms of the syndrome identified the fundamental problem. Specific observations which support this conclusion are noted throughout the paragraphs which follow. Teams are in order by 2005 GCE team number.

XV.D.1. Team 2004-02 / 2005-01

Based on a review of the published record, the author concluded Team 2004-02 / 2005-01 was potentially disruptive:

- Team 2004-02 / 2005-01 completed zero miles of the 2004 GCE course. The challenge vehicle "circled the wrong way in the start area" and was removed from the course ([30]). However, Team 2004-02 / 2005-01 completed 66.2 miles of the 2005 GCE course, the seventh greatest distance of any team which participated in the 2005 GCE, and was one of seven teams which completed more than the average number of miles completed.

  Concerning their performance during the 2005 GCE, Team 2004-02 / 2005-01 stated: "[Team 2004-02 / 2005-01] was ranked 3rd of all autonomous vehicles teams at the 2005 DARPA NQE. [The challenge vehicle] started fourth (3rd Team) at the last DARPA Grand Challenge and finished ahead of Caltech, UCLA, Princeton, Cornell, Virginia Tech, and Ford. Only 3 of 11 teams funded by DARPA ($1M) drove farther in 2005..." ([86]).

- Team 2004-02 / 2005-01 did not report a 2004 GCE budget. Team 2004-02 / 2005-01 later stated: "There were Defense funded teams that could not be 'Completely Accepted' for the 2004 DARPA Grand Challenge, while we spent 5 cents to every dollar spent by other Defense teams." ([213]). However, it is unclear which teams Team 2004-02 / 2005-01 identified as "Defense teams", or how Team 2004-02 / 2005-01 arrived at an estimate of "5 cents to every dollar spent by other Defense teams". Team 2004-02 / 2005-01 reported a 2005 GCE budget of $450,000. See paragraph V.E.2.

Team 2004-02 / 2005-01 reported limited corporate sponsorship during the 2004 and 2005 GCE. See Table LXVIII. Nevertheless, Team 2004-02 / 2005-01 reported a greater number of high-quality sensors were in use by the team than other teams with prior experience or significant corporate or academic sponsorship. Only one team reported a greater number of high-quality sensors in use during the 2004 GCE: Team 2004-23. Team 2004-02 / 2005-01 reported the greatest number of high-quality sensors in use by any team which participated in the 2005 GCE. See Table XLII.

This was a distinguishing key factor.

- Team 2004-02 / 2005-01 did not reduce the number of obstacle and path detection sensors in use by eliminating other sensors.

Six sensor types were in use by Team 2004-02 / 2005-01 during the 2004 QID and GCE: one unknown AVT camera, one FLIR A20M, an estimated three Point Grey Bumblebee stereo camera pairs, one Epsilon Lambda ELSC71-1A, one SICK LMS 211-30206, and four Team 2004-02 MetalSense B1 touch sensors. See Table XXV.

Although Team 2004-02 / 2005-01 did not report touch sensors were in use by the team during the 2005 GCE, at least eight sensor types were in use by the team: one unknown AVT camera, one FLIR A20M, five Point Grey Bumblebee stereo camera pairs, one unknown Eaton RADAR, one Amphitech OASys, an unknown number of unknown other RADARS, one SICK LMS 211-30206, and three unknown SICK LIDAR sensors. See Table XXVII.

The net increase from 2004 to 2005 was two sensor types.

- Team 2004-02 / 2005-01 used high-quality sensors which provide a point-map of the environment.

An estimated five high-quality sensors were in use by Team 2004-02 / 2005-01 during the 2004 QID and GCE: an estimated three Point Grey Bumblebee stereo camera pairs, one Epsilon Lambda ELSC71-1A, and one SICK LMS 211-30206. Three Point Grey Bumblebee stereo camera pairs are asserted. The Epsilon Lambda ELSC71-1A does not provide a point-map of the environment. See paragraph VI.D.2. As a result, four high-quality sensors which provide a point-map of the environment were in use by Team 2004-02 / 2005-01 during the 2004 QID and GCE. See Table XXV.

Nine high-quality sensors which provide a point-map of the environment were in use by Team 2004-02 / 2005-01 during the 2005 GCE: five Point Grey Bumblebee stereo camera pairs, one SICK LMS 211-30206, and three unknown SICK LIDAR sensors. See Table LVII.

The net increase from 2004 to 2005 was five high-quality sensors which provide a point-map of the environment.

- Team 2004-02 / 2005-01 used LIDAR sensors with capabilities similar to the SICK LMS 291 product family.

  One SICK LMS 211-30206 was in use by Team 2004-02 / 2005-01 during the 2004 QID and GCE.

  The author concluded one SICK LMS 211-30206 and three unknown SICK LIDAR sensors were in use by Team 2004-02 / 2005-01 during the 2005 GCE. See paragraph V.C.26.c. Via Figure 4 ("Sensing & Stopping Distances") of the team technical proposal ([10], p. 9), Team 2004-02 / 2005-01 reported three "SICK 291 LADAR" sensors were in use by the team during the 2005 GCE.

  The net increase from 2004 to 2005 was three LIDAR sensors with capabilities similar to the SICK LMS 291 product family.

- Team 2004-02 / 2005-01 used a COTS component to integrate navigation sensors during the 2004 and 2005 GCE. See paragraph VII.B.

- Team 2004-02 / 2005-01 did not report a Kalman filter was in use by the team during the 2004 and 2005 GCE to integrate navigation sensors. The author concluded an other sensor fusion strategy was in use by Team 2004-02 / 2005-01 during the 2004 and 2005 GCE. See paragraph VII.B.

- Team 2004-02 / 2005-01 did not effectively visualize the interaction of the challenge vehicle with the environment.

  Team 2004-02 / 2005-01 stated: "The top speed of [the challenge vehicle] is estimated to be approximately 100 miles per hour, as per manufacturer specifications. However, sensing range and programming constraints limit the vehicle's speed to 50 mph." ([9], p. 14).

  Team 2004-02 / 2005-01 also stated: "[Team 2004-02 / 2005-01] has also determined the required distance to stop at specific vehicle speeds. This information is used to insure that [the challenge vehicle] always has enough time and space to complete all necessary stops." ([10], p. 9). Figure 4 ("Sensing & Stopping Distances") of the team technical proposal ([10], p. 9) reported "Suggested Highway stopping distances" for speeds of 20, 30, 40, 50, and 60 mph. However, it is unclear if these stopping distances were calculated for the challenge vehicle on loose dirt and gravel or asphalt (dry), although the team technical proposal referred to them as "Suggested *Highway* stopping distances" [*emphasis added*], implying that they were calculated for asphalt (dry).

Although Team 2004-02 / 2005-01 was one of only a few teams which participated in the 2004 or 2005 GCE to refer specifically to sensor range limiting the speed of the challenge vehicle, and which reported an estimated stopping distance for the challenge vehicle, Team 2004-02 / 2005-01 consistently overestimated the maximum effective range of sensors in use by the team during the 2004 and 2005 GCE. See Tables LVI and LIX.

- Team 2004-02 / 2005-01 did not increase the processing power available to the challenge vehicle controlling intelligence. See paragraph IX.B. However, Team 2004-02 / 2005-01 increased the number of high-quality sensors in use. The author proposes no increase in processing power was required.

- Team 2004-02 / 2005-01 identified the fundamental problem.

Team 2004-02 / 2005-01 stated: "An autonomous vehicle race through the desert such as the DARPA Grand Challenge presents tremendous technical challenges that push the limit of existing individual technologies, as well as their synthesis into an integrated system. The challenges can be broken down into the following distinct components: goal identification, map assessment and planning to define a path to the goal, real time sensing of the environment to avoid obstacles, selection of the optimal route, and transmission of commands to mechanically move the vehicle. Separately, each of these components has been solved by existing technology." ([9], p. 2).

Team 2004-02 / 2005-01 also stated: "The DARPA Grand Challenge provides tremendous technical challenges that push the limit of existing individual technologies, as well as their synthesis into an integrated system. The Challenge can be broken down into distinct components: goal identification, map assessment and planning to define a path to the goal, real time sensing of the environment to avoid obstacles, selection of the optimal route, and transmission of commands to mechanically move the vehicle. Separately, each of these components has been solved by existing technology." ([10], p. 2).

- Team 2004-02 / 2005-01 leveraged the capabilities of the challenge vehicle platform.

Team 2004-02 / 2005-01 reported the challenge vehicle alternator and batteries were in use by the team to provide power for computing hardware and sensors during the 2004 and 2005 GCE. See Tables LXXI and LXXII.

- Team 2004-02 / 2005-01 leveraged existing COTS components.

  A COTS component was in use by Team 2004-02 / 2005-01 during the 2004 and 2005 GCE to integrate navigation sensors. Team 2004-02 / 2005-01 reported an AGNC Land Navigator was in use by the team during the 2004 QID and GCE. See Table XXVI. Team 2004-02 / 2005-01 reported a Northrop Grumman LN-270 was in use by the team during the 2005 GCE. See Table XXVIII.

  High-quality sensors were in use by Team 2004-02 / 2005-01 during the 2004 and 2005 GCE. See paragraph XIV.B.2.c.

- Team 2004-02 / 2005-01 selected reliable components.

  Team 2004-02 / 2005-01 reported an emphasis on "reliability" ([9], p. 2 and [10], p. 2). In addition, Team 2004-02 / 2005-01 stated: "Five Dell Servers have proven reliability while working in the field." and "[The challenge vehicle's] Artificial Intelligence software is written in Linux [*sic*], which is know for its reliability..." ([10], p. 5). See paragraph XIV.C.1.

- Team 2004-02 / 2005-01 increased redundancy in key components.

  Team 2004-02 / 2005-01 reported "independent alternators operating redundantly" were in use by the team during the 2004 and 2005 GCE. See paragraph XIV.C.2.

  Team 2004-02 / 2005-01 reported "Multipath errors and GPS failure" were the cause of the the team's failure to complete the 2004 GCE ([86]). The author was unable to determine if the AGNC Land Navigator requires the use of an external GPS or DGPS antenna, and Team 2004-02 / 2005-01 did not report an external GPS or DGPS antenna was in use by the team. As a result, the author considers it likely the AGNC Land Navigator's internal antenna was in use by Team 2004-02 / 2005-01 during the 2004 QID and GCE. See paragraph V.C.2.g. Team 2004-02 / 2005-01 later stated: "[Team 2004-02 / 2005-01] installs second of three GPS units to fight '05 race route multipath errors." ([86]). Team 2004-02 / 2005-01 reported two NavCom SF-2050G GPS receivers were in use by the team during the 2005 GCE. See Table XXVIII.

- Team 2004-02 / 2005-01 did not report proactive measures were taken to ensure reliability.

- Team 2004-02 / 2005-01 reported a focus on test and evaluation. See paragraph XIV.D.1. However, the team did not perform adequate test and evaluation. See the discussion below.

- Team 2004-02 / 2005-01 did not report robust software development methodologies were in use by the team.

- Team 2004-02 / 2005-01 did not report simulation of sensor noise and sensor failure. See the discussion below.

- Team 2004-02 / 2005-01 did not report development of tools to analyze the results of test and evaluation.

Team 2004-02 / 2005-01 failed to complete the 2005 GCE. On October 8, 2005 (the date of the 2005 GCE) Team 2004-02 / 2005-01 stated: “[The challenge vehicle] goes 70 miles before suffering mechanical failure.” ([86]).

Team 2004-02 / 2005-01 reported insufficient technical detail to determine the cause of the mechanical failure reported by the team, or if the failure was preventable. Team 2004-02 / 2005-01 did not report its results via the Journal of Field Robotics. As a result, the author was unable to determine why Team 2004-02 / 2005-01, which was potentially disruptive, did not successfully complete the 2005 GCE.

However, as with several other teams which failed to complete the 2004 or 2005 GCE due to unspecified “mechanical failure”, the author asserts GPS “jump” and position error similar to that Team 2004-02 / 2005-01 encountered during the 2004 GCE caused the challenge vehicle to leave the course, sustain damage, and be unable to continue, and proposes inadequate test and evaluation, specifically failure to simulate sensor noise and sensor failure, was ultimately the cause of Team 2004-02 / 2005-01 failure to complete the 2005 GCE.

XV.D.2. Team 2004-07 / 2005-05

Based on a review of the published record, the author concluded Team 2004-07 / 2005-05 was potentially disruptive:

- Team 2004-07 / 2005-05 completed 5.1 miles of the 2004 GCE course, the fourth greatest distance of any team which participated in the 2004 GCE. Team 2004-07 / 2005-05 completed 22.4 miles of the 2005 GCE course, less than the average number of miles completed. However, 22.4 miles was more than the greatest number of miles of the 2004 GCE course completed by any team: 7.4 miles by Team 2004-10. As a result, Team 2004-07 / 2005-05 performance during the 2005 GCE exceeded that of every team which participated in the 2004 GCE.

  Concerning their performance during the 2005 GCE, Team 2004-07 / 2005-05 stated: “We got off to a good start, passing the sixteen mile checkpoint faster than any other vehicle...” ([115]).

- Team 2004-07 / 2005-05 reported a 2004 GCE budget of $35,000. Team 2004-07 / 2005-05 did not report a 2005 GCE budget. See paragraph V.E.2.

Team 2004-07 / 2005-05 reported limited corporate sponsorship during the 2004 GCE and limited corporate and academic sponsorship during the 2005 GCE. See Table LXVIII.

- Team 2004-07 / 2005-05 reduced the number of obstacle and path detection sensors in use by eliminating other sensors.

  Five sensor types were in in use by Team 2004-07 / 2005-05 during the 2004 QID and GCE: one unknown SICK LIDAR sensor, one Epsilon Lambda ELSC71-1A, one unknown "ground whisker", one FLIR Omega, and two Sony DFW-VL500 cameras. See Table XXV.

  Two sensor types were in use by Team 2004-07 / 2005-05 during the 2005 GCE: five unknown SICK LIDAR sensors and a Mobileye ACP5. See Table XXVII.

  The net decrease from 2004 to 2005 was three sensor types.

- Team 2004-07 / 2005-05 used high-quality sensors which provide a point-map of the environment.

  Two high-quality sensors were in use by Team 2004-07 / 2005-05 during the 2004 QID and GCE: one unknown SICK LIDAR sensor and one Epsilon Lambda ELSC71-1A. The Epsilon Lambda ELSC71-1A does not provide a point-map of the environment. See paragraph VI.D.2. As a result, one high-quality sensor which provides a point-map of the environment was in use by Team 2004-07 / 2005-05 during the 2004 QID and GCE.

  Five high-quality sensors which provide a point-map of the environment were in use by Team 2004-07 / 2005-05 during the 2005 GCE: five unknown SICK LIDAR sensors.

  The net increase from 2004 to 2005 was four high-quality sensors which provide a point-map of the environment.

- Team 2004-07 / 2005-05 used LIDAR sensors with capabilities similar to the SICK LMS 291 product family.

  The author concluded one unknown SICK LIDAR sensor was in use by Team 2004-07 / 2005-05 during the 2004 QID and GCE. See paragraph V.C.7.c.

  The author concluded five SICK LIDAR sensors were in use by Team 2004-07 / 2005-05 during the 2005 GCE, but considers the model number of these sensors unknown. See paragraph V.C.30.a. However, Team 2004-07 / 2005-05 stated: "The sensors used for terrain perception included a Sick LMS-221 ladar... There were also four Sick LMS-291 ladars..." ([170], p. 529).

The net increase from 2004 to 2005 was four LIDAR sensors with capabilities similar to the SICK LMS 291 product family.

- Team 2004-07 / 2005-05 did not report a COTS component was in use by the team during the 2004 QID and GCE to integrate navigation sensors. However, a COTS component was in use by Team 2004-07 / 2005-05 during the 2005 GCE. See paragraph VII.B.

- Although Team 2004-07 / 2005-05 independently implemented an other sensor fusion strategy during the 2004 QID and GCE to integrate navigation sensors, Team 2004-07 / 2005-05 used a COTS component which implemented a Kalman filter during the 2005 GCE. See paragraph VII.B.

- Team 2004-07 / 2005-05 effectively visualized the interaction of the challenge vehicle with the environment.

  Team 2004-07 / 2005-05 reported a top speed corresponding to a stopping distance between the maximum effective ranges for the various sensors in use by the team during the 2004 QID and GCE. See paragraph VIII.C.1.

  Team 2004-07 / 2005-05 stated one of the objectives of the path planning algorithm in use by the team was to "avoid all ladar-detected positive or negative obstacles by a distance of at least one half-truck-width" ([34], p. 11) and referred specifically to a sensor capable of detecting obstacles in the direction the challenge vehicle is turning during the 2005 GCE. See paragraph VIII.B.30.b.

- Team 2004-07 / 2005-05 did not increase the processing power available to the challenge vehicle controlling intelligence. On the contrary, Team 2004-07 / 2005-05 significantly decreased the processing power available to the challenge vehicle controlling intelligence. See paragraph IX.B.

  This was a distinguishing key factor.

- Team 2004-07 / 2005-05 identified the fundamental problem.

  Team 2004-07 / 2005-05 stated: "Reviewing the outcome of the 2004 Grand Challenge, we believe that generally speaking ... vehicles based on commercial platforms did better than entirely custom-made vehicles. We felt this vindicated our choice of platform." ([34], p. 2).

- Team 2004-07 / 2005-05 leveraged the capabilities of the challenge vehicle platform.

  Although an external generator and batteries were in use by Team 2004-07 / 2005-05 during the 2004 QID and GCE to provide power for computing hardware and sensors, the challenge vehicle alternator was in use by Team 2004-07 / 2005-05 during the 2005 GCE. See Tables LXXI and LXXII.

- Team 2004-07 / 2005-05 leveraged existing COTS components.

  High-quality sensors were in use by Team 2004-07 / 2005-05 during the 2004 and 2005 GCE. See paragraph XIV.B.2.c.

- Team 2004-07 / 2005-05 selected reliable components.

  Although Team 2004-07 / 2005-05 selected a 1994 Ford F-150 4x4 as challenge vehicle platform (see Table XV) during the 2004 QID and GCE, Team 2004-07 / 2005-05 selected a 2005 Dodge Ram 2500 (see Table XVI) during the 2005 GCE for "better mechanical reliability". See paragraph XIV.C.1.

- Team 2004-07 / 2005-05 increased redundancy in key components. See paragraph XIV.C.2.

- Team 2004-07 / 2005-05 took proactive measures to ensure reliability. See paragraph XIV.C.3.

- Team 2004-07 / 2005-05 did not perform adequate test and evaluation. See the discussion below.

- Team 2004-07 / 2005-05 did not report robust software methodologies were in use by the team.

- Team 2004-07 / 2005-05 simulated sensor noise and sensor failure. See paragraph XIV.D.3.

- Team 2004-07 / 2005-05 developed tools to analyze the results of test and evaluation. See paragraph XIV.D.4.

Team 2004-07 / 2005-05 reported some completed component test and evaluation prior to the 2004 QID and GCE: "These subsystems have been tested with positive results: steering actuation, throttle actuation, braking actuation, GPS, laser measurement system, cameras, path planner, steering encoder, axle encoder." ([46], p. 9). However, Team 2004-07 / 2005-05 also stated: "So far we have done little system testing of the vehicle as an integrated whole." ([46], p. 9).

Team 2004-07 / 2005-05 reported planned test and evaluation prior to the 2004 QID and GCE: "We envision the following system tests: the vehicle autonomously steers, accelerates, and brakes in an empty environment; the vehicle autonomously drives around some trash cans in a parking lot; the vehicle autonomously follows an off-road trail. All pre-Challenge system tests will have a human in the driver's seat for oversight." ([46], p. 9).

The Team 2004-07 / 2005-05 2004 technical proposal is not dated. However, team technical proposals were required to be submitted by October 14, 2003. See Appendix C, paragraph I.A.4. The author considers it likely Team 2004-07 / 2005-05 was unable to complete waypoint following and path detection and obstacle detection and avoidance test and evaluation in the 146 days between the last day of the application period for the 2004 GCE on October 14, 2003 and the first day of the 2004 QID on March 8, 2004.

Team 2004-07 / 2005-05 reported completed test and evaluation of limited scope, including an evaluation of sensor performance in the rain, prior to the 2005 GCE. See paragraph XIV.D.3.a. However, Team 2004-07 / 2005-05 did not perform an "endurance test".

Team 2004-07 / 2005-05 failed to complete the 2005 GCE due to "static memory over-allocation" and stated: "It turns out that we had overallocated the computer's memory, but this did not become apparent until we had actually used a lot of it to record data. We had never driven such a long and winding course without stopping the program before, so we had never encountered this memory bug. (We were fully aware of the desirability of a hundred-mile endurance test, but with limited time and resources, we never got around to it.) The computer's memory filled up and the program quit." ([115]). Team 2004-07 / 2005-05 later stated: "[The challenge vehicle] had made experimental autonomous runs of 10 miles or so, but had never made a continuous overland journey on the scale of the GCE. Furthermore, an endurance trial which consisted of driving for long periods around a track would probably not have uncovered this bug." ([170], p. 551).

During an interview given several months after the 2005 GCE, Team 2004-07 / 2005-05 acknowledged the impact of lack of time to perform adequate test and evaluation: "The memory problem, which amounted to a tiny misallocation, 'would have come out in testing if we had done a long, 200-mile run,'" [the Team 2004-07 / 2005-05 team leader] remarked, but as it was, the team didn't have time." ([249]).

The author concluded inadequate test and evaluation, specifically lack of time to perform adequate test and evaluation, was ultimately the cause of Team 2004-07 / 2005-05 failure to complete the 2005 GCE.

XV.D.3. Team 2005-06

Based on a review of the published record, the author concluded Team 2005-06 was potentially disruptive:

- Team 2005-06 successfully completed the 2005 GCE, placing fourth behind Teams 2005-16, 2005-14, and 2005-13, all of which had prior experience. Team 2005-06 had no prior experience.

- Team 2005-06 reported a 2005 GCE budget of $650,000, the second-highest budget reported. See paragraph V.E.2.

  Team 2005-06 reported moderate corporate sponsorship during the 2005 GCE. See Table LXVII.

- By using an oscillating mount, Team 2005-06 used the minimum number of obstacle and path detection sensors necessary while retaining redundancy.

  The Team 2005-06 technical proposal reported three sensor types were in use by the team during the 2005 GCE: an unknown stereo camera pair, three unknown SICK LIDAR sensors, and one Riegl LMS-Q120. However, the author concluded one sensor type was in use by the team during the 2005 GCE: two unknown SICK LIDAR sensors. See paragraph V.C.31. and Table XXVII.

- Team 2005-06 used high-quality sensors which provide a point-map of the environment.

  The author concluded two high-quality sensors which provide a point-map of the environment were in use by Team 2005-06 during the 2005 GCE: two unknown SICK LIDAR sensors.

- Team 2005-06 used LIDAR sensors with capabilities similar to the SICK LMS 291 product family.

  The author concluded two SICK LIDAR sensors were in use by Team 2005-06, but considers the model number of these sensors unknown. See paragraph V.C.31.c. However, Team 2005-06 later stated: "Two Sick LMS 291 Laser Detecting and Ranging (LADAR) devices provided the autonomous vehicle with environmental sensing." ([28], p. 513).

- Team 2005-06 used a COTS component to integrate navigation sensors during the 2005 GCE. See paragraph VII.B.

- Team 2005-06 used a COTS component which implemented a Kalman filter during the 2005 GCE. See paragraph VII.B.

- Team 2005-06 effectively visualized the interaction of the challenge vehicle with the environment.

  Team 2005-06 did not report challenge vehicle top speed. The 77.1 m Team 2005-06 challenge vehicle stopping distance at the 2005 GCE course-wide speed limit of 50 mph exceeded both the 50 m maximum obstacle detection range reported by Team 2005-06 and the 20 m maximum effective range of short-range LIDAR sensors. In addition, the author concluded the Team 2005-06 challenge vehicle would not be able to reliably detect obstacles in the direction of a turn, and that the challenge vehicle was at greater risk if one sensor failed. See paragraph VIII.B.31.

However, by using vertically-aligned LIDAR sensors, Team 2005-06 was able to gain a sensing advantage over teams which reported multiple LIDAR sensors were in use which intersected the ground at different distances from the challenge vehicle. Vertically-aligned LIDAR sensors, by scanning a vertical plane, returned range readings to the maximum effective range of the LIDAR sensors in a horizontal plane despite the attitude of the vehicle, i.e., whether the vehicle was traveling downhill or uphill.

In addition, by using an oscillating mount, Team 2005-06 was able to use two vertically-aligned LIDAR sensors to detect obstacles directly in front of the vehicle and eliminate the field-of-view limitations consistent with fixed-mount vertically-aligned LIDAR sensors noted by Team 2004-07 / 2005-05.

Team 2005-06 reported the maximum obstacle detection range for the unknown SICK LIDAR sensors in use by the team was “approximately 40 to 50 m” ([28], p. 516). As a result, Team 2005-06 was able to extend the maximum obstacle detection range of the LIDAR sensors in use by the team to twice the maximum effective range reported by Teams 2005-13, 2005-14, and 2005-16.

This was a distinguishing key factor.

- Team 2005-06 did not participate in the 2004 QID or GCE. As a result, there was no increase in processing power available to the challenge vehicle controlling intelligence. However, the author concluded corporate and academic sponsorship allowed teams which participated in the 2005 GCE but not the 2004 GCE to effectively “buy in” by providing access to resources such as labor, high-quality sensors, and computing equipment, and COTS technologies such as integrated challenge vehicle controls and COTS components used to integrate navigation sensors. See paragraph IX.D.

- Team 2005-06 identified the fundamental problem.

Team 2005-06 stated: “[Team 2005-06] has approached the 2005 DARPA Grand Challenge from the standpoint of integrators rather than inventors. This design philosophy has driven its decisions in choosing proven technologies such as the AEVIT vehicle control system and the Oxford integrated INS/GPS, rather than trying to develop these types of technologies itself. This has allowed [Team

2005-06] to focus its considerable manpower on the algorithms and innovative ideas necessary to win the 2005 DARPA Grand Challenge." ([172], p. 2).

Team 2005-06 later stated: "...we would like to think that reaching the finish line after 132 miles of autonomous driving in the desert was not just beginner's luck but rather the result of our simple design methods, good decisions, and good system integration." ([28], p. 525).

This was a distinguishing key factor.

- Team 2005-06 leveraged the capabilities of the challenge vehicle platform.

  Team 2005-06 selected a 2005 Ford Escape Hybrid as challenge vehicle platform. See Table XVI. As a result, by careful selection of the platform for their challenge vehicle, Team 2005-06 was able to leverage the capabilities of the challenge vehicle platform to provide power for computing hardware and sensors. See paragraph XIV.B.1.b.i.

  Team 2005-06 leveraged the vehicle's air conditioning system. See paragraph XIV.B.1.b.ii.

  Team 2005-06 reported the challenge vehicle suspension was in use to reduce the impact of off-road terrain on computing hardware and sensors. See paragraph XIV.B.1.b.iii.

  This was a distinguishing key factor.

- Team 2005-06 leveraged existing COTS components.

  Integrated COTS controls and high-quality sensors were in use by Team 2005-06 during the 2005 GCE. See paragraphs XIV.B.2.a. and XIV.B.2.c.

- Team 2005-06 selected reliable components. See paragraph XIV.C.1.

- Team 2005-06 increased redundancy in key components. See paragraph XIV.C.2.

- Team 2005-06 took proactive measures to ensure reliability. See paragraph XIV.C.3.

- Team 2005-06 did not perform adequate test and evaluation. See the discussion below.

- Team 2005-06 used robust software development methodologies. See paragraph XIV.D.2.

- Team 2005-06 simulated sensor noise and sensor failures. See paragraph XIV.D.3.

- Team 2005-06 did not report development of tools to analyze the results of test and evaluation.

Team 2005-06 stated: “We had anticipated that the path planning algorithms might occasionally time out and, therefore, we had programmed [the challenge vehicle] to slow down to 3 mph for safety reasons until the algorithms had a chance to recover. However, whenever [the challenge vehicle] encountered sections with an extremely wide lateral boundary, the algorithms timed out continuously due to the error until a section with a narrower lateral boundary was encountered. This caused [the challenge vehicle] to drive the dry lake bed sections of the race, which were considered the easiest, at 3 mph instead of 40 mph. Calculations by both DARPA and [Team 2005-06] about the time lost due to this bug have shown that if this error had not occurred, [the challenge vehicle] would have posted a much better finishing time. This bug has since been fixed.” ([28], p. 525). Team 2005-06 referred to this as the “$2 million bug” ([31]).

The 2004 RDDF defines 12 segments with lateral boundary offset exceeding 50 ft. See paragraph II.C.7.d. As a result, the author concluded Team 2005-06 should have expected to encounter areas of extreme lateral boundary offset, and considers the “$2 million bug” a preventable system integration failure. See paragraph XIII.B.4. The author concluded inadequate test and evaluation was ultimately the cause of Team 2005-06's failure to “post a much better finishing time” during the 2005 GCE.

The author concluded Team 2005-06 was the most successful team which participated in either the 2004 or 2005 GCE based on successful completion of the 2005 GCE, key factors contributing to success, distinguishing key factors, and focus on system integration as the fundamental problem of the Grand Challenge. Team 2005-06 successfully completed the 2005 GCE despite the “$2 million bug”, placing fourth, and emerged as the only disruptive team which participated in either the 2004 or 2005 GCE.

This directly contradicts DARPA's assessment, which determined Team 2005-16 was the most successful team which participated in either the 2004 or 2005 GCE, and forms the basis for the author's conclusion that the the actual goal of the Grand Challenge was concealed by the format of the Grand Challenge as a race. The Grand Challenge was not designed to “promote innovative technical approaches that will enable the autonomous operation of unmanned ground combat vehicles.” The fundamental problem of the Grand Challenge was system integration, not innovation.

XV.D.4. Team 2005-12

Based on a review of the published record, the author concluded Team 2005-12 was potentially disruptive:

- Team 2005-12 completed 9.5 miles of the 2005 GCE course. However, Team 2005-12 did not participate in the 2004 QID or GCE and 9.5 miles was more than the greatest number of miles of the 2004 GCE course completed by any team: 7.4 miles by Team 2004-10. As a result, Team 2005-12 performance during the 2005 GCE exceeded that of every team which participated in the 2004 GCE.

  In addition, Team 2005-12 later completed the major portion of the 2005 GCE course several weeks after the 2005 GCE and after having corrected the programming error responsible for failure to complete the course during the 2005 GCE. See the discussion below.

- Team 2005-12 reported a 2005 GCE budget of $125,000. See paragraph V.E.2.

  Team 2005-12 reported limited corporate sponsorship and moderate academic sponsorship during the 2005 GCE. See Table LXVII.

- By using one stereo camera pair, Team 2005-12 used the minimum number of obstacle and path detection sensors necessary to provide a point-map of the environment. One Point Grey Bumblebee stereo camera pair was in use by Team 2005-12 during the 2005 GCE. See Table XXVII.

- Team 2005-12 used high-quality sensors which provide a point-map of the environment.

  One high-quality sensor which provides a point-map of the environment was in use by Team 2005-12 during the 2005 GCE: one Point Grey Bumblebee stereo camera pair.

- Team 2005-12 did not use LIDAR sensors with capabilities similar to the SICK LMS 291 product family.

  Team 2005-12 was the only team which participated in the 2005 GCE which did not report high-quality LIDAR sensors were in use by the team. See Table XXXIX. Team 2005-12 reported a rationale for the selection of the Point Grey Bumblebee stereo camera pair over LIDAR sensors. See paragraph XIV.D.3.c.

  This was a distinguishing key factor.

- Team 2005-12 did not use a COTS component to integrate navigation sensors. See paragraph VII.B.

- Team 2005-12 independently implemented a Kalman filter. See paragraph VII.B.

- Team 2005-12 did not effectively visualize the interaction of the challenge vehicle with the environment.

  Team 2005-12 did not report challenge vehicle top speed. The 77.1 m Team 2005-12 challenge vehicle stopping distance at the 2005 GCE course-wide speed limit of 50 mph exceeded both the 15.2 m maximum obstacle detection range reported by Team 2005-12 and the 70 m maximum effective range of VISION sensors. See paragraph VIII.B.37.

- Team 2005-12 did not participate in the 2004 QID or GCE. As a result, there was no increase in processing power available to the challenge vehicle controlling intelligence. However, the author concluded corporate and academic sponsorship allowed teams which participated in the 2005 GCE but not the 2004 GCE to effectively "buy in" by providing access to resources such as labor, high-quality sensors, and computing equipment, and COTS technologies such as integrated challenge vehicle controls and COTS components used to integrate navigation sensors. See paragraph IX.D.

- Team 2005-12 identified the fundamental problem.

- Team 2005-12 leveraged the capabilities of the challenge vehicle platform.

  Team 2005-12 reported the challenge vehicle alternator and batteries were in use by the team to provide power for computing hardware and sensors. See Table LXXII.

- Team 2005-12 leveraged existing COTS components.

  High-quality sensors were in use by Team 2005-12 during the 2005 GCE. See paragraph XIV.B.2.c.

- Team 2005-12 did not report choosing reliable components.

- Team 2005-12 did not report increasing redundancy in key components.

- Team 2005-12 took proactive measures to ensure reliability. See paragraph XIV.C.3.

- Team 2005-12 did not perform adequate test and evaluation. See the discussion below.

- Team 2005-12 did not report robust software development methodologies were in use by the team.

- Team 2005-12 did not report simulation of sensor noise and sensor failure.
- Team 2005-12 did not report development of tools to analyze the results of test and evaluation.

Team 2005-12 completed[36] the major portion of the 2005 GCE course several weeks after the 2005 GCE and after having corrected the programming error responsible for failure to complete the course during the 2005 GCE. Team 2005-12 stated ([250]):

> Early Monday morning, October 31, 2005, ironically Halloween, we set out to run the 2005 Grand Challenge course exactly as we did during the actual Grand Challenge. [The challenge vehicle] was using the same RDDF (file of GPS waypoints that define the course) and the same global constraints and control coefficients. The only substantive difference was the change in the "one line of code"...
>
> Launch came at PST and was uneventful. Everything was perfect until just miles into the course when a mirage seemed to appear in the distance. Not to worry, it's the desert; however, it quickly became apparent that the "dry" lake was not so dry. It had rained since the Grand Challenge and the course was not traversable in a non-amphibious vehicle. The decision was to cease autonomous operation in order to not lose the vehicle. A precise autonomous run of the 2005 GC course was infeasible because of the rain. With the current condition, no Grand Challenge vehicle could have made it beyond this point. In fact, if this condition would have existed during the Grand Challenge, DARPA would have altered the course. It now became evident why, during the Grand Challenge, the course was not divulged earlier than 2 hours before the race. I [*sic*] was to ensure that the course was a fair one and that some environmental condition had not made a part of the course impassable.
>
> Rather than go home, the decision was to continue to uncover [the challenge vehicle's] autonomous operational limits by continuing on the traversable portions of the 2005 GC course. The first limit had been established: it can't traverse lakes and isn't

smart enough to figure out a way around them, if the "desired" course is through them. That's the first thing that was discovered that we need to work on.

After a brief diversion around the lake, autonomous operation was reinitiated at reemergence of the 2005 GC course. This incident made it apparent that two people were needed inside the vehicle to properly monitor the road ahead. Other than the lake situation (which occurred at 2 other points), the only non-autonomous diversions were due to

1. places where the "road" had been "bulldozed" probably to discourage exactly what we were trying to do. These places existed at XXXX and XXXX, and

2. on XXXX a public road, where we pulled over to let a cement truck pass us (if this situation would have occurred during the Challenge, DARPA would have paused the vehicle and instructed the cement truck to carefully pass the vehicle).

These two incidents refine the operational limits that need to be worked on. Specifically, [the challenge vehicle] needs the capacity to be able to violate its desired route constraints and set out to find any feasible path ahead. At present, it does not have this capability.

Also, [the challenge vehicle] was paused several times, much the same way that DARPA may have legitimately paused the vehicle during the Grand Challenge. Pauses were instituted prior to crossing public roads, the Union Pacific at-grade crossing, upon encountering closed gates, that once opened, were negotiated autonomously and for preparing the onboard camera to record the traverse of Beer Bottle Pass at night.

Except for the above constraints, none of which existed during the Grand Challenge, [the challenge vehicle] autonomously traversed the course. No changes, corrections or alterations were made to any of [the challenge vehicle's] autonomous systems. It can be argued that [the challenge vehicle] autonomously traversed an even more challenging course than that of the 2005 Grand Challenge. Except for the two lakes and the two "bulldozed" areas, [the challenge vehicle] was autonomous, including places where the road was significantly rougher than what existed in early October.

Team 2005-12 is the only team known to have completed the 2005 GCE course, as described above, using a STEREO sensor only: one Point Grey Bumblebee stereo camera pair. No other environment sensors were in use by Team 2005-12. See Table XXVII. The author considers this accomplishment significant, despite the fact that Team 2005-12 did not disclose they were able to complete the course with a maximum corrected time of less than ten hours because a STEREO sensor provided the challenge vehicle controlling intelligence with environment sensor capabilities most similar to those of a human driver. As a result, the author considers Team 2005-12 to be the most potentially disruptive team which participated in either the 2004 or 2005 GCE.

Team 2005-12 reported completed test and evaluation of limited scope. Team 2005-12 stated ([185], p. 7):

> [The challenge vehicle] has been tested at [the university] as well as at off-site locations. Fields in and around [the university] provide hills and tree-lined dirt roads. Testing has also been conducted at [a] pick-your-own blueberry farm, which includes narrow roads, berms, and extensive foliage.
>
> Testing in the ... area has enabled the fine-tuning of the control and obstacle detection algorithms. The blueberry farm test site was particularly instructive with respect to lane detection and precise vehicle control.

However, Team 2005-12 did not perform the equivalent of an "endurance test".

Team 2005-12 failed to complete the 2005 GCE due to "a bug in the obstacle tracking code, as obstacles were never entirely cleared from the list of tracked obstacles when passed. Tracking the position of thousands of irrelevant obstacles overwhelmed the processor, and starved critical code." ([183], p. 752). The author considers it likely this error would have been detected during an "endurance test". Team 2005-12 referred to "testing" after the 2005 GCE, and stated: "Performance of the system is evaluated both during the Grand Challenge and in subsequent desert testing." ([183], p. 745). Team 2005-12 did not report testing in preparation for the 2005 GCE via the Journal of Field Robotics. The author concluded inadequate test and evaluation was ultimately the cause of Team 2005-12 failure to complete the 2005 GCE.

XV.D.5. Team 2004-16 / 2005-17

Based on a review of the published record, the author concluded Team 2004-16 / 2005-17 was potentially disruptive:

- Team 2004-16 / 2005-17 completed zero miles of the 2004 GCE course. Team 2005-17 completed 17.2 miles of the 2005 GCE course, less than the average number of miles completed. However, 17.2 miles was more than the greatest number of miles of the 2004 GCE course completed by any team: 7.4 miles by Team 2004-10. As a result, Team 2004-16 / 2005-17 performance during the 2005 GCE exceeded that of every team which participated in the 2004 GCE.

  Concerning their performance during the 2005 GCE, Team 2004-16 / 2005-17 stated: "We are very confident that, but for the mechanical failures, the vehicle would have completed the track..." ([196], p. 576).

- Team 2004-16 / 2005-17 did not report a 2004 or 2005 GCE budget.

  Team 2004-16 / 2005-17 reported moderate corporate and academic sponsorship during both the 2004 and 2005 GCE. See Table LXVIII.

- Team 2004-16 / 2005-17 reduced the number of obstacle and path detection sensors in use by eliminating other sensors.

  Four sensor types were in use by Team 2004-16 / 2005-17 during the 2004 QID and GCE: unknown RADAR sensors, unknown SONAR sensors, two unknown SICK LIDAR sensors, and two unknown cameras. See Table XXV.

  One sensor type was in use by Team 2004-16 / 2005-17 during the 2005 GCE: two unknown SICK LIDAR sensors. See Table XXVII.

  The net decrease from 2004 to 2005 was three sensor types.

- Team 2004-16 / 2005-17 used high-quality sensors which provide a point-map of the environment.

  An unknown number of high-quality sensors were in use by Team 2004-16 / 2005-17 during the 2004 QID and GCE: two unknown SICK LIDAR sensors and an unknown number of unknown RADAR sensors. See Table XXV. The unknown RADAR sensors do not provide a point-map of the environment. See paragraph VI.D.2. As a result, two high-quality sensors which provide a point-map of the environment was in use by Team 2004-16 / 2005-17 during the 2004 QID and GCE: two unknown SICK LIDAR sensors. See Table XXV.

Two high-quality sensors which provide a point-map of the environment were in use by Team 2004-16 / 2005-17 during the 2005 GCE: two unknown SICK LIDAR sensors. See Table XXVII.

There was no change from 2004 to 2005.

- Team 2004-16 / 2005-17 used LIDAR sensors with capabilities similar to the SICK LMS 291 product family.

  The author concluded two unknown SICK LIDAR sensors were in use by Team 2004-16 / 2005-17 during the 2004 QID and GCE. Team 2004-16 / 2005-17 stated: "The single (functional) SICK LMS 221 is augmented by four SICK LMS 291s." ([140], p. 2). The author concluded the unknown SICK LIDAR sensors did not have capabilities similar to the SICK LMS 291 product family. See paragraph V.C.16.f.

  The author concluded two SICK LIDAR sensors were in use by Team 2004-16 / 2005-17 during the 2005 GCE, but considers the model number of these sensors unknown. See paragraph V.C.41.a. However, Team 2004-16 / 2005-17 later stated: "[The challenge vehicle] uses … two lidar scanners (SICK LMS 291) for autonomous operation." ([196], p. 559).

  The net increase from 2004 to 2005 was two LIDAR sensors with capabilities similar to the SICK LMS 291 product family.

- Although Team 2004-16 / 2005-17 did not use a COTS component to integrate navigation sensors during the 2004 QID and GCE, Team 2004-16 / 2005-17 used a COTS component to integrate navigation sensors during the 2005 GCE. See paragraph VII.B.

- Although Team 2004-16 / 2005-17 independently implemented a Kalman filter to integrate navigation sensors during the 2004 QID and GCE, Team 2004-16 / 2005-17 used a COTS component which implemented a Kalman filter during the 2005 GCE. See paragraph VII.B.

- Team 2004-16 / 2005-17 effectively visualized the interaction of the challenge vehicle with the environment.

  Team 2004-16 / 2005-17 reported a top speed corresponding to a stopping distance between the maximum effective ranges for the various sensors in use by the team prior to the 2004 QID and GCE. Team 2004-16 / 2005-17 reported a top speed corresponding to a stopping distance less than the maximum effective range for the unknown SICK LIDAR sensors in use by the team prior to the 2005 GCE. See paragraph VIII.C.1.

Team 2004-16 / 2005-17 was the only team which participated in both the 2004 and 2005 GCE and reported a challenge vehicle top speed corresponding to a stopping distance which did not exceed either the average maximum obstacle detection range or average maximum effective range for the sensors in use by the team. See paragraph VIII.D.3. and Table LXV.

- Team 2004-16 / 2005-17 significantly increased the processing power available to the challenge vehicle controlling intelligence. See paragraph IX.B.

- Team 2004-16 / 2005-17 identified the fundamental problem.

  Team 2004-16 / 2005-17 reported the implementation of several key factors as improvements over their 2004 challenge vehicle via their 2005 technical proposal. Team 2004-16 / 2005-17 stated: "While the base vehicle in the two editions is the same six wheeled, skid-steered MAX IV ATV, everything else in the 2005 edition has changed... The student crafted cage using aluminum rods purchased from a local hardware store has been replaced by a student-designed but professionally manufactured aluminum structure. A hand rigged case that served as a rack is now replaced by a MIL-spec rack manufactured by Hardigg. A single, garden variety mother board is replaced by two Dell Power Edge 750 computers and two mini-ITX boards. The single (functional) SICK LMS 221 is augmented by four SICK LMS 291s. The radar and sonar sensors are removed. The POS/MV INS from Applanix has been replaced by RT3102 from Oxford Technologies. The single Honda EU2000 generator now shares a berth with another identical generator. Two linear actuators from Ultramotion still form the electromechanical interface for steering, as does a servo motor for throttle." ([140], p. 2).

  In summary, Team 2004-16 / 2005-17 reported implementing many of the key factors identified herein based on experience gained from participation in the 2004 GCE. The author concluded Team 2004-16 / 2005-17 identified the fundamental problem. In addition, the author considers this supports a conclusion that participation in the 2004 GCE forms the basis for a claim of prior experience. See paragraph X.C.1. However, the author concluded experience gained from participation in the 2004 GCE was not a contributing factor to the increase in the average number of miles of the 2005 GCE course which were completed. See paragraph X.D.1.

- Team 2004-16 / 2005-17 did not leverage the capabilities of the challenge vehicle platform. See the discussion below.

- Team 2004-16 / 2005-17 leveraged existing COTS components.

  High-quality sensors were in use by Team 2004-16 / 2005-17 during the 2004 and 2005 GCE. See paragraph XIV.B.2.c.

- Team 2004-16 / 2005-17 selected reliable components.

  Although Team 2004-16 / 2005-17 did not report selecting components for their reliability, design decisions implemented by the team revealed increased focus on reliability during the 2005 GCE. See paragraph XIV.C.1.

- Team 2004-16 / 2005-17 increased redundancy in key components. See paragraph XIV.C.2.

- Team 2004-16 / 2005-17 took proactive measures to ensure reliability. See paragraph XIV.C.3.

- Team 2004-16 / 2005-17 performed adequate test and evaluation.

  Team 2004-16 / 2005-17 reported a fully autonomous challenge vehicle prior to the 2005 GCE. Although the author concluded Team 2004-16 / 2005-17 failed to complete the 2005 GCE due to a preventable system integration failure, he also concluded it would be difficult to simulate in practice because it was not an expected failure mode of the vehicle, and that it was unreasonable to expect a team to willfully sabotage its own entry to determine the impact of re-assembling the vehicle incorrectly after component failure. See the discussion below.

  In addition, Team 2004-16 / 2005-17 reported the most comprehensive use of simulation to perform test and evaluation of any team which participated in either the 2004 or 2005 GCE.

  Team 2004-16 / 2005-17 stated: "A vehicle simulator is included in [the challenge vehicle] software suite. The simulator provides a test environment that emulates the physical environment in which the vehicle operates. Daily builds of the software are tested against a collection of test cases gathered from the real world. Developers perform unit level testing of changes to the software using the combination of the vehicle simulator and visualization tools included in the software suite." ([140], p. 10).

  Team 2004-16 / 2005-17 later stated ([196], p. 563):

  > [The challenge vehicle's simulator] is a physics-based simulator developed using the Open Dynamics Engine physics engine. Along with simulating the vehicle dynamics and terrain, [the simulator] also simulates all the onboard sensors. It populates the same [queues] with data in the same format as the sensor drivers. It also reads vehicle control commands from [queues] and interprets them to have the desired effect on the simulated vehicle.

```
While [the simulator] is a physics-based simulator,
such as Stage ... and Gazebo ... it has two
interesting differences.  First, [the simulator] does
not provide any visual/graphical interface.  The
visualization of the world and the vehicle state is
provided by the Visualizer module, discussed later.
Second, [the simulator] also generates a clock, albeit
a simulated one, using the [queues].
```

Team 2004-16 / 2005-17 later stated: "By maintaining a system-wide simulated time, [the simulator] is able to create a higher fidelity simulation than that provided by Stage and Gazebo. The computation in the entire system can be stopped by stopping the clock; and its speed can be altered by slowing down or speeding up the clock. This also makes it feasible to run the application in a single-step mode, executing one cycle of all programs at a time, thereby significantly improving testing and debugging." ([196], p. 563).

This was a distinguishing key factor.

- Team 2004-16 / 2005-17 used robust software development methodologies. See paragraph XIV.D.2.
- Team 2004-16 / 2005-17 did not report simulation of sensor noise and sensor failure.
- Team 2004-16 / 2005-17 did not report development of tools to analyze the results of test and evaluation.

Team 2004-16 / 2005-17 failed to complete the 2005 GCE due to a problem related to the failure caused by the broken transmission which occurred during the 2005 NQE. Team 2004-16 / 2005-17 improperly calibrated an actuator, causing the challenge vehicle controlling intelligence to continue to apply maximum current to the actuator motors until the motors burned out. See paragraph XIII.B.10.

Although the author considers this a preventable system integration failure[37], he also concluded it would be difficult to simulate in practice because it was not an expected failure mode of the vehicle, and that it was unreasonable to expect a team to willfully sabotage its own entry to determine the impact of re-assembling the vehicle incorrectly after component failure.

Team 2004-16 / 2005-17 later stated ([196], pp. 576 - 577):

```
Our experience suggests that field testing is one of
the most expensive parts of developing an [autonomous
```

> ground vehicle]. To field test, one must have a fully operational vehicle, a field for testing it, correct weather conditions, and a significant amount of staff. Unless the procedures for bringing the vehicle to the field are very well-defined, small issues, such as insufficient gas in the generator, can consume significant time.
>
> Having a fully operational vehicle is no small requirement, given that an [autonomous ground vehicle] has linear dependencies between the automotive, the electromechanical components, the electrical, electronics, sensors, and the software. Failure in any one of the components can hold back the testing.

The author concluded Team 2004-16 / 2005-17 may not have adequately *field tested* their challenge vehicle. However, field testing was unlikely to have resulted in the failure caused by the broken transmission which occurred during the 2005 NQE unless the transmission was also broken in an identical manner and repaired incorrectly during field testing. As a result, the author was unable to conclude Team 2004-16 / 2005-17 did not perform adequate test and evaluation.

Team 2004-16 / 2005-17 selected a commercially-available ATV as challenge vehicle platform (see Tables XV and XVI). As a result of this decision, Team 2004-16 / 2005-17 was unable to use integrated COTS controls and was required to independently implement challenge vehicle controls.

The author concluded the selection of a commercially-available ATV as challenge vehicle platform during the 2005 GCE was ultimately the cause of Team 2004-16 / 2005-17 failure to complete the 2005 GCE[38]. Despite the fact that Team 2004-16 / 2005-17 implemented many key factors, the team did not have prior experience, including experience independently implementing challenge vehicle controls, and was unable to integrate COTS controls or leverage test and evaluation performed by the manufacturer to ensure the reliability of the component.

XV.D.6. Team 2004-17 / 2005-18

Based on a review of the published record, the author concluded Team 2004-17 / 2005-18 was potentially disruptive:

- Team 2004-17 / 2005-18 completed 1.3 miles of the 2004 GCE course, the fifth greatest distance of any team which participated in the 2004 GCE. Team 2004-17 / 2005-18 completed 8.0 miles of the 2005 GCE course, less than the average number of miles completed. However, 8.0 miles was more than the greatest number of miles of the 2004 GCE course completed by any team: 7.4

miles by Team 2004-10. As a result, Team 2004-17 / 2005-18 performance during the 2005 GCE exceeded that of every team which participated in the 2004 GCE.

Concerning their performance during the 2005 GCE, Team 2004-17 / 2005-18 stated: “Although, as mentioned above, the system we have described performed well over the course of hundreds of miles of testing in the desert prior to the Grand Challenge, we believe the pathological nature of this particular failure scenario demonstrates a few of the more important weaknesses of the system and exemplifies the need for further ongoing research.” ([54], pp. 805 - 806). Team 2004-17 / 2005-18 continued with a detailed chronology of events which contributed to the challenge vehicle failure to complete the 2005 GCE. See the discussion below.

- Team 2004-17 / 2005-18 did not report a 2004 GCE budget. Team 2004-17 / 2005-18 reported a 2005 GCE budget of $120,000. See paragraph V.E.2.

  Team 2004-17 / 2005-18 reported moderate corporate and academic sponsorship during the 2004 and 2005 GCE. See Table LXVIII.

- Team 2004-17 / 2005-18 did not reduce the number of obstacle and path detection sensors in use by eliminating other sensors.

  Three sensor types were in use by Team 2004-17 / 2005-18 during the 2004 QID and GCE: one Point Grey Dragonfly, two SICK LMS 221-30206 LIDAR sensors, and two Point Grey Dragonfly stereo camera pairs. See Table XXV.

  Six sensor types were in use by Team 2004-17 / 2005-18 during the 2005 GCE: two SICK LMS 221-30206 LIDAR sensors, one SICK LMS 291-S14, one SICK LMS 291-S05, one Riegl LMS-Q120i, two Point Grey Dragonfly stereo camera pairs, and one Point Grey Dragonfly. See Table XXVII.

  The net increase from 2004 to 2005 was three sensor types.

- Team 2004-17 / 2005-18 used high-quality sensors which provide a point-map of the environment.

  Four high-quality sensors which provide a point-map of the environment were in use by Team 2004-17 / 2005-18 during the 2004 QID and GCE: two SICK LMS 221-30206 LIDAR sensors and two Point Grey Dragonfly stereo camera pairs. See Table XXV.

  Seven high-quality sensors which provide a point-map of the environment were in use by Team 2004-17 / 2005-18 during the 2005 GCE: two SICK LMS 221-30206 LIDAR sensors, one SICK LMS 291-S14, one SICK LMS 291-S05, one Riegl LMS-Q120i, and two Point Grey Dragonfly stereo camera pairs. See Table XXVII.

The net increase from 2004 to 2005 was three high-quality sensors which provide a point-map of the environment.

- Team 2004-17 / 2005-18 used LIDAR sensors with capabilities similar to the SICK LMS 291 product family.

  Team 2004-17 / 2005-18 did not use LIDAR sensors with capabilities similar to the SICK LMS 291 product family during the 2004 QID and GCE.

  One SICK LMS 291-S14 and one SICK LMS 291-S05 were in use by Team 2004-17 / 2005-18 during the 2005 GCE.

  The net increase from 2004 to 2005 was two LIDAR sensors with capabilities similar to the SICK LMS 291 product family.

- Team 2004-17 / 2005-18 did not use a COTS component to integrate navigation sensors during the 2004 or 2005 GCE. See paragraph VII.B.

- Although Team 2004-17 / 2005-18 independently implemented an other sensor fusion strategy during the 2004 QID and GCE, Team 2004-17 / 2005-18 independently implemented a Kalman filter during the 2005 GCE. See paragraph VII.B.

- Team 2004-17 / 2005-18 effectively visualized the interaction of the challenge vehicle with the environment.

  Team 2004-17 / 2005-18 reported a top speed corresponding to a stopping distance between the maximum effective ranges for the various sensors in use by the team during the 2004 and 2005 GCE. See paragraph VIII.C.1.

- Team 2004-17 / 2005-18 increased the processing power available to the challenge vehicle controlling intelligence. See paragraph IX.B.

- Team 2004-17 / 2005-18 identified the fundamental problem.

  Team 2004-17 / 2005-18 reported a fully autonomous challenge vehicle and a focus on “full system integration” through “an extensive test plan”. See paragraph XIV.D.1.

- Team 2004-17 / 2005-18 did not report leveraging the capabilities of the challenge vehicle platform.

- Team 2004-17 / 2005-18 leveraged existing COTS components.

  High-quality sensors were in use by Team 2004-17 / 2005-18 during the 2004 and 2005 GCE. See paragraph XIV.B.2.c.

- Team 2004-17 / 2005-18 did not report choosing reliable components.
- Team 2004-17 / 2005-18 did not report increasing redundancy in key components.
- Team 2004-17 / 2005-18 took proactive measures to ensure reliability. See paragraph XIV.C.3.
- Team 2004-17 / 2005-18 did not perform adequate test and evaluation. See the discussion below.
- Team 2004-17 / 2005-18 used robust software development methodologies. See paragraph XIV.D.2.
- Team 2004-17 / 2005-18 simulated sensor noise and sensor failure, specifically GPS "jump" and position error. See paragraph XIV.D.3.b. However, Team 2004-17 / 2005-18 simulation of sensor noise and sensor failure was not effective. See the discussion below.
- Team 2004-17 / 2005-18 developed tools to analyze the results of test and evaluation. See paragraph XIV.D.4.

Although the team reported experimenting with ways to degrade or block GPS reception (see paragraph XIV.D.3.b.), Team 2004-17 / 2005-18 did not effectively simulate sensor noise and sensor failures.

Team 2004-17 / 2005-18 reported a detailed chronology of events which contributed to the challenge vehicle failure to complete the 2005 GCE, and which is discussed in detail in paragraph XIII.B.11. Although Team 2004-17 / 2005-18 attributed their failure to complete the 2005 GCE to multiple causes, the author concluded failure to perform adequate test and evaluation, specifically simulation of sensor noise and sensor failure, was ultimately the cause of Team 2004-17 / 2005-18 failure to complete the 2005 GCE.

XV.E. Results

The evidence supports a conclusion that inadequate test and evaluation was the leading cause of failure during the 2004 and 2005 GCE among potentially disruptive teams:

- Four of the six (66 percent) potentially disruptive teams failed to complete the 2005 GCE due to inadequate test and evaluation: Teams 2004-02 / 2005-01, 2004-07 / 2005-05, 2005-12, and 2004-17 / 2005-18.

- Although Team 2005-06 successfully completed the 2005 GCE, Team 2005-06 failed to “post a much better finishing time” during the 2005 GCE due to inadequate test and evaluation. Adequate test and evaluation may have helped Team 2005-06 identify the “$2 million bug” prior to the 2005 GCE and complete the 2005 GCE course in less time than the team which placed first, Team 2005-16, and Teams 2005-13 and 2005-14, all of which had prior experience and extensive corporate or academic sponsorship.

- Team 2004-16 / 2005-17 failed to complete the 2005 GCE due to selection of a commercially-available ATV as challenge vehicle platform. The team did not have prior experience, including experience independently implementing challenge vehicle controls, and was unable to integrate COTS controls or leverage test and evaluation performed by the manufacturer to ensure the reliability of the component.

XV.F. Conclusions

In general, teams which failed to identify the fundamental problem of the Grand Challenge, did not reduce complexity, did not increase reliability and redundancy, and did not perform adequate test and evaluation were not potentially disruptive.

In general, potentially disruptive teams were able to identify the fundamental problem, reduce complexity, and increase reliability and redundancy. However, inadequate test and evaluation was the leading cause of failure during the 2005 GCE among potentially disruptive teams, suggesting that even if a greater number of teams were potentially disruptive, inadequate test and evaluation may have prevented them from being competitive with Teams 2005-13, 2005-14, and 2005-16, all of which had prior experience and extensive corporate or academic sponsorship.

As discussed in Chapter I., the perspective of this research is that the Grand Challenge was a failure, despite the fact that prize money was awarded by DARPA, for the following reasons:

- the technical achievement was consistent with the state of the art,

- the development of basic algorithms and strategies for control of an autonomous vehicle was not the focus of the Grand Challenge,

- the cost of proposed solutions far exceeds what the Department of Defense may reasonably be expected to pay to procure them,

- DARPA failed to structure the Grand Challenge to ensure long-term realization of its stated goals, and

- significant progress toward the actual goal has not been made in the years since the 2005 GCE.

The 2004 and 2005 GCE were highly publicized, and received a great deal of attention from the public. DARPA stated: “There was significant publicity as a result of the event, which increased the public’s awareness about the DoD desire to develop autonomous ground vehicles.” ([3], p. 9). DARPA continued with a detailed description of media coverage of the 2004 GCE.

The author was ultimately unable to determine whether the Grand Challenge was an engineering challenge or an exercise in public relations, and believes the evidence supports a conclusion that DARPA was unable to adequately determine what problem Grand Challenge participants were being asked to solve because the difference between the stated goal of the Grand Challenge and actual goal of the Grand Challenge resulted in proposed solutions which did not result in significant progress toward the actual goal of the Grand Challenge. Offered solutions were too expensive, and improvement in challenge vehicle average speed was more a result of improvements in processing speed due to Moore's Law and increased time for test and evaluation than any other factor.

As a result of the emphasis on public relations, DARPA made several unfortunate decisions concerning team participation. As a result of the enormity of the problem domain, teams did not have enough time to fully document development of the team challenge vehicle, fully implement the team challenge vehicle, or complete planned testing. Consequently, the overall quality of published records is low.

In addition, the precise definition of the Grand Challenge as a system integration exercise which required some expertise in the area of artificial intelligence applied to autonomous ground vehicle development was concealed by the format of the Grand Challenge as a race. Yet the results of the 2004 and 2005 GCE confirm this conclusion. The teams with the most experience in the problem domain were successful, not because they were better able to code an artificial intelligence, but because they more quickly realized the limits of their sensors and computing equipment, and were able to optimize their solution to make full use of limited sensor technology.

In addition, if an unstated goal of DARPA was to “seed” industry with graduates with experience in autonomous vehicle development, it was a failure. The Grand Challenge was not designed to “promote innovative technical approaches that will enable the autonomous operation of unmanned ground combat vehicles.” The fundamental problem of the Grand Challenge was system integration, not innovation.

Team 2005-12, for example, completed the major portion of the 2005 GCE course several weeks after the 2005 GCE and after having corrected the programming error responsible for failure to complete the course during the 2005 GCE. See paragraph XV.D.4.

Team 2005-12 is the only team known to have completed the 2005 GCE course using a STEREO sensor only: one Point Grey Bumblebee stereo camera pair. No other environment sensors were in use by Team 2005-12. As a result, the author considers

Team 2005-12 to be the most potentially disruptive team which participated in the 2004 or 2005 GCE.

The most successful team, and only disruptive team which participated in either the 2004 or 2005 GCE, Team 2005-06, was not declared the winner of the 2005 GCE. Again, this was because the fundamental problem of the Grand Challenge was concealed by the format of the Grand Challenge as a race.

Overall, the Grand Challenge heavily favored teams with prior experience and significant sponsorship. As a result, the utility of technical solutions proposed by most successful teams is suspect. Analysis reveals that most teams spent a significant amount of money on their solutions to the problem, and that the total cost of team solutions represents an investment which exceeds what the Department of Defense may reasonably be expected to pay to procure them. DARPA did not establish a relative weighting scheme which would allow challenge vehicle performance to be directly compared, and the published record is utterly inadequate to the task.

Teams participating in the Grand Challenge should first have been required to implement a challenge vehicle in simulation. This would minimize real cost to the teams. In addition, some team programming hours would have been focused on improvements to the simulation environment, such as those described by Team 2004-16 / 2005-17.

The development and testing of a challenge vehicle should have been an iterative process, first of "tuning" the simulation environment to accurately model real world interaction, then increasing the difficulty and duration of field testing of team challenge vehicles via a series of challenges, moving from concept to actual prototype and culminating in a 2004 or 2005 GCE-like event. Field testing should have been accompanied by a requirement that teams participating in the Grand Challenge deliver periodic updates documenting the results of test and evaluation.

This would have resulted in the development of a simulation environment which would have made it possible to fully separate the development of artificial intelligence applied to autonomous ground vehicle development from the system integration portion of the Grand Challenge, allowing continued participation by teams lacking the resources of some teams participating in the 2004 or 2005 GCE.

DARPA's selection of teams to continue to field testing should have been made on the basis of the performance of team implementation of a challenge vehicle controlling intelligence in simulation when compared to the real world.

Those teams should have been provided a budget and been required to follow basic accounting rules and account for their expenses via the published record. This would have helped "level the playing field" by mitigating the advantage of teams with significant sponsorship (the effect of sponsorship), allowing teams with limited sponsorship to compete on a more even basis with teams with significant sponsorship.

The use of simulation as a complement to the Grand Challenge, including the development and application of standard reference terrain and standard problems, would provide a framework for evaluating the application of artificial intelligence to autonomous ground vehicle development free from the distraction of system integration problems which plagued teams participating in both the 2004 and 2005 GCE. As a result, the emphasis on artificial intelligence would be restored.

In addition, the use of simulation would have provided teams participating in the Grand Challenge with a way to identify key factors contributing to success prior to field trials and increased focus on the development of basic algorithms and strategies for control of an autonomous vehicle. This would have helped “level the playing field” by mitigating the advantage of teams with prior experience (the effect of experience), allowing teams with no experience to compete on a more even basis with teams with prior experience.

Key factors became the basis for evaluation of the use of simulation during autonomous vehicle development. Key factors which could be tested in simulation were considered for evaluation. Simulations were designed to evaluate selected key factors using Player and Gazebo, free and open source software for robot and sensor applications. The use of simulation was effective, however successful simulation was only possible after many problems with the applications Player and Gazebo were resolved.

The results of this evaluation are documented by the thesis for which this technical report is the foundation.

CHAPTER XVI. RESEARCH METHODOLOGY

The foundation of much of this research is *critical scholarship*. To the extent possible, any conclusions presented by the author are supported by *objective evidence*. For the purposes of this research, objective evidence is considered to be that presented by primary public and academic sources which can be independently confirmed. These sources are referred to herein as “published records”. The complete body of published records is referred to herein as “the published record”.

To support objective, independent analysis, the author has attempted to separate the reputations of the universities and corporations involved from analysis where possible through the use of team numbers, in lieu of names, focus on participation in the 2004 and 2005 GCE in lieu of competition, and eliminate completely the use of informal testimony, or hearsay.

It is possible that participants in the 2004 and 2005 GCE are able to remember details and events which did not become part of the published record, and many of the teams which participated in the 2004 and 2005 GCE maintain websites providing points-of-contact through which the author could have solicited additional technical information or requested clarification of published records. However, the author determined that reliance on informal testimony or hearsay would introduce an additional element of uncertainty into what is already an uncertain record, and the decision was made early to rely on published records alone. As a result, no attempt was made to reconcile the published record with informal testimony or hearsay through email or telephone conversations with the teams.

The author does not consider manufacturer product literature to which access is directly controlled by the manufacturer or indirectly controlled by an agent of the manufacturer to be published records. Although the manufacturer may have a practice of granting access to product literature on a non-discriminatory basis, the manufacturer is in the sole position of being able to revise such literature without review. Although access to academic sources is similarly controlled, in general, publishers grant access to academic sources on a non-discriminatory basis, and academic sources are peer-reviewed. The author considers the scrutiny of peer review to be essential to the reliability of academic sources as published records. The lack of equivalent independent peer review of manufacturer product literature is a significant deficiency.

Where the author was unable to present adequate objective evidence, anecdotal evidence is presented, and is so noted.

In addition, from detailed review of technical guidance published by DARPA, technical proposals published by teams participating in the 2004 and 2005 GCE, and final published results, it is clear that published records are self-contradictory, provide incomplete or incorrect technical information, and do not provide enough information to answer key questions concerning team strategies during the 2004 and 2005 GCE, which would allow the author to independently assess the success of the DARPA Grand Challenge in one of its principal goals ([3], p. 2):

> Accelerate autonomous ground vehicle technology development in the United States in the areas of sensors, navigation, control algorithms, vehicle systems, and systems integration.

As a result, the decision was made early to reconcile published records with other published records where possible.

Since the conclusion of the 2007 Urban Challenge, the author has become aware of two additional sources of published records: a “privately compiled” collection of public domain files and documents ([251]) and a book about the Grand Challenge ([252]).

The publisher alternately stated the author of the collection ([251]) was the Department of Defense and: “Our news and educational discs are privately compiled collections of official public domain U.S. government files and documents - they are not produced by the federal government.” ([253]). The author concluded review of the collection, as a “privately compiled” collection of public domain files and documents, would not result in improvement in quality over the existing published record. As a result, the author did not review the collection.

Review of the table of contents for the book ([252]) hosted by an Internet retailer ([253]) indicates the articles published by the Journal of Field Robotics constitute the majority of source material. The author concluded review of the book would not result in improvement in quality over the existing published record. As a result, the author did not review the book.

Table III. Team reference numbers.		
Team name[39]	**2004**	**2005**
A. I. Motorvators	01	
Axion Racing	02	01
The Blue Team	03	
Center for Intelligent Machines and Robotics (CIMAR)	04	02
CyberRider	05	
Digital Audio Drive (Team DAD)	06	03
Desert Buckeyes		04
The Golem Group (2004) / The Golem Group/UCLA (2005)	07	05
The Gray Team[a]		06
Insight Racing	08	07
Intelligent Vehicle Safety Systems I		08
Mitre Meteorites		09
Mojavaton		10
MonsterMoto		11
Princeton University		12
Palos Verdes High School Warriors	09	
Red Team	10	13
Red Team Too		14
Rob Meyer Productions	11	
Rover Systems	12	
SciAutonics I (2004) / SciAutonics/Auburn Engineering (2005)	13	15
SciAutonics II	14	
Stanford Racing Team		16
Team Arctic Tortoise	15	
Team Cajunbot	16	17
Team Caltech	17	18
Team Cornell		19
Team ENSCO	18	20
Team LoGHIQ	19	

Team Overbot	20	
Team Phantasm	21	
Team Spirit of Las Vegas	22	
Team TerraMax	23	21
Terra Engineering	24	
Virginia Tech (2004) / Virginia Tech Grand Challenge Team (2005)	25	22
Virginia Tech Team Rocky		23

Note:

[a] The title of the technical proposal hosted by the Archived Grand Challenge 2005 website ([19]) is “GreyTeam.pdf”. All other references, including the Team 2005-06 technical proposal, are to “Gray Team” or “Team Gray”. The team's preferred spelling is used herein.

Table IV. "Drop dead time".						
Waypoint	Distance to waypoint, miles (ideal)		Time to waypoint, HH:MM:SS (ideal)		"Drop dead time", HH:MM:SS	
	Completed	Remaining	Elapsed	Remaining	Time	Remaining
732	33.871	108.422	1:50:24	8:09:36	13:30:00	3:00:00
946	53.881	88.412	2:46:12	7:13:48	14:15:00	2:15:00
1627	82.099	60.194	3:56:24	6:03:36	15:30:00	1:00:00
2024	109.036	33.257	4:58:12	5:01:48	16:30:00	0:00:00

Table V. Adopted and derived geometric constants for major coordinate systems.			
Coordinate system	a	b	1/f
WGS84	6 378 137	6 356 752 . 314 2	298 . 257 223 563
GRS80	6 378 137	6 356 752 . 314 140	298 . 257 222 101
WGRS80/84	6 378 137	6 356 752 . 3	298 . 26

Table VI. Course length.		
Year	Calculated length, miles / km	Reported length, miles
2004	142.3 / 229.0	142
2005	131.8 / 212.0	131.6

Table VII. Average course segment length.	
Year	Average course segment length, m
2004	88.6
2005	72.3

Table VIII. Calculated turn radius and notional diameter using SSF = 1.02.				
Speed, mph	**Radius, m (calculated)**	**Diameter, m**	**Diameter, m (notional)**	**Equivalent square root**
5	0.4998	0.9996	1	1
10	1.9992	3.9985	4	2
15	4.4983	8.9966	9	3
20	7.9970	15.9940	16	4
25	12.4953	24.9906	25	5
30	17.9932	35.9864	36	6
35	24.4908	48.9816	49	7
40	31.9880	63.9759	64	8
45	40.4848	80.9695	81	9
50	49.9812	99.9624	100	10
55	60.4772	120.9545	121	11
60	71.9729	143.9458	144	12

Table IX. Course segment speed.				
Speed, mph	2004		2005	
	Number	Percent (cumulative)	Number	Percent (cumulative)
< 11	406	15.7	810	27.6
11 - 15	703	42.9	318	38.4
16 - 20	211	51.1	679	61.6
21 - 25	870	84.7	379	74.5
26 - 30	55	86.8	458	90.1
31 - 35	0	86.8	59	92.1
36 - 40	245	96.3	136	96.8
41 - 45	2	96.4	95	100.0
> 45	93	100.0	N/A	N/A

Table X. Course segments per group.					
Speed, mph	Number		Speed, mph (cumulative)	Percent (cumulative)	
	2004	2005		2004	2005
< 11	406	810	2 - 10	15.7	27.6
11 - 20	914	997	2 - 20	51.1	61.6
21 - 30	925	837	2 - 30	86.8	90.1
31 - 40	245	195	2 - 40	96.3	96.8
> 40	95	95	All	100.0	100.0

Table XI. Total distance per group.					
Speed, mph	**Distance, km**		**Speed, mph (cumulative)**	**Percent (cumulative)**	
	2004[a]	**2005[b]**		**2004[c]**	**2005[d]**
< 11	13.6	24.6	2 - 10	5.9	11.6
11 - 20	41.6	54.4	2 - 20	24.1	37.3
21 - 30	109.7	94.5	2 - 30	72.0	81.8
31 - 40	39.4	25.9	2 - 40	89.2	94.1
> 40	24.7	12.7	All	100.0	100.0

Notes:

[a] Distance may not sum to 229.0 km due to rounding error.

[b] Distance may not sum to 212.0 km due to rounding error.

[c] Cumulative percentages are based on a total course length of 229.0 km.

[d] Cumulative percentages are based on a total course length of 212.0 km.

Table XII. Reportable change in bearing.

Change in bearing	2004		2005	
	Number	Percent	Number	Percent
<= 5[a]	1345	52.0	1979	67.5
> 5	1240	48.0	955	32.5
> 10	613	23.7	428	14.6
> 15	295	11.4	225	7.7
> 20	145	5.6	120	4.1
> 25	69	2.7	66	2.2
> 30	40	1.5	39	1.3
> 35	24	0.9	21	0.7
> 40	13	0.5	12	0.4
> 45	10	0.4	2	0.1
> 50	5	0.2	0	0.0

Note:

[a] Calculated by difference. The RDDF analysis application calculates the number of changes in bearing that exceed a reportable change in bearing (see Appendix A).

Table XIII. 2004 and 2005 GCE course completion times given notional course-wide speed limits.

Year	Notional course-wide speed limit, mph	Number of segments	Total length, km	Time, hours
2004	35[a]	340	64.1	6.66
	30	340	64.1	6.66
	25	395	70.6	7.14
	20	1265	173.8	8.22
	15	1476	187.8	10.17
2005	35	231	30.9	6.29
	30	290	38.6	6.41
	25	748	98.4	6.81
	20	1127	133.1	7.64
	15	1806	175.6	9.45

Note:

[a] The results are identical to those for 30 mph because the 2004 GCE RDDF does not define any course segments with a speed of 35 mph.

Table XIV. Challenge vehicle platform.				
Challenge vehicle platform	**Type**	**2004 QID**	**2004 GCE**	**2005 GCE**
Commercially-available SUV	1	6	4	7
Commercially-available truck	2	2	2	4
Commercially-available ATV[a]	3	8	5	6
Military service vehicle	4	2	2	3
Purpose-built vehicle	5	6	1	2
TOTAL		25[b]	15[b]	23[c]

Notes:

[a] "Commercially-available ATV" includes both 4- and 6-wheeled commercially-available ATVs.

[b] Team 2004-03 selected a motorcycle as challenge vehicle platform ([92]).

[c] Team 2005-18 selected a 2005 Ford E-350 Van as challenge vehicle platform ([197], p. 5).

Table XV. Team vehicles (2004 QID and GCE participants).		
Team	**Vehicle**	**Type**
2004-01	“purpose-built”	5
2004-02	1994 Jeep Grand Cherokee Limited 4x4	1
2004-03	[motorcycle]	
2004-04	1993 Isuzu Trooper	1
2004-05	“air bag suspended class 1 race vehicle”	5
2004-06	2003 Toyota Tundra (SR5 V8 Access Cab)	2
2004-07	1994 Ford F-150 4x4	2
2004-08	1987 Chevrolet Suburban[42]	1
2004-09	2004 Acura MDX[40]	1
2004-10	M998 HMMWV	4
2004-11	“Coyote vehicle”	5
2004-12	[purpose-built vehicle]	5
2004-13	2003 ATV Prowler[41]	3
2004-14	“Tomcar” (model TM27G)	3
2004-15	1992 Jeep Cherokee	1
2004-16	MAX IV ATV	3
2004-17	1996 Chevy Tahoe	1
2004-18	Honda Rincon ATV	3
2004-19	[purpose-built vehicle]	5
2004-20	Polaris Ranger Series 11	3
2004-21	Kawasaki KFX ATV	3
2004-22	2003 Honda 4x4 ATV	3
2004-23	Oshkosh Trucks MTVR Model MK23	4
2004-24	[purpose-built vehicle]	5
2004-25	“off-road, four-wheel drive utility cart made by Club Car”	3

Table XVI. Team vehicles (2005 GCE participants).

Team	Vehicle	Type
2005-01	1994 Jeep Grand Cherokee Limited 4x4	1
2005-02	"... all terrain vehicle custom built ..."	5
2005-03	2003 Toyota Tundra (SR5 V8 Access Cab model)	2
2005-04	2005 Polaris Ranger 6x6	3
2005-05	2005 Dodge Ram 2500	2
2005-06	2005 Ford Escape Hybrid	1
2005-07	1987 Chevrolet Suburban[42]	1
2005-08	2005 Ford F-250 SuperDuty	2
2005-09	2004 Ford Explorer Sport Trac	1
2005-10	2001 Nissan Xterra	1
2005-11	2004 Kawasaki KFX700	3
2005-12	2005 GMC Canyon	2
2005-13	1986 AM General M998 HMMWV	4
2005-14	1999 AM General H1 Hummer	1
2005-15	2003 ATV Prowler	3
2005-16	2004 Volkswagen Touareg R5	1
2005-17	MAX IV ATV	3
2005-18	2005 Ford E-350 Van	
2005-19	Spider Light Strike Vehicle	4
2005-20	"... custom-made chassis ..."	5
2005-21	Oshkosh MTVR Model MK23 Standard Cargo Truck	4
2005-22	Ingersoll-Rand Club Car XRT-1500	3
2005-23	Ingersoll-Rand Club Car XRT-1500	3

Table XVII. Team vehicle closest match (2004 QID and GCE participants).		
Team	**Closest match**	**SSF**
2004-01	N/A	
2004-02	1993 2001 2003 Jeep Grand Cherokee	1.11
2004-03	N/A	
2004-04	1992 1994 Isuzu Trooper 4-DR 4x4	1.07
2004-05	N/A	
2004-06	2000 2002 2003 Toyota Tundra Access Cab 4x2	1.16
2004-07	1985 1996 Ford F-150 4x4 Pickup	1.20
2004-08	1982 1985 1991 Chevrolet K20/V20 4x4 Suburban	1.02
2004-09	2001 2002 2003 Acura MDX 4-DR 4x4	1.29
2004-10	N/A - Military service vehicle	
2004-11	N/A	
2004-12	N/A	
2004-13	N/A - Commercially-available ATV	
2004-14	N/A - Military service vehicle	
2004-15	1997 2001 Jeep Cherokee 4x4	1.08
2004-16	N/A	
2004-17	1995 1998 1999 Chevrolet Tahoe 4-DR 4x4	1.13
2004-18	N/A - Commercially-available ATV	
2004-19	N/A	
2004-20	N/A - Commercially-available ATV	
2004-21	N/A - Commercially-available ATV	
2004-22	N/A - Commercially-available ATV	
2004-23	N/A - Military service vehicle[a]	1.00
2004-24	N/A	
2004-25	N/A - Commercially-available ATV	

Note:

[a] The author was unable to determine the height of vehicle CG reported by the manufacturer at the time of the 2004 and 2005 GCE ([255]) because the figure providing dimensions is illegible. However, the manufacturer later reported a track

width of 80.8 in and height of vehicle CG of 40.4 in ([256]). SSF was calculated for these values.

Table XVIII. Team vehicle closest match (2005 GCE participants).		
Team	**Closest match**	**SSF**
2005-01	1993 2001 2003 Jeep Grand Cherokee 4x4	1.11
2005-02	N/A	
2005-03	2000 2002 2003 Toyota Tundra Access Cab 4x2	1.16
2005-04	N/A - Commercially-available ATV	
2005-05	2002 Dodge Ram 1500 Quad Cab 4x4	1.15
2005-06	N/A[a]	1.17
2005-07	1982 1985 1991 Chevrolet K20/V20 4x4 Suburban	1.02
2005-08	1981 1985 1997 Ford F250 4x4 Pickup	1.11
2005-09	2001 2002 2003 Ford Explorer Sport 2-DR 4x4	1.07
2005-10	2000 2001 2002 Nissan Xterra 4-DR 4x4	1.12
2005-11	N/A - Commercially-available ATV	
2005-12	N/A[b]	
2005-13	N/A - Military service vehicle	
2005-14	N/A	
2005-15	N/A - Commercially-available ATV	
2005-16	N/A[c]	
2005-17	N/A - Commercially-available ATV	
2005-18	N/A	
2005-19	N/A - Military service vehicle	
2005-20	N/A	
2005-21	N/A - Military service vehicle[d]	1.00
2005-22	N/A - Commercially-available ATV	
2005-23	N/A - Commercially-available ATV	

Notes:

[a] The author was unable to determine SSF for the Ford Escape Hybrid, which was new for model year 2005. A commercial used vehicle search service ([257]) reported a SSF of 1.17 for a “2005 Ford Escape 4-DR”. A SSF of 1.17 is used herein.

[b] The GMC Canyon was new for model year 2004.

[c] The Volkswagen Touareg was new for model year 2004.

[d] The author was unable to determine the height of vehicle CG reported by the manufacturer at the time of the 2004 and 2005 GCE ([255]) because the figure providing dimensions is illegible. However, the manufacturer later reported a track width of 80.8 in and height of vehicle CG of 40.4 in ([256]). SSF was calculated for these values.

Table XIX. Typical values for the kinetic coefficient of friction.		
Material 1	**Material 2**	μ_k
Rubber	Asphalt (dry)	0.50 – 0.80
Rubber	Asphalt (wet)	0.25 – 0.75
Rubber	Concrete (dry)	0.60 – 0.85
Rubber	Concrete (wet)	0.45 – 0.75

Table XX. Turning circle for selected challenge vehicles[a].			
Team	**Edmunds[b] Turning Circle, ft**	**Cars.com[c] Turning Radius, ft**	**MotorTrend[d] Turning Circle, ft**
2004-02 and 2005-01	36.6	N/A	N/A
2004-06 and 2005-03	44.9 ([258])		
2004-09	38.0	19.0	38.0
2004-14	27.9[e]		
2004-17		N/A	42.9[f]
2-DR 4x4 LS/LT	38.1		
4-DR 4x4 LS	42.9		
2004-23	85.4[g]		
2004-24	0.0[h]		
2004-25	10.0[i]		
2005-04	N/A[j]		
2005-06	37.7	18.3	35.4
2005-08[k]			
Low:	46.1	23.1	47.7
High:	56.5	28.3	56.5
2005-09	43.1	21.5	43.1
2005-10	N/A	17.7	35.4[l]
2005-12[m]	44.6	N/A	44.3
2005-14	53.0	26.5[n]	26.5[o]
2005-16	N/A	19.0	N/A
2005-17	9.0[p]		
2005-18	48.0	24.0	48.0
2005-21	58.0[q]		
2005-22 and 2005-23	23.0[r]		

Notes:

[a] In general, vehicle manufacturers' websites, including their “certified pre-owned vehicle” sections, did not report detailed information for past models of vehicles, such as those selected as challenge vehicle platform by teams participating in the 2004 QID and GCE and 2005 GCE. As a result, the author surveyed commercial used vehicle search services to determine values for turning circle and SSF.

[b] Edmunds, Inc. (“Edmunds”) reported “turning circle” ([41]).

[c] Cars.com (“Cars.com”) reported “turning radius” ([42]).

[d] MotorTrend Magazine (“MotorTrend”) reported “curb-to-curb turning circle” ([43]).

[e] Team 2004-14 reported a “turn radius” of “27.9 ft or 8.5 m” ([132], p. 1). Tomcar did not report turn radius or turning circle information for the Tomcar model TM27G ([259]). However a turning circle of 55.8 ft exceeds that of all other challenge vehicles with the exceptions of Teams 2004-23 and 2005-21, and possibly Team 2005-08. The author considers it unlikely a vehicle marketed primarily to off-road enthusiasts would have a turning circle greater than the Teams 2004-23 and 2005-21 challenge vehicle, and concluded the “turn radius” reported by Team 2004-14 was a turning circle. A turning circle of 55.8 ft is used herein.

[f] MotorTrend reported the turning circle was 13,076 mm ([43]).

[g] The manufacturer reported “wall-to-wall” turning circle, and reported the turning circle of the Team 2004-23 challenge vehicle platform was 85.4 ft ([255]). Team 2004-23 reported a “minimum turning radius” of 42.7 feet ([159]), or half of the turning circle reported by the manufacturer.

[h] Team 2004-24 reported “turning radius”, and stated: “Inter segment articulation provides a turning radius as small as 30 feet for higher speed turning. Low speed turning down to zero radius is accomplished with differential drive to the motors.” ([161], p. 2).

[i] Team 2004-25 reported a “turning radius” of “approximately 10 feet” ([49], p. 2).

[j] Team 2005-04 reported “turn radius”, and stated: “The Polaris Ranger was selected due to its agility, off-road driving capability, small turn radius and ease of modification.” ([169], p. 3). However, Team 2005-04 did not report the turning radius of the challenge vehicle.

[k] In general, American motor vehicle manufacturers support many more vehicle options than foreign motor vehicle manufacturers. For example, the 2005 Ford F-250 SuperDuty was available in three trim levels: XL, XLT, and Lariat; three cab options:

Standard (Regular) cab, Extended (Super) cab, and Crew cab; and two bed lengths: short and long. As a result, each 2005 Ford F-250 SuperDuty may have a 137-, 142-, 156-, 158-, or 172-inch wheelbase, each with a different turn radius. Rather than report the turning radius for every possible combination of options, only the low and high values are recorded herein as the best and worst possible case, respectively.

[l] MotorTrend reported the turning circle was 10,790 mm ([43]).

[m] Team 2005-12 stated: "[The challenge vehicle] has... a turning radius of 13 meters." ([185], p. 3). A "turning radius" of 13 m corresponds to a turning circle of 85.3 ft (26.0 m). Edmunds and MotorTrend ([41] and [43]) reported the turning circle of a 2005 GMC Canyon (Crew Cab) is 44.6 ft (13.6 m) and 44.3 ft (13.5 m), respectively. The turning circle reported by Team 2005-12 is approximately twice these values. As a result, the author concluded the "turning radius" reported by Team 2005-12 was a turning circle. The turning circles reported by commercial used vehicle search services is used herein.

[n] Cars.com ([42]) did not report detailed information for AM General H1 Hummer model years prior to 2000. The turning radius for a 2000 AM General H1 Hummer is used herein.

[o] MotorTrend reported the turning circle was 8,077 mm, which equals the turning radius reported by Cars.com or half the turning circle reported by Edmunds. The author concluded the turning circle reported by MotorTrend is a turning radius, not a turning circle.

[p] Team 2005-17 reported a "minimum turning radius" of "9ft" ([140], p. 3). However, Team 2005-17 later stated: "This vehicle was chosen because: ... it has a very small turning radius, about 1.2 m..." ([196], p. 557). A turning radius of 1.2 m is approximately 3.9 ft. The manufacturer did not report the turning radius or turning circle of the MAX IV ATV ([260]). As a result, the author was unable to resolve the discrepancy. A turning radius of 9.0 ft is used herein.

[q] Team 2005-21 reported "turning radius", and stated: "Rear steer has been added to [the challenge vehicle] to give it a 29-foot turning radius." ([160], p. 3).

[r] Teams 2005-22 and 2005-23 reported "turning radius", and stated: "This vehicle suits our application well with an 11.5' turning radius..." ([58], p. 2 and [164], p. 2). Teams 2005-22 and 2005-23 later stated: " The XRT 1500 is extremely agile with a turning radius of 3.5 m.", or approximately 11.5 ft ([59], p. 710).

Table XXI. Calculated rollover speed for selected challenge vehicles.				
Team	**Rollover speed, mph**			**SSF**
	Edmunds ([41])	**Cars.com ([42])**	**MotorTrend ([43])**	
2004-02 and 2005-01	17.4	N/A	N/A	1.11
2004-06 and 2005-03	19.7			1.16
2004-09	19.2	19.2	19.2	1.29
2004-17		N/A	19.1	
2-DR 4x4 LS/LT	17.9			1.13
4-DR 4x4 LS	19.1			1.13
2004-23	25.3			1.00
2005-06	18.2	17.9	17.6	1.17
2005-08				
Low:	19.6	19.6	19.9	1.11
High:	21.7	21.7	21.7	1.11
2005-09	18.6	18.6	18.6	1.07
2005-10	N/A	17.2	17.2	1.12
2005-12	20.0	N/A	19.9	1.20
2005-14	20.1	20.1	20.1	1.02
2005-16	N/A	17.0	N/A	1.02
2005-18	19.1	19.1	19.1	1.02
2005-21	20.8			1.00

Table XXII. 2004 GCE standard questions.	
1.a.1	Describe the means of ground contact. Include a diagram showing the size and geometry of any wheels, tracks, legs, and/or other suspension components.
1.a.2	Describe the method of Challenge Vehicle locomotion, including steering and braking.
1.a.3	Describe the means of actuation of all applicable components.
1.b.1	What is the source of Challenge Vehicle power?
1.b.2	Approximately how much maximum peak power (expressed in Watts) does the Challenge Vehicle consume?
1.b.3	What type and how much fuel will be carried by the Challenge Vehicle?
1.c.1	What kind of computing systems (hardware) does the Challenge Vehicle employ? Describe the number, type, and primary function of each.
1.c.2	Describe the methodology for the interpretation of sensor data, route planning, and vehicle control. How does the system classify objects? How are macro route planning and reactive obstacle avoidance accomplished? How are these functions translated into vehicle control?
1.d.1	What types of map data will be pre-stored on the vehicle for representing the terrain, the road network, and other mobility or sensing information? What is the anticipated source of this data?
1.e.1	What sensors does the challenge vehicle use for sensing the environment, including the terrain, obstacles, roads, other vehicles, etc.? For each sensor, give its type, whether it is active or passive, its sensing horizon, and its primary purpose?
1.e.2	How are the sensors located and controlled? Include any masts, arms, or the tethers that extend from the vehicle?
1.f.1	What sensors does the challenge vehicle use for sensing vehicle state?

1.f.2	How does the vehicle monitor performance and use such data to inform decision making?
1.g.1	How does the system determine its geolocation with respect to the Challenge Route?
1.g.2	If GPS is used, how does the system handle GPS outages?
1.g.3	How does the system process and respond to Challenge Route boundaries?
1.h.1	Will any information (or any wireless signals) be broadcast from the Challenge Vehicle? This should include information sent to any autonomous refueling/servicing equipment.
1.h.2	What wireless signals will the Challenge Vehicle receive?
1.i.1	Does the system refuel during the race? If so, describe the refueling procedure and equipment.
1.i.2	Are any additional servicing activities planned for the checkpoint? If so, describe the function and equipment.
1.j.1	How will the vehicle be controlled before the start of the challenge and after its completion? If it is to be remotely controlled by a human, describe how these controls will be disabled during the competition.
1.j.2	If it is to be remotely controlled by a human, describe how these controls will be disabled during the competition.
2.a	What tests have already been conducted with the Challenge Vehicle or key components? What were the results?
2.b	What tests will be conducted in the process of preparing for the Challenge?
3.a	What is the top speed of the vehicle?
3.b	What is the maximum range of the vehicle?

3.c	List all safety equipment on-board the Challenge Vehicle, including:
3.c.1	Fuel containment
3.c.2	Fire suppression
3.c.3	Audio and visual warning devices
3.d.1	How does the Challenge Vehicle execute emergency stop commands? Describe in detail the entire process from the time the on-board E-Stop receive outputs a stop signal to the time the signal is cleared and the vehicle may proceed. Include descriptions of both the software controlled stop and the hard stop.
3.d.2	Describe the manual E-Stop switch(es). Provide details demonstrating that this device will prevent unexpected movement of the vehicle once engaged.
3.d.3	Describe in detail the procedure for placing the vehicle in "neutral", how the "neutral" function operates, and any additional requirements for safely manually moving the vehicle. Is the vehicle towable by a conventional tow truck?
3.e.1	Itemize all devices on the Challenge Vehicle that actively radiate EM energy, and state their operating frequencies and power output. (E.g., lasers, radar apertures, etc.).
3.e.2	Itemize all devices on the Challenge Vehicle that may be considered a hazard to eye or ear safety and their OSHA classification level.
3.e.3	Describe any safety measures and/or procedures related to all radiators.
3.f.1	Describe any Challenge Vehicle properties that may conceivably cause environmental damage, including damage to roadways and off-road surfaces.
3.f.2	What are the maximum physical dimensions (length, width, and height) and weight of the vehicle?

3.f.3	What is the area of the vehicle footprint? What is the maximum ground pressure?

Table XXIII. 2005 GCE standard questions.	
1	Vehicle Description
1.1	Describe the vehicle. If it is based on a commercially available platform, provide the year, make and model. If it uses a custom-built chassis or body, describe the major characteristics. If appropriate, please provide a rationale for the choice of this vehicle for the DGC.
1.2	Describe the unique vehicle drive-train or suspension modifications made for the DGC including fuel-cells or other unique power sources.
2	Autonomous Operations
2.1	Processing
2.1.1	Describe the computing systems (hardware and software) including processor selection, complexity considerations, software implementation and anticipated reliability.
2.1.2	Provide a functional block diagram of the processing architecture that describes how the sensing, navigation, and actuation are coupled to the processing element(s) to enable autonomous operation. Show the network architecture and discuss the challenges faced in realization of the system.
2.1.3	Describe unique methods employed in the development process, including model-driven design or other methods used.
2.2	Localization
2.2.1	Explain the GPS system used and any inertial navigation systems employed during GPS outages (as in tunnels). Include a discussion of component errors and their effort on system performance.
2.2.2	If map data was an integral part of the vehicles navigation system, describe the requirements for this data and the way in which it was used.
2.3	Sensing

2.3.1	Describe the location and mounting of the sensors mounted on the vehicle. Include a discussion of sensor range and field of view. Discuss any unique methods used to compensate for conditions such as vibration, light level, rain, or dust.
2.3.2	Discuss the overall sensing architecture, including any fusion algorithms or other means employed to build models of the external environment.
2.3.3	Describe the internal sensing system and architecture used to sense the vehicle state.
2.3.4	Describe the sensing-to-actuation system used for waypoint following, path finding, obstacle detection, and collision avoidance. Include a discussion of vehicle models in terms of braking, turning, and control of the accelerator.
2.4	Vehicle Control
2.4.1	Describe the methods employed for common autonomous operation contingencies such as missed-waypoint, vehicle-stuck, vehicle-outside-lateral-boundary-offset, or obstacle-detected-in-path.
2.4.2	Describe the methods used for maneuvers such as braking, starting on a hill, or making a sharp turn without leaving the boundaries.
2.4.3	Describe the method for integration of navigation information and sensing information.
2.4.4	Discuss the control of the vehicle when it is not in autonomous mode.
2.5	System Tests
2.5.1	Describe the testing strategy to ensure vehicle readiness for DGC, including a discussion of component reliability, and any efforts made to simulate the DGC environment.
2.5.2	Discuss test results and key challenges discovered.

Table XXIV. State sensors in use by 2004 QID and GCE participants.

Team	Number	Manufacturer	Model number
2004-01	(1)	**-unknown-**	**-unknown-** ("engine RPM")
2004-01	(1)	**-unknown-**	**-unknown-** ("intake manifold pressure")
2004-01	(1)	**-unknown-**	**-unknown-** ("brake settings")
2004-01	(1)	**-unknown-**	**-unknown-** ("brake hydraulic pressure")
2004-01	(1)	**-unknown-**	**-unknown-** ("fuel level")
2004-01	(1)	**-unknown-**	**-unknown-** ("water temperature")
2004-01	(1)	**-unknown-**	**-unknown-** ("transmission gear position")
2004-01	(1)	**-unknown-**	**-unknown-** ("throttle position")
2004-01	(1)	**-unknown-**	**-unknown-** ("steering angle")
2004-02	**-n-**	**-unknown-**	**-unknown- (**"Some of the above mentioned sensors...")
2004-02	1	OEM	OBD-II
2004-03	(1)	**-unknown-**	**-unknown-** (AOE, "steering position")
2004-03	(1)	**-unknown-**	**-unknown-** (potentiometer, "steering position")
2004-04	1	Honeywell	RT600-360-01 ("steering angle")
2004-04	1	Motion Systems	85615 ("throttle state")
2004-04	1	OEM	RPM sensor ("throttle response")
2004-04	1	Motion Systems	85615 ("transmission gear state")
2004-04	(1)	Honeywell	ML500PS1PC ("brake pressure")
2004-05	1	**-unknown-**	**-unknown-** ("engine tachometer")
2004-05	1	**-unknown-**	**-unknown-** ("shifter position sensor")

2004-05	2	**-unknown-**	**-unknown-** (pressure transducers, “feedback from the brake lines”)
2004-05	4	**-unknown-**	**-unknown-** (pressure transducers)
2004-05	4	**-unknown-**	**-unknown-** (linear motion position sensor, “shock absorber extension”)
2004-05	1	**-unknown-**	**-unknown-** (linear motion position sensor, “throttle position”)
2004-05	1	**-unknown-**	**-unknown-** (linear motion position sensor, “steering rack position”)
2004-05	1	**-unknown-**	**-unknown-** (“cooling water temperature sensor”)
2004-05	**-n-**	**-unknown-**	**-unknown-** (“certain other sensors”)
2004-07	1	**-unknown-**	**-unknown-** (potentiometer, “position of the steering column”)
2004-08	1	OEM	fuel sender (fuel level)
2004-08	1	**-unknown-**	**-unknown-** (“optical sensor”, steering position)
2004-08	2	**-unknown-**	**-unknown-** (ten-turn potentiometer, brake and accelerator pedal position)
2004-09	(1)	**-unknown-**	**-unknown-** (“engine speed”)
2004-09	(1)	**-unknown-**	**-unknown-** (“steering wheel position”)
2004-10	**-n-**	**-unknown-**	**-unknown-** (OE)
2004-10	**-n-**	**-unknown-**	**-unknown-** (“potentiometers”)
2004-10	**-n-**	**-unknown-**	**-unknown-** (“rotational variable differential transformers (RVDT)”)
2004-10	**-n-**	**-unknown-**	**-unknown-** (“current” sensor)
2004-10	**-n-**	**-unknown-**	**-unknown-** (“voltage” sensor)
2004-11	1	**-unknown-**	**-unknown-** (“tachometer”, “engine speed data”)
2004-12	2	Ultra Motion	2-B.125-DC426_12-4-P-/4-300 (linear potentiometer, “wheel angle for front and rear”)
2004-12	1	Omron	E2E-CR8B1 (“engine speed”)
2004-13	(1)	**-unknown-**	**-unknown-** (“state of the vehicle's transmission”)
2004-13	(1)	**-unknown-**	**-unknown-** (“throttle position”)

2004-13	(1)	**-unknown-**	**-unknown-** (“braking pressure”)
2004-13	1	**-unknown-**	**-unknown- (“**absolute encoder”, “steering rate and angle”)
2004-14	(1)	**-unknown-**	**-unknown-** (“state of the vehicle's transmission”)
2004-14	(1)	**-unknown-**	**-unknown-** (“throttle position”)
2004-14	(1)	**-unknown-**	**-unknown-** (“braking pressure”)
2004-14	1	**-unknown-**	**-unknown-** (“angular encoder”, “steering rate and angle”)
2004-15	(1)	**-unknown-**	**-unknown-** (“brake position”)
2004-15	(1)	**-unknown-**	**-unknown-** (“throttle position”)
2004-15	(1)	**-unknown-**	**-unknown-** (“RPM”)
2004-15	(1)	**-unknown-**	**-unknown-** (“low oil pressure”)
2004-15	(1)	**-unknown-**	**-unknown-** (“transmission shifter position”)
2004-15	(1)	**-unknown-**	**-unknown-** (“transfer case shifter position”)
2004-15	(1)	**-unknown-**	**-unknown-** (“air conditioning information”)
2004-15	(1)	**-unknown-**	**-unknown-** (stepper motor, “steering position”)
2004-17	1	OEM	OBD-II (“engine temperature”, “engine RPM”, and “present gear”)
2004-18	(1)	**-unknown-**	**-unknown-** (“engine is running”)
2004-18	(1)	**-unknown-**	**-unknown-** (“brakes are applied”)
2004-18	(1)	**-unknown-**	**-unknown-** (“acceleration is applied”)
2004-18	(1)	**-unknown-**	**-unknown-** (“position of the steering motor”)
2004-18	**-n-**	**-unknown-**	**-unknown-** (“temperature sensors”)
2004-20	(1)	**-unknown-**	**-unknown-** (“engine RPM”)
2004-20	(1)	**-unknown-**	**-unknown-** (“driveshaft RPM”)
2004-20	**-n-**	**-unknown-**	**-unknown-** (“voltage”)

2004-20	**-n-**	**-unknown-**	**-unknown-** (“temperature”)
2004-20	**-n-**	**-unknown-**	**-unknown-** (“actuators”, “position and velocity”)
2004-21	(1)	**-unknown-**	**-unknown-** (“fuel”)
2004-21	**-n-**	**-unknown-**	**-unknown-** (“temperature”)
2004-21	**-n-**	**-unknown-**	**-unknown-** (“electrical output”)
2004-21	**-n-**	**-unknown-**	**-unknown-** (“etcetera”)
2004-22	3	**-unknown-**	**-unknown-** (“temperature sensors”, “engine, oil, and outside temperatures”)
2004-22	(4)	SpaceAge Control	**-unknown-** (string potentiometer, “actual position of the shock (compressed or uncompressed)”)
2004-23	(1)	**-unknown-**	**-unknown-** (“vehicle and actuator sensors”, “throttle”)
2004-23	(1)	**-unknown-**	**-unknown-** (“vehicle and actuator sensors”, “brakes”)
2004-23	(1)	**-unknown-**	**-unknown-** (“vehicle and actuator sensors”, “engine condition”)
2004-24	16	**-unknown-**	**-unknown-** (“pressure sensors”, suspension and steering)
2004-24	2	**-unknown-**	**-unknown-** (“pressure sensors”, brake actuators)
2004-24	1	**-unknown-**	**-unknown-** (“pressure sensors”, storage tanks)
2004-24	(1)	**-unknown-**	**-unknown-** (“voltage sensors”, batteries)
2004-24	(1)	**-unknown-**	**-unknown-** (“current sensors”, batteries)
2004-24	(1)	**-unknown-**	**-unknown-** (“voltage sensors”, generator)
2004-24	(1)	**-unknown-**	**-unknown-** (“speed sensors”, generator)
2004-24	(1)	**-unknown-**	**-unknown-** (“water temperature sensors”, generator)
2004-25	1	**-unknown-**	**-unknown-** (linear actuator, “position and velocity of the brake... [motor]”)
2004-25	1	Bodine Electric	42A-5N (model number 0941 integral OE, “position and velocity of the... steering... [motor]”)
2004-25	1	Japan Servo	DME 60B6HF (integral OE, “position and velocity of the... throttle [motor]”)
2004-25	2	**-unknown-**	**-unknown-** (“battery voltage for each on-board battery”)

2004-25	**-n-**	**-unknown-**	**-unknown-** (“temperature inside all electronic enclosures”)

Table XXV. Environment sensors in use by 2004 QID and GCE participants.

Team	Number	Manufacturer	Model number	Sensor Type
2004-01	1	**-unknown-**	**-unknown-** (“digital camera”)	VISION
2004-01	1	**-unknown-**	**-unknown-** (“monochrome camera, sensitive to near IR”)	VISION
2004-01	**-n-**	**-unknown-**	**-unknown-** (“ultrasonic sensors”)	X
2004-01	2	SICK	**-unknown-** (LMS 211-30106 or -30206)	LIDAR
2004-02	1	AVT	**-unknown-** (“Dolphin”)	VISION
2004-02	1	FLIR	A20M	VISION
2004-02	(3)	Point Grey	Bumblebee	STEREO
2004-02	1	Epsilon Lambda	ELSC71-1A	RADAR
2004-02	1	SICK	LMS 211-30206	LIDAR
2004-02	4	2004-02	MetalSense B1 (“touch sensor”)	X
2004-03	2	Cognex	**-unknown-** (“ethernet cameras”)	STEREO
2004-03	1	**-unknown-**	**-unknown-** (“color camera”)	VISION
2004-03	1	Epsilon Lambda	ELSC71-1A	RADAR
2004-04	1	Videre Design	**-unknown-** (“stereo vision system”)	STEREO
2004-04	1	SICK	LMS 200-30106 (“rotating”)	LIDAR
2004-04	1	**-unknown-**	**-unknown-** (“long-range RADAR”)	RADAR
2004-04	1	SICK	LMS 200-30106 (“fixed”)	LIDAR
2004-04	3	Preco	**-unknown-** (“PreView”)	RADAR
2004-04	3	**-unknown-**	**-unknown-** (“stationary cameras”)	VISION
2004-05	14	**-unknown-**	**-unknown-** (“SONAR array”)	X

2004-05	2	**-unknown-**	**-unknown-** (“depth finders”)	X
2004-05	2	SICK	**-unknown-** (“LMS 291”)	LIDAR
2004-05	2	**-unknown-**	**-unknown-** (“conductivity sensor”)	X
2004-05	7	**-unknown-**	**-unknown-** (“tactile sensor”)	X
2004-05	1	Eaton	**-unknown-** (“Vorad VBOX 83001-001”)	RADAR
2004-05	1	Point Grey	Bumblebee	STEREO
2004-06	1	2004-06	Digital Auto Drive (DAD)	STEREO
2004-07	1	SICK	**-unknown-** (LIDAR)	LIDAR
2004-07	1	Epsilon Lambda	ELSC71-1A	RADAR
2004-07	1	**-unknown-**	**-unknown-** (“ground whisker”)	X
2004-07	1	FLIR	Omega	VISION
2004-07	2	Sony	DFW-VL500	VISION
2004-08	4	Laseroptronix	LDM 800-RS232	LIDAR
2004-08	1	Laseroptronix	Sea-Lynx	VISION/LIDAR
2004-08	2	Cohu	1330	VISION
2004-09	1	**-unknown-**	**-unknown-** (“vibration sensor”)	X
2004-09	1	SICK	**-unknown-** (“LMS 211 or 221”)	LIDAR
2004-09	1	**-unknown-**	**-unknown-** (“generic, high-resolution color digital camera”)	VISION
2004-10	1	Riegl	LMS-Q140i	LIDAR
2004-10	3	SICK	**-unknown-** (LIDAR)	LIDAR
2004-11	3	Polaroid	6500	X
2004-11	1	**-unknown-**	**-unknown-** (“scanning laser range finder”)	LIDAR
2004-11	1	**-unknown-**	**-unknown-** (“long-range laser ranger”)	LIDAR

2004-11	1	Omnivision	**-unknown-** (“digital image sensor array”)	VISION
2004-12	3	**-unknown-**	**-unknown-** (“ultrasonic distance sensors”)	X
2004-12	1	SICK	LMS 291-S05	LIDAR
2004-13	(24)	Rockwell Automation	**-unknown-** (“photoelectric sensors”)	X
2004-13	4	SICK	**-unknown-** (LIDAR)	LIDAR
2004-13	**-n-**	**-unknown-**	**-unknown-** (“ultrasonic range finders”)	X
2004-13	1	**-unknown-**	**-unknown-** (“video camera”)	VISION
2004-13	1	Epsilon Lambda	**-unknown-** (RADAR)	RADAR
2004-13	1	**-unknown-**	**-unknown-** (accelerometer, “roughness of the terrain”)	X
2004-14	**-n-**	**-unknown-**	**-unknown-** (“tactile sensors”)	X
2004-14	**-n-**	**-unknown-**	**-unknown-** (“video cameras”)	VISION
2004-14	4	SICK	**-unknown-** (LIDAR)	LIDAR
2004-14	(24)	Rockwell Automation	**-unknown-** (“photoelectric sensors”)	X
2004-14	**-n-**	**-unknown-**	**-unknown-** (“ultrasonic range finder”)	X
2004-14	1	Epsilon Lambda	**-unknown-** (RADAR)	RADAR
2004-14	1	**-unknown-**	**-unknown-** (accelerometer, “roughness of the terrain”)	X
2004-15	1	Eaton	EVT-300	RADAR
2004-15	**-n-**	**-unknown-**	**-unknown-** (“tactile sensors”)	X
2004-15	5	Polaroid	6500	X
2004-15	1	SICK	LMS 211-30206	LIDAR
2004-16	**-n-**	**-unknown-**	**-unknown-** (RADAR)	RADAR
2004-16	**-n-**	**-unknown-**	**-unknown-** (SONAR)	X
2004-16	2	SICK	**-unknown-** (LIDAR)	LIDAR

2004-16	2	**-unknown-**	**-unknown-** (“passive cameras”)	VISION
2004-17	1	Point Grey	Dragonfly (“road-following camera”)	VISION
2004-17	2	SICK	LMS 221-30206	LIDAR
2004-17	4	Point Grey	Dragonfly (“stereovision cameras”)	STEREO
2004-18	1	**-unknown-**	**-unknown-** (“stereo camera system”)	STEREO
2004-18	1	SICK	LMS 220-30106	LIDAR
2004-18	3	**-unknown-**	**-unknown-** (“doppler radars”)	RADAR
2004-19	1	**-unknown-**	**-unknown-** (“stereo vision system”)	STEREO
2004-19	1	SICK	DME 2000	LIDAR
2004-19	3	**-unknown-**	**-unknown-** (“ultrasonic rangefinders”)	X
2004-20	1	SICK	LMS 221-30206	LIDAR
2004-20	1	Eaton	EVT-300	RADAR
2004-20	**-n-**	**-unknown-**	**-unknown-** (“water sensors”)	X
2004-20	**-n-**	**-unknown-**	**-unknown-** (“ultrasonic sonars”)	X
2004-20	1	Unibrain	Fire-i 400	VISION
2004-21	1	Epsilon Lambda	ELSC71-1A	RADAR
2004-21	1	SensComp	Developer's Kit	X
2004-22	1	2004-22	Video System (proprietary)	VISION
2004-23	12	Massa	**-unknown-** (“ultrasonic sensors”)	X
2004-23	4	SICK	**-unknown-** (“LMS 221”)	LIDAR
2004-23	2	Eaton	**-unknown-** (“Eaton-Vorad radars”)	RADAR
2004-23	2	**-unknown-**	**-unknown-** (“CCD digital color cameras”)	VISION
2004-23	4	**-unknown-**	**-unknown-** (“CCD digital color cameras”)	STEREO

2004-24	1	**-unknown-**	**-unknown-** (LIDAR)	LIDAR
2004-24	(2)	**-unknown-**	**-unknown-** ("road ID cameras")	VISION
2004-24	1	**-unknown-**	**-unknown-** ("matched set of machine vision cameras")	STEREO
2004-24	1	Eaton	**-unknown-** ("VORAD radar")	RADAR
2004-24	**-n-**	**-unknown-**	**-unknown-** ("boundary ID cameras")	VISION
2004-25	2	Eaton	**-unknown-** ("Eaton VORAD radar")	RADAR
2004-25	3	SICK	**-unknown-** (LIDAR)	LIDAR
2004-25	1	**-unknown-**	**-unknown-** ("visible light camera")	VISION

Table XXVI. Navigation sensors in use by 2004 QID and GCE participants.			
Team	**Number**	**Manufacturer**	**Model number**
2004-01	1	Trimble	AgGPS 114
2004-01	(4)	**-unknown-**	**-unknown-** (“individual wheel speed”)
2004-01	**-n-**	**-unknown-**	**-unknown-** (“3-axis accelerometer”)
2004-01	**-n-**	**-unknown-**	**-unknown-** (“3-axis rate gyroscope”)
2004-01	1	**-unknown-**	**-unknown-** (“compass”, “digital compass”, and “electronic compass”)
2004-02	1	AGNC	Land Navigator
2004-03	1	**-unknown-**	**-unknown-** (DGPS)
2004-03	(2)	**-unknown-**	**-unknown-** (AOEs, “wheel rotational positions”)
2004-03	1	Crossbow	**-unknown-** (“VG400”)
2004-03	1	Crossbow	**-unknown-** (“AHRS400”)
2004-03	1	Crossbow	**-unknown-** (IMU)
2004-04	1	Garmin	**-unknown-** (“WAAS GPS”)
2004-04	1	NavCom	**-unknown-** (“Starfire 2050”)
2004-04	1	**-unknown-**	**-unknown-** (“quadrature shaft encoder”, “position and velocity data”)
2004-04	1	OEM	“OEM anti-lock brake speed sensors” (“ground speed”)
2004-04	1	Smiths Aerospace	North Finding Module
2004-05	**-n-**	**-unknown-**	**-unknown-** (“...multiple [DGPS] receivers...”)
2004-05	1	CSI Wireless	Vector
2004-05	1	CSI Wireless	DGPS MAX
2004-05	1	**-unknown-**	**-unknown-** (two-axis inclinometer, “operating plane (tilt measurement) of the vehicle”)

2004-05	1	**-unknown-**	**-unknown-** (“gyroscope”)
2004-05	1	**-unknown-**	**-unknown-** (“gyroscope”)
2004-05	2	**-unknown-**	**-unknown-** (“accelerometer”)
2004-05	4	**-unknown-**	**-unknown-** (“rotary wheel-speed sensors”, “dead reckoning”)
2004-05	1	**-unknown-**	**-unknown-** (“compass”, “digital compass”, and “electronic compass”)
2004-06	1	NavCom	SF-2050G
2004-06	6	Analog Devices	ADXRS150
2004-06	(1)	Honeywell	HMC1002
2004-06	4	Analog Devices	ADXL203
2004-07	1	Garmin	GPS V
2004-07	1	Trimble	AgGPS 114
2004-07	1	Rotomotion	**-unknown-** (“magnetometer”)
2004-07	1	**-unknown-**	**-unknown-** (Hall Effect sensor, “velocity” by “rotation of the rear axle”)
2004-07	1	Rotomotion	**-unknown-** (IMU)
2004-08	1	Applanix	**-unknown-** (“POS LV”)
2004-09	1	MiTAC	Ashtech DG16
2004-09	1	MiTAC	NavmanTU60-D120
2004-09	1	Garmin	16A
2004-09	(4)	**-unknown-**	**-unknown-** (“wheel rotation speed”)
2004-09	(1)	**-unknown-**	**-unknown-** (“ground speed”)
2004-09	(1)	**-unknown-**	**-unknown-** (“current direction”)
2004-09	(1)	**-unknown-**	**-unknown-** (“vehicle attitude with respect to the horizon”)
2004-09	(1)	**-unknown-**	**-unknown-** (“3-axis acceleration”)

2004-09	1	**-unknown-**	**-unknown-** (“gyroscope”)
2004-10	1	Applanix	**-unknown-** (“POS-LV”)
2004-10	(1)	**-unknown-**	**-unknown-** (“vehicle pose (roll, pitch, yaw)”)
2004-10	(1)	**-unknown-**	**-unknown-** (“vehicle velocity”)
2004-11	1	MiTAC	A12
2004-11	1	CSI Wireless	**-unknown-** (“differential beacon receiver”)
2004-11	1	**-unknown-**	**-unknown-** (“standard industrial laser rangefinder”, “pitch and roll relative to the ground”)
2004-11	1	**-unknown-**	**-unknown-** (OE, “ground speed”)
2004-11	1	**-unknown-**	**-unknown-** (“solid-state magnetic compass module”)
2004-12	1	Trimble	AgGPS 114
2004-12	2	Analog Devices	ADXL311
2004-12	1	Omron	E2E-CR8B1
2004-13	1	Rockwell Collins	GNP-10
2004-13	1	NavCom	SF-2050G
2004-13	1	**-unknown-**	**-unknown-** (“digital compass”)
2004-13	1	**-unknown-**	**-unknown-** (Hall Effect sensor, “incremental distance” and “speed”)
2004-14	1	Rockwell Collins	GNP-10
2004-14	1	NavCom	SF-2050G
2004-14	1	**-unknown-**	**-unknown-** (Hall Effect sensor, “incremental distance” and “speed”)
2004-14	1	**-unknown-**	**-unknown-** (“magnetometer”)
2004-15	1	Trimble	AgGPS 114
2004-15	4	**-unknown-**	**-unknown-** (“wheel encoders”, “distance traveled”)
2004-15	1	**-unknown-**	**-unknown-** (“accelerometer”)

2004-15	1	KVH	Azimuth 1000
2004-16	1	C&C Technologies	**-unknown-** (“C-Nav”)
2004-16	1	**-unknown-**	**-unknown-** (INS)
2004-16	**-n-**	**-unknown-**	**-unknown-** (“solar sensors”)
2004-16	1	**-unknown-**	**-unknown-** (“compass”, “digital compass”, and “electronic compass”)
2004-17	1	NavCom	SF-2050G
2004-17	1	PNI	TCM2-50
2004-17	1	Northrop Grumman	LN-200
2004-18	1	NovAtel	ProPak-LBplus
2004-18	1	ISI	**-unknown-** (“RRS75”)
2004-18	1	**-unknown-**	**-unknown-** (“magnetic compass”)
2004-19	1	Trimble	AgGPS 122
2004-19	2	Electro Switch	**-unknown-** (“900 Series” OE, “speed of each [rear] wheel”)
2004-19	1	PNI	Vector 2X
2004-20	1	NovAtel	ProPak-LBplus
2004-20	1	DICKEY-john	**-unknown-** (“doppler radar speedometer”, “vehicle speed relative to the ground”)
2004-20	1	Crossbow	**-unknown-** (“AHRS inertial system”)
2004-20	1	**-unknown-**	**-unknown-** (“magnetic compass”)
2004-21	1	Garmin	GPS V
2004-22	1	NovAtel	ProPak-LBplus
2004-22	1	u-blox	**-unknown-** (GPS)
2004-22	1	**-unknown-**	**-unknown-** (“1-axis gyroscope”)
2004-22	1	Microstrain	**-unknown-** (“3-axis gyroscope”)

2004-22	1	Honeywell	**-unknown-** (“pressure transducer”, “altitude”)
2004-22	4	**-unknown-**	**-unknown-** (“Hall-State proximity sensors”)
2004-23	2	NovAtel	ProPak-LBplus
2004-23	6	**-unknown-**	**-unknown-** (“individual wheel speed”)
2004-23	1	Honeywell	HMR3000
2004-23	1	**-unknown-**	**-unknown-** (IMU)
2004-24	1	NavCom	**-unknown-** (GPS)
2004-24	6	2004-24	custom (“motor/wheel speed”)
2004-24	1	Northrop Grumman	LN-200
2004-24	3	**-unknown-**	**-unknown-** (“magnetometers”, “Coarse Heading Sensor”)
2004-24	3	**-unknown-**	**-unknown-** (“gyros”, “Coarse Heading Sensor”)
2004-24	3	**-unknown-**	**-unknown-** (“accelerometers”, “Coarse Heading Sensor”)
2004-25	1	Honeywell	**-unknown-** (“TALIN integrated DGPS/INS system”)
2004-25	1	**-unknown-**	**-unknown-** (“wheel encoder”, “wheel velocity”)

Table XXVII. Environment sensors in use by 2005 GCE participants.				
Team	**Number**	**Manufacturer**	**Model number**	**Sensor Type**
2005-01	1	AVT	**-unknown-** (“Dolphin”)	VISION
2005-01	1	FLIR	A20M	VISION
2005-01	5	Point Grey	Bumblebee	STEREO
2005-01	1	Eaton	**-unknown-** (“Eaton VORAD RADAR”)	RADAR
2005-01	1	Amphitech	OASys	RADAR
2005-01	**-n-**	**-unknown-**	**-unknown-**	RADAR
2005-01	1	SICK	LMS 211-30206	LIDAR
2005-01	3	SICK	**-unknown-** (“SICK 291 LADAR”)	LIDAR
2005-02	3	SICK	LMS 291-S05	LIDAR
2005-02	1	**-unknown-**	**-unknown-** (“color camera”)	VISION
2005-03	1	2005-03	Digital Auto Drive (DAD)	LIDAR
2005-04	4	SICK	LMS 221-30206	LIDAR
2005-04	1	Eaton	EVT-300	RADAR
2005-04	1	2005-04	**-unknown-** (“second radar”)	RADAR
2005-04	1	**-unknown-**	**-unknown-** (“stereo camera system”)	STEREO
2005-04	8	**-unknown-**	**-unknown-** (“ultrasonic rangefinders”)	X
2005-05	4	SICK	**-unknown-** (“LMS 291”)	LIDAR
2005-05	1	SICK	**-unknown-** (“LMS 221”)	LIDAR
2005-05	1	Mobileye	ACP5	VISION
2005-06	2	SICK	**-unknown-** (“LMS 291”)	LIDAR

2005-07	2	SICK	**-unknown-** (LIDAR)	LIDAR
2005-07	**-n-**	**-unknown-**	**-unknown-** ("stereo cameras")	STEREO
2005-08	2	Riegl	LMS-Q120	LIDAR
2005-08	1	SICK	LMS 291-S14	LIDAR
2005-08	1	SICK	LMS 211-30106	LIDAR
2005-08	3	Delphi	Forewarn ACC3	RADAR
2005-08	1	Delphi	Dual-beam RADAR Back-Up Aid (BUA)	X
2005-08	4	**-unknown-**	**-unknown-** ("ultrasonic sensors")	X
2005-08	2	Sony	DFW-VL500	STEREO
2005-08	2	**-unknown-**	**-unknown-** ("road following" cameras)	VISION
2005-08	1	**-unknown-**	**-unknown-** ("active bumper")	X
2005-09	8	SICK	**-unknown-** ("laser range finders")	LIDAR
2005-10	2	SICK	**-unknown-** ("LMS-291")	LIDAR
2005-10	2	Cognex	DVT 542C	VISION
2005-10	1	**-unknown-**	**-unknown-** ("stereo camera")	STEREO
2005-10	1	Optech	ILRIS-3D	LIDAR
2005-11	**-n-**	SICK	**-unknown-** ("LMS 291")	LIDAR
2005-12	1	Point Grey	Bumblebee	STEREO
2005-13	1	Riegl	LMS-Q140i	LIDAR
2005-13	4	SICK	**-unknown-** ("LMS 291")	LIDAR
2005-13	1	Navtech	DS2000	RADAR
2005-14	1	Riegl	LMS-Q140i	LIDAR
2005-14	4	SICK	**-unknown-** ("LMS 291")	LIDAR

2005-14	1	Navtech	DS2000	RADAR
2005-15	4	SICK	**-unknown-** (“LMS-221”)	LIDAR
2005-15	1	2005-15	Stereo Vision System (SVS)	STEREO
2005-16	5	SICK	**-unknown-** (“laser range finders”)	LIDAR
2005-16	1	**-unknown-**	**-unknown-** (“color camera”)	VISION
2005-17	2	SICK	**-unknown-** (“LMS 291”)	LIDAR
2005-18	2	SICK	LMS 221-30206	LIDAR
2005-18	1	SICK	LMS 291-S14	LIDAR
2005-18	1	SICK	LMS 291-S05	LIDAR
2005-18	1	Riegl	LMS-Q120i	LIDAR
2005-18	4	Point Grey	Dragonfly (“Stereovision” cameras)	STEREO
2005-18	1	Point Grey	Dragonfly (“Road-finding camera”)	VISION
2005-19	3	SICK	**-unknown-** (“LMS 291”)	LIDAR
2005-20	**-n-**	**-unknown-**	**-unknown-** (LIDAR)	LIDAR
2005-20	**-n-**	**-unknown-**	**-unknown-** (“millimeter wave RADAR”)	RADAR
2005-20	**-n-**	**-unknown-**	**-unknown-** (“stereo camera”)	STEREO
2005-21	2	SICK	**-unknown-** (“LMS-291”)	LIDAR
2005-21	1	Ibeo	**-unknown-** (“ALASCA”)	LIDAR
2005-21	3	**-unknown-**	**-unknown-** (“trinocular camera system”)	STEREO
2005-22	1	SICK	**-unknown-** (“LMS-291”)	LIDAR
2005-22	1	Point Grey	Bumblebee	VISION
2005-23	3	SICK	**-unknown-** (“LMS-291”)	LIDAR
2005-23	1	Point Grey	Bumblebee	VISION

Table XXVIII. Navigation sensors in use by 2005 GCE participants.			
Team	**Number**	**Manufacturer**	**Model number**
2005-01	2	NavCom	SF-2050G
2005-01	1	Northrop Grumman	LN-270
2005-02	1	Smiths Aerospace	North Finding Module
2005-02	1	Garmin	16
2005-02	1	NavCom	**-unknown-** (“Starfire 2050”)
2005-03	1	NavCom	SF-2050G
2005-03	1	NovAtel	ProPak-LBplus
2005-03	1	KVH	DSP-5000
2005-03	1	**-unknown-**	**-unknown-** (“6-axis inertial system”)
2005-03	1	OEM	vehicle odometer
2005-04	1	NovAtel	ProPak-LBplus
2005-04	1	Crossbow	VG700AA-201
2005-04	(6)	**-unknown-**	**-unknown-** (“wheel speed sensors”)
2005-05	1	NovAtel	ProPak-LBplus
2005-05	1	Systron Donner	C-MIGITS III
2005-05	1	**-unknown-**	**-unknown-** (Hall Effect sensor, “odometry”)
2005-06	1	Oxford	RT3000
2005-06	1	**-unknown-**	**-unknown-** (“wheel speed sensor”)
2005-07	(1)	**-unknown-**	**-unknown-** (GPS)
2005-08	1	Honeywell	TALIN-5000

2005-08	1	NovAtel	ProPak-LBplus
2005-08	1	Vansco	**-unknown-** (“Doppler radar sensor”)
2005-09	2	Trimble	AgGPS 132
2005-09	1	Microbotics	MIDG-II
2005-09	1	**-unknown-**	**-unknown-** (“quadrature shaft encoder”, “vehicle displacement”)
2005-09	1	**-unknown-**	**-unknown-** (“encoder”, “steering wheel angle”)
2005-10	1	NavCom	SF-2050G
2005-10	1	Garmin	GPSMAP 76CS
2005-10	1	Kearfott	**-unknown-** (“MIL-NAV”)
2005-10	1	Crossbow	**-unknown-** (“3 axis accelerometer”)
2005-10	1	PNI	TCM2
2005-11	1	Crossbow	**-unknown-** (“Navigation Attitude Heading Reference System (NAHRS) module”)
2005-11	1	NovAtel	**-unknown-** (GPS)
2005-11	**-n-**	**-unknown-**	**-unknown-** (“wheel speed sensors”, “odometry data”)
2005-12	1	Trimble	**-unknown-** (GPS)
2005-12	1	**-unknown-**	**-unknown-** (“optical rotary encoder”, “precise position feedback”)
2005-13	1	Applanix	**-unknown-** (“POS LV”)
2005-13	1	Trimble	AgGPS 252
2005-14	1	Applanix	**-unknown-** (“POS LV”)
2005-14	1	Trimble	AgGPS 252
2005-15	1	NavCom	**-unknown-** (“Starfire”)
2005-15	1	Rockwell Collins	**-unknown-** (“GIC-100”)
2005-15	1	PNI	TCM2

2005-15	1	Microstrain	3DM-GX1
2005-15	1	OEM	“speedometer encoder” (“speed data”)
2005-16	1	**-unknown-**	**-unknown-** (“GPS positioning system”)
2005-16	1	**-unknown-**	**-unknown-** (“GPS compass”)
2005-16	1	**-unknown-**	**-unknown-** (“six degree-of-freedom IMU”)
2005-17	1	Oxford	RT3102
2005-17	1	C&C Technologies	**-unknown-** (“C-Nav”)
2005-18	1	NavCom	SF-2050G
2005-18	1	NovAtel	DL-4plus
2005-18	1	Northrop Grumman	LN-200
2005-19	1	Trimble	AgGPS 252
2005-19	1	Northrop Grumman	LN-200
2005-19	1	**-unknown-**	**-unknown-**
2005-20	2	NovAtel	ProPak-LBplus
2005-20	1	NovAtel	HG1700 SPAN
2005-21	2	Oxford	RT3100
2005-21	1	Trimble	AgGPS 132
2005-21	1	**-unknown-**	**-unknown-** (“wheel speed sensor”, “sensed wheel speed”)
2005-21	1	**-unknown-**	**-unknown-** (“encoder”, “wheel angle”)
2005-22	1	NovAtel	ProPak-LBplus
2005-22	1	NovAtel	HG1700 SPAN
2005-22	1	**-unknown-**	**-unknown-** (“throttle” encoder)
2005-22	1	**-unknown-**	**-unknown-** (“steering” encoder)

2005-23	1	NovAtel	ProPak-LBplus
2005-23	1	NovAtel	HG1700 SPAN
2005-23	1	**-unknown-**	**-unknown-** (“throttle” encoder)
2005-23	1	**-unknown-**	**-unknown-** (“steering” encoder)

Table XXIX. Known sensors by quantity (2004 QID and GCE participants).

Team	State				Environment				Navigation			
	Total	K	U	E	Total	K	U	E	Total	K	U	E
2004-10	5		5		2	2			3	1		2
2004-14	4	1		3	7	3	3	1	4	4		
2004-06					1	1			4	3		1
2004-07	1	1			5	5			5	5		
2004-17	1	1			3	3			3	3		
2004-23	3			3	4	4			4	4		
2004-13	4	1		3	6	4	1	1	4	4		
2004-04	5	4	1		6	6			5	5		
2004-18	5		1	4	3	3			3	3		
2004-02	2	1	1		6	5		1	1	1		
2004-09	2			2	3	3			9	4		5
2004-16					4	2	2		4	3	1	
2004-25	5	4	1		3	3			2	2		
2004-03	2			2	3	3			5	4		1
2004-24	8	3		5	5	3	1	1	6	6		
GCE	47	16	9	22	61	50	7	4	62	52	1	9
2004-01	9			9	4	3	1		5	2	2	1
2004-05	9	8	1		7	7			9	8	1	
2004-08	3	3			3	3			1	1		
2004-11	1	1			4	4			5	5		
2004-12	2	2			2	2			3	3		
2004-15	8			8	4	3	1		4	4		
2004-19					3	3			3	3		
2004-20	5		3	2	5	3	2		4	4		
2004-21	4		3	1	2	2			1	1		
2004-22	2	1		1	1	1			6	6		
QID	90	31	16	43	96	81	11	4	103	89	4	10

Table XXX. Known sensors by manufacturer (2004 QID and GCE participants).

Team	State			Environment			Navigation		
	Total	K	U	Total	K	U	Total	K	U
2004-10	5		5	2	2		3	1	2
2004-14	4		4	7	3	4	4	2	2
2004-06				1	1		4	4	
2004-07	1		1	5	4	1	5	4	1
2004-17	1	1		3	3		3	3	
2004-23	3		3	4	3	1	4	2	2
2004-13	4		4	6	3	3	4	2	2
2004-04	5	5		6	4	2	5	4	1
2004-18	5		5	3	1	2	3	2	1
2004-02	2	1	1	6	6		1	1	
2004-09	2		2	3	1	2	9	3	6
2004-16				4	1	3	4	1	3
2004-25	5	2	3	3	2	1	2	1	1
2004-03	2		2	3	2	1	5	3	2
2004-24	8		8	5	1	4	6	3	3
GCE	47	9	38	61	37	24	62	36	26
2004-01	9		9	4	1	3	5	1	4
2004-05	9		9	7	3	4	9	2	7
2004-08	3	1	2	3	3		1	1	
2004-11	1		1	4	2	2	5	2	3
2004-12	2	2		2	1	1	3	3	
2004-15	8		8	4	3	1	4	2	2
2004-19				3	1	2	3	3	
2004-20	5		5	5	3	2	4	3	1
2004-21	4		4	2	2		1	1	
2004-22	2	1	1	1	1		6	4	2
QID	90	13	77	96	57	39	103	58	45

Table XXXI. Known sensors by manufacturer and model number (2004 QID and GCE participants).

Team	State			Environment			Navigation		
	Total	K	U	Total	K	U	Total	K	U
2004-10				2	1	1	1		1
2004-14				3		3	2	2	
2004-06				1	1		4	4	
2004-07				4	3	1	4	2	2
2004-17	1	1		3	3		3	3	
2004-23				3		3	2	2	
2004-13				3		3	2	2	
2004-04	5	5		4	2	2	4	2	2
2004-18				1	1		2	1	1
2004-02	1	1		6	5	1	1	1	
2004-09				1		1	3	3	
2004-16				1		1	1		1
2004-25	2	2		2		2	1		1
2004-03				2	1	1	3		3
2004-24				1		1	3	2	1
GCE	9	9		37	17	20	36	24	12
2004-01				1		1	1	1	
2004-05				3	1	2	2	2	
2004-08	1	1		3	3		1		1
2004-11				2	1	1	2	1	1
2004-12	2	2		1	1		3	3	
2004-15				3	3		2	2	
2004-19				1	1		3	2	1
2004-20				3	3		3	1	2
2004-21				2	2		1	1	
2004-22	1		1	1	1		4	1	3
QID	13	12	1	57	33	24	58	38	20

Table XXXII. Known sensors by quantity (2005 GCE participants).												
Team	**State**				**Environment**				**Navigation**			
	Total	**K**	**U**	**E**	**Total**	**K**	**U**	**E**	**Total**	**K**	**U**	**E**
2005-16					2	2			3	3		
2005-13					3	3			2	2		
2005-14					3	3			2	2		
2005-06					1	1			2	2		
2005-21					3	3			4	4		
2005-20					3		3		2	2		
2005-01					8	7	1		2	2		
2005-22					2	2			4	4		
2005-23					2	2			4	4		
2005-04					5	5			3	2		1
2005-03					1	1			5	5		
2005-07					2	1	1		1			1
2005-10					4	4			5	5		
2005-05					3	3			3	3		
2005-17					1	1			2	2		
2005-15					2	2			5	5		
2005-08					9	9			3	3		
2005-02					2	2			3	3		
2005-12					1	1			2	2		
2005-19					1	1			3	3		
2005-18					6	6			3	3		
2005-11					1		1		3	2	1	
2005-09					1	1			4	4		
TOTAL					66	60	6		70	67	1	2

Table XXXIII. Known sensors by manufacturer (2005 GCE participants).									
Team	**State**			**Environment**			**Navigation**		
	Total	**K**	**U**	**Total**	**K**	**U**	**Total**	**K**	**U**
2005-16				2	1	1	3		3
2005-13				3	3		2	2	
2005-14				3	3		2	2	
2005-06				1	1		2	1	1
2005-21				3	2	1	4	2	2
2005-20				3		3	2	2	
2005-01				8	7	1	2	2	
2005-22				2	2		4	2	2
2005-23				2	2		4	2	2
2005-04				5	3	2	3	2	1
2005-03				1	1		5	4	1
2005-07				2	1	1	1		1
2005-10				4	3	1	5	5	
2005-05				3	3		3	2	1
2005-17				1	1		2	2	
2005-15				2	2		5	5	
2005-08				9	6	3	3	3	
2005-02				2	1	1	3	3	
2005-12				1	1		2	1	1
2005-19				1	1		3	2	1
2005-18				6	6		3	3	
2005-11				1	1		3	2	1
2005-09				1	1		4	2	2
TOTAL				66	52	14	70	51	19

Table XXXIV. Known sensors by manufacturer and model number (2005 GCE participants).

Team	State			Environment			Navigation		
	Total	K	U	Total	K	U	Total	K	U
2005-01				7	4	3	2	2	
2005-02				1	1		3	2	1
2005-03				1	1		4	4	
2005-04				3	2	1	2	2	
2005-05				3	1	2	2	2	
2005-06				1		1	1	1	
2005-07				1		1			
2005-08				6	6		3	2	1
2005-09				1		1	2	2	
2005-10				3	2	1	5	3	2
2005-11				1		1	2		2
2005-12				1	1		1		1
2005-13				3	2	1	2	1	1
2005-14				3	2	1	2	1	1
2005-15				2	1	1	5	3	2
2005-16				1		1			
2005-17				1		1	2	1	1
2005-18				6	6		3	3	
2005-19				1		1	2	2	
2005-20							2	2	
2005-21				2		2	2	2	
2005-22				2	1	1	2	2	
2005-23				2	1	1	2	2	
TOTAL				52	31	21	51	39	12

Table XXXV. Alphabetical list of acronyms in use throughout this technical report.	
6DOF	Six (6) Degrees-Of-Freedom
AHRS	Attitude and Heading Reference System
AOE	Absolute Optical Encoder
CG	Center of Gravity
COTS	Commercial Off-The-Shelf
CWFM	Continuous Wave Frequency Modulated
DARPA	Defense Advanced Research Projects Agency
DGPS	Differential Global Positioning System
DOD	Department of Defense
DOF	Degrees-Of-Freedom
FMCW	Frequency Modulated Continuous Wave
GCE	Grand Challenge Event
GPS	Global Positioning System
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LIDAR	LIght Detection And Ranging
MEMS	Micro-Electrical Mechanical System
NQE	National Qualification Event
OBD	On-Board Diagnostic
OE	Optical Encoder
OEM	Original Equipment Manufacturer
PC	Personal Computer
QID	Qualification, Inspection, and Demonstration
RADAR	RAdio Detection And Ranging
RDDF	Route Data Definition File
SSF	Static Stability Factor
SUV	Sport Utility Vehicle
WAAS	Wide-Area Augmentation System

Table XXXVI. Major obstacle and path detection sensors by type (2004 QID and GCE participants).

Team	VISION		LIDAR		RADAR		QID	GCE
	Stereo Camera Pair	Other Cameras	Scanning laser range finder	Other LIDAR	Navigation RADAR	Other RADAR		
2004-10			4				Y	7.4
2004-14		**-n-**	4		1		Y	6.7
2004-06	1						Y	6.0
2004-07		3	1		1		Y	5.2
2004-17	2	1	2				Y	1.3
2004-23	2	2	4		2		Y	1.2
2004-13		1	4		1		Y	0.75
2004-04	1	3	2			4	Y	0.45
2004-18	1		1			3	Y	0.20
2004-02	3	2	1		1		Y	0.0
2004-09		1	1				Y	0.0
2004-16		2	2		1		Y	0.0
2004-25		1	3		2		Y	0.0
2004-03		3			1		Y	WD
2004-24	1	2+	1		1		Y	WD
2004-01		2	2				N	–
2004-05	1		2		1		N	–
2004-08		2		5[a]			N	–
2004-11		1	1	1			N	–
2004-12			1				N	–

2004-15			1			1	N	–
2004-19	1			1			N	–
2004-20		1	1		1		N	–
2004-21					1		N	–
2004-22		1					N	–

Note:

[a] Four Laseroptronix LDM 800-RS232 and one Laseroptronix Sea-Lynx LIDAR sensors were in use by Team 2004-08 during the 2004 QID.

Table XXXVII. Major obstacle and path detection sensors by type (2005 GCE participants).							
Team	**VISION**		**LIDAR**		**RADAR**		**GCE[43]**
	Stereo Camera Pair	**Other Cameras**	**Scanning laser range finder**	**Other LIDAR**	**Navigation RADAR**	**Other RADAR**	
2005-16		1	5				131.7
2005-13			5		1		131.7
2005-14			5		1		131.7
2005-06			2				131.7
2005-21	3		3				131.7
2005-20	**-n-**		**-n-**		**-n-**		81.2
2005-01	5	2	4		2+		66.2
2005-22	1		1				43.5
2005-23	1		3				39.4
2005-04	1		4		1+		29.0
2005-03			1				26.2
2005-07	**-n-**		2				25.6
2005-10	1	2	3				23.0
2005-05		1	5				22.4
2005-17			2				17.2
2005-15	1		4				15.9
2005-08	1	2	4			3	14.0
2005-02		1	3				13.6
2005-12	1						9.5
2005-19			3				8.9

2005-18	2	1	5				8.0
2005-11			**-n-**				7.2
2005-09			8				0.7

Table XXXVIII. High-quality obstacle and path detection sensors (2004 QID and GCE participants).					
Team	**STEREO**	**LIDAR**	**RADAR**	**QID**	**GCE**
2004-10		4		Y	7.4
2004-14		4	1	Y	6.7
2004-06				Y	6.0
2004-07		1	1	Y	5.2
2004-17	2	2		Y	1.3
2004-23	2	4	2	Y	1.2
2004-13		4	1	Y	0.75
2004-04	1	2		Y	0.45
2004-18	1	1		Y	0.20
2004-02	3	1	1	Y	0.0
2004-09		1		Y	0.0
2004-16		2	1	Y	0.0
2004-25		3	2	Y	0.0
2004-03			1	Y	WD
2004-24		1	1	Y	WD
2004-01		2		N	–
2004-05	1	2	1	N	–
2004-08				N	–
2004-11		1		N	–
2004-12		1		N	–
2004-15		1		N	–
2004-19				N	–
2004-20		1	1	N	–
2004-21			1	N	–
2004-22				N	–

Table XXXIX. High-quality obstacle and path detection sensors (2005 GCE participants).

Team	STEREO	LIDAR	RADAR	GCE[43]
2005-16		5		131.7
2005-13		5	1	131.7
2005-14		5	1	131.7
2005-06		2		131.7
2005-21	3	3		131.7
2005-20		**-n-**	**-n-**	81.2
2005-01	5	4		66.2
2005-22	1	1		43.5
2005-23	1	3		39.4
2005-04	1	4		29.0
2005-03		1		26.2
2005-07		2		25.6
2005-10		3		23.0
2005-05		5		22.4
2005-17		2		17.2
2005-15	1	4		15.9
2005-08	1	4		14.0
2005-02		3		13.6
2005-12	1			9.5
2005-19		3		8.9
2005-18	2	5		8.0
2005-11		**-n-**		7.2
2005-09		8		0.7

Table XL. Number of teams using high-quality sensors[a].					
2004 GCE			**2005 GCE**		
STEREO	**LIDAR**	**RADAR**	**STEREO**	**LIDAR**	**RADAR**
5/15 (33 percent)	13/15 (87 percent)	9/15 (60 percent)	9/23 (39 percent)	22/23 (96 percent)	3/23 (13 percent)

Note:

[a] The information presented by this table is formatted as follows: number of teams using this type of high-quality sensor / number of teams participating in the 2004 or 2005 GCE (percent of teams using this type of high-quality sensor).

Table XLI. Number of high-quality sensors in use[a].					
2004 GCE			**2005 GCE**		
STEREO	**LIDAR**	**RADAR**	**STEREO**	**LIDAR[b]**	**RADAR[c]**
9/5 (1.8)	30/13 (2.3)	11/9 (1.2)	16/9 (1.8)	72/20 (3.6)	2/2 (1.0)

Notes:

[a] The information presented by this table is formatted as follows: number of high-quality sensors of this type in use by teams participating in the 2004 or 2005 GCE / number of teams using this type of high-quality sensor (average number of high-quality sensors of this type in use by each team).

[b] An unknown number of high-quality LIDAR sensors were in use by Teams 2005-11 and 2005-20. See paragraphs VI.B.3.a., V.C.36.a., and V.C.44.a.

[c] An unknown number of high-quality RADAR sensors were in use by Team 2005-20. See paragraphs VI.B.2.a. and V.C.44.b.

Table XLII. Number of high-quality sensors in use by teams which participated in both the 2004 and 2005 GCE.

Team	STEREO	LIDAR	RADAR	Team	STEREO	LIDAR	RADAR
2004-02	3	1	1	2005-01	5	4	
2004-04	1	2		2005-02		3	
2004-06				2005-03		1	
2004-07		1	1	2005-05		5	
2004-08				2005-07		2	
2004-10		4		2005-13		5	1
2004-13		4	1	2005-15	1	4	
2004-16		2	1	2005-17		2	
2004-17	2	2		2005-18	2	5	
2004-18	1	1		2005-20		**-n-**	**-n-**
2004-23	2	4	2	2005-21	3	3	
2004-25		3	2	2005-22	1	1	

Table XLIII. Number of SICK LMS LIDAR sensors in use by teams which participated in the 2004 and 2005 GCE.

LMS	2004	2005
200	2	
211	1	2
220	1	
221	6	11
291		36[a]
Unknown	18	15
TOTAL	28	64

Note:

[a] An unknown number of high-quality LIDAR sensors were in use by Teams 2005-11 and 2005-20. See paragraphs VI.B.3.a., V.C.36.a., and V.C.44.a.

Table XLIV. Navigation sensor integration (2004 QID and GCE participants).						
Team	**COTS Integration**		**Team Integration**		**QID**	**GCE**
	Kalman	**Other**	**Kalman**	**Other**		
2004-10	X				Y	7.4
2004-14			X		Y	6.7
2004-06				X	Y	6.0
2004-07				X	Y	5.2
2004-17				X	Y	1.3
2004-23				X	Y	1.2
2004-13			X		Y	0.75
2004-04	X				Y	0.45
2004-18			X		Y	0.20
2004-02		X			Y	0.0
2004-09				X	Y	0.0
2004-16			X		Y	0.0
2004-25	X				Y	0.0
2004-03	X				Y	WD
2004-24			X		Y	WD
2004-01				X	N	–
2004-05				X	N	–
2004-08	X				N	–
2004-11				X	N	–
2004-12				X	N	–
2004-15			X		N	–
2004-19				X	N	–
2004-20	X				N	–
2004-21[a]					N	–
2004-22	X				N	–

Notes:

[a] GPS only was in use by Team 2004-21. See paragraph VII.B.

Table XLV. Navigation sensor integration (2005 GCE participants).					
Team[a]	COTS Integration		Team Integration		GCE[43]
	Kalman	Other	Kalman	Other	
2005-16			X		131.7
2005-13	X				131.7
2005-14	X				131.7
2005-06	X				131.7
2005-21	X				131.7
2005-20		X			81.2
2005-01		X			66.2
2005-22		X			43.5
2005-23		X			39.4
2005-04			X		29.0
2005-03				X	26.2
2005-07				X	25.6
2005-10	X				23.0
2005-05	X				22.4
2005-17	X				17.2
2005-15			X		15.9
2005-08	X				14.0
2005-02	X				13.6
2005-12			X		9.5
2005-19			X		8.9
2005-18			X		8.0
2005-11	X				7.2
2005-09				X	0.7

Note:

[a] Teams are in decreasing order of number of miles of the 2005 GCE course completed. Grey shading denotes teams which completed less than 25 percent of the 2005 GCE course (32.9 miles).

Table XLVI. Navigation sensor integration strategies and Kalman filter usage by teams which participated in both the 2004 and 2005 GCE.

Team[a]	COTS Integration		Team Integration		Team	COTS Integration		Team Integration	
	K[b]	O[c]	K	O		K	O	K	O
2004-10	X				2005-13	X			
2004-23				X	2005-21	X			
2004-18			X		2005-20		X		
2004-02		X			2005-01		X		
2004-25	X				2005-22		X		
2004-06				X	2005-03				X
2004-08	X				2005-07				X
2004-07				X	2005-05	X			
2004-16			X		2005-17	X			
2004-13			X		2005-15			X	
2004-04	X				2005-02	X			
2004-17				X	2005-18			X	

Notes:

[a] Teams are in decreasing order of number of miles of the 2005 GCE course completed. Grey shading denotes teams which completed less than 25 percent of the 2005 GCE course (32.9 miles).

[b] "K" denotes use of a Kalman filter to integrate navigation sensors.

[c] "O" denotes independent implementation of an other sensor fusion strategy.

Table XLVII. Navigation sensor integration strategies in use by teams which participated in the 2004 or 2005 GCE.		
	COTS Integration	**Team Integration**
2004 (15 teams)	5 (33.3 percent)	10 (66.7 percent)
2005 (23 teams)	14 (60.9 percent)	9 (39.1 percent)

Table XLVIII. Kalman filter usage by teams which participated in the 2004 or 2005 GCE.	
2004 (15 teams)	9 (60.0 percent)
2005 (23 teams)	16 (69.6 percent)

Table XLIX. COTS integration using a Kalman filter by teams which participated in the 2004 or 2005 GCE.	
2004 (15 teams)	4 (26.6 percent)
2005 (23 teams)	10 (43.5 percent)

Table L. Navigation sensor integration strategies in use by teams which participated in both the 2004 and 2005 GCE.		
	COTS Integration	**Team Integration**
2004	5 (41.7 percent)	7 (58.3 percent)
2005	8 (66.7 percent)	4 (33.3 percent)

Table LI. Kalman filter usage by teams which participated in both the 2004 and 2005 GCE.	
2004	7 (58.3 percent)
2005	7 (58.3 percent)

Table LII. COTS integration using a Kalman filter by teams which participated in both the 2004 and 2005 GCE.	
2004	4 (33.3 percent)
2005	5 (41.7 percent)

Table LIII. Stopping distance for selected values of v and μ_k.

v, mph	Stopping distance (d_s), m (ft), for μ_k =											
	0.1	**0.2**	**0.3**	**0.33**	**0.4**	**0.5**	**0.6**	**0.65**	**0.7**	**0.73**	**0.8**	**0.9**
5	2.6 (8.4)	1.3 (4.2)	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
10	10.2 (33.4)	5.1 (16.7)	3.4 (11.1)	3.1 (10.1)	2.6 (8.4)	2.0 (6.7)	1.7 (5.6)	1.6 (5.1)	1.5 (4.8)	1.4 (4.6)	1.3 (4.2)	1.1 (3.7)
15	22.9 (75.2)	11.5 (37.6)	7.7 (25.1)	6.9 (22.8)	5.7 (18.8)	4.6 (15.0)	3.8 (12.5)	3.5 (11.6)	3.3 (10.7)	3.2 (10.4)	2.9 (9.4)	2.6 (8.4)
20	40.7 (133.6)	20.4 (66.8)	13.6 (44.5)	12.3 (40.5)	10.2 (33.4)	8.1 (26.7)	6.8 (22.3)	6.3 (20.6)	5.8 (19.1)	5.6 (18.4)	5.1 (16.7)	4.5 (14.8)
25	63.6 (208.8)	31.8 (104.4)	21.2 (69.6)	19.3 (63.3)	15.9 (52.2)	12.7 (41.8)	10.6 (34.8)	9.8 (32.1)	9.1 (29.8)	8.8 (28.8)	8.0 (26.1)	7.1 (23.2)
30	91.6 (300.6)	45.8 (150.3)	30.5 (100.2)	27.8 (91.1)	22.9 (75.2)	18.3 (60.1)	15.3 (50.1)	14.1 (46.2)	13.1 (42.9)	12.6 (41.5)	11.5 (37.6)	10.2 (33.4)
35	124.7 (409.2)	62.4 (204.6)	41.6 (136.4)	37.8 (124.0)	31.2 (102.3)	24.9 (81.8)	20.8 (68.2)	19.2 (63.0)	17.8 (58.5)	17.2 (56.4)	15.6 (51.1)	13.9 (45.5)
40	162.9 (534.4)	81.4 (267.2)	54.3 (178.1)	49.4 (162.0)	40.7 (133.6)	32.6 (106.9)	27.2 (89.1)	25.1 (82.2)	23.3 (76.3)	22.5 (73.7)	20.4 (66.8)	18.1 (59.4)
45	206.2 (676.4)	103.1 (338.2)	68.7 (225.5)	62.5 (205.0)	51.5 (169.1)	41.2 (135.3)	34.4 (112.7)	31.7 (104.1)	29.4 (96.6)	28.4 (93.3)	25.8 (84.5)	22.9 (75.2)
50	254.5 (835.1)	127.3 (417.5)	84.9 (278.4)	77.1 (253.0)	63.6 (208.8)	50.9 (167.0)	42.4 (139.2)	39.2 (128.5)	36.4 (119.3)	35.1 (115.2)	31.8 (104.4)	28.3 (92.8)
55	[b]	154.0 (505.2)	102.7 (336.8)	93.3 (306.2)	77.0 (252.6)	61.6 (202.1)	51.3 (168.4)	47.4 (155.4)	44.0 (144.3)	42.5 (139.4)	38.5 (126.3)	34.2 (112.3)
60	[b]	183.2 (601.2)	122.2 (400.8)	111.1 (364.4)	91.6 (300.6)	73.3 (240.5)	61.1 (200.4)	56.4 (185.0)	52.4 (171.8)	50.6 (165.9)	45.8 (150.3)	40.7 (133.6)

Notes:

[a] Stopping distance is less than 1.0 m (3.3 ft).

[b] Stopping distance is greater than 304.8 m (1000.0 ft).

Table LIV. Maximum distance between the path of travel in a constant-radius turn and the left- or right-limit of field-of-view of various RADAR systems.

Turn radius, ft	Maximum distance, d, ft / in		
	Eaton EVT-300 ($\alpha = \pm 6$ degrees)	Epsilon Lambda ELSC71-1A	
		Narrow-scan mode ($\alpha = \pm 8$ degrees)	Wide-scan mode ($\alpha = \pm 20$ degrees)
10	0.05 / 0.6	0.10 / 1.2	0.60 / 7.2
20	0.11 / 1.3	0.19 / 2.3	1.21 / 14.5
30	0.16 / 1.9	0.29 / 3.5	1.81 / 21.7
40	0.22 / 2.6	0.39 / 4.7	2.41 / 28.9
50	0.27 / 3.2	0.49 / 5.9	3.02 / 36.2
60	0.33 / 4.0	0.58 / 7.0	3.62 / 43.4
70	0.38 / 4.6	0.68 / 8.2	4.22 / 50.6
80	0.44 / 5.3	0.78 / 9.4	4.82 / 57.8

Table LV. Comparison of stopping distance to maximum obstacle detection range for VISION, STEREO, LIDAR, and RADAR sensors (2004 QID and GCE participants).						
Team	**Speed, mph**	**Stopping distance, m**	**Sensor**	**Maximum obstacle detection range, m**	**Exceeded**	**Range ratio**
2004-01	45	62.5	Unknown cameras	45.7	Y	1.37
			Unknown SICK LIDAR sensors	61.0	Y	1.02
2004-02	50	77.1	SICK LMS 211-30206	30.0	Y	2.57
			Point Grey Bumblebee stereo camera pairs	50.0	Y	1.54
			FLIR A20M camera	50.0	Y	1.54
			Unknown AVT cameras	50.0	Y	1.54
			Epsilon Lambda ELSC71-1A RADAR (wide-scan mode)	30.0	Y	2.57
			Epsilon Lambda ELSC71-1A RADAR (narrow-scan mode)	110.0	N	0.70
2004-03	25	19.3	Unknown Cognex cameras	100.0	N	0.19
			Unknown other camera	100.0	N	0.19
			Epsilon Lambda ELSC71-1A RADAR (wide-scan mode)	30.0	N	0.64
			Epsilon Lambda ELSC71-1A RADAR (narrow-scan mode)	40.0	N	0.48
2004-04	50	77.1	Unknown Videre Design stereo camera pair	[a]	N/A	N/A
			Unknown other cameras	[a]	N/A	N/A
			Unknown long-range RADAR	30.5	Y	2.53
			SICK LMS 200-30106	30.0	Y	2.57
2004-05	55	93.3	Unknown SICK LIDAR sensors	45.7	Y	2.04
			Unknown Eaton RADAR	91.4	Y	1.02
			Point Grey Bumblebee stereo camera pair	[a]	N/A	N/A

2004-06	60	111.1	Proprietary stereo camera pair	91.4	Y	1.22
2004-07	45	62.5	Unknown SICK LIDAR sensor	10.0	Y	6.25
			Epsilon Lambda ELSC71-1A RADAR (wide-scan mode)	30.0	Y	2.08
			Epsilon Lambda ELSC71-1A RADAR (narrow-scan mode)	40.0	Y	1.56
			FLIR Omega camera	[a]	N/A	N/A
			Sony DFW-VL500 cameras	[a]	N/A	N/A
2004-08	55	93.3	Laseroptronix LDM 800-RS232	400.0	N	0.23
			Laseroptronix Sea-Lynx	350.0	N	0.27
			Cohu 1330 cameras	100.0	N	0.93
2004-09	60	111.1	Unknown SICK LIDAR sensor	15.2	Y	7.31
			Unknown camera	12.2	Y	9.11
2004-10	36	40.0	Unknown SICK LIDAR sensors	25.0	Y	1.60
			Riegl LMS-Q140i	75.0	N	0.53
2004-11	60	111.1	Unknown long-range laser ranger	152.4	N	0.73
			Unknown scanning laser range finder	61.0	Y	1.82
			Unknown Omnivision sensor	[a]	N/A	N/A
2004-12	40	49.4	SICK LMS 291-S05	50.0	N	0.99
2004-13	60	111.1	Unknown SICK LIDAR sensors	80.0	Y	1.39
			Unknown camera	100.0	Y	1.11
			Epsilon Lambda ELSC71-1A RADAR (wide-scan mode)	30.0	Y	3.70
			Epsilon Lambda ELSC71-1A RADAR (narrow-scan mode)	110.0	Y	1.01
2004-14	40	49.4	Unknown cameras	100.0	N	0.49
			Unknown SICK LIDAR sensors	80.0	N	0.62

			Epsilon Lambda ELSC71-1A RADAR (wide-scan mode)	30.0	Y	1.65
			Epsilon Lambda ELSC71-1A RADAR (narrow-scan mode)	110.0	N	0.45
2004-15	50	77.1	SICK LMS 211-30206	80.0	N	0.96
			Eaton EVT-300 RADAR	100.0	N	0.77
2004-16	30	27.8	Unknown cameras	90.0	N	0.31
			Unknown RADAR	100.0	N	0.28
			Unknown SICK LIDAR sensors	100.0	N	0.28
2004-17	40	49.4	Point Grey Dragonfly stereo camera pair	30.0	Y	1.65
			SICK LMS 221-30206	30.0	Y	1.65
2004-18	60	111.1	Unknown RADAR	304.8	N	0.36
			SICK LMS 220-30106	30.5	Y	3.64
			Unknown stereo camera pair	91.4	Y	1.22
2004-19	30	27.8	Unknown stereo camera pair	[a]	N/A	N/A
			SICK DME 2000	10.7	Y	2.60
2004-20	40	49.4	SICK LMS 221-30206	45.0	Y	1.10
			Eaton EVT-300 RADAR	50.0	N	0.99
			Unibrain Fire-i 400 camera	[a]	N/A	N/A
2004-21	60	111.1	Epsilon Lambda ELSC71-1A RADAR (wide-scan mode)	30.0	Y	3.70
			Epsilon Lambda ELSC71-1A RADAR (narrow-scan mode)	110.0	Y	1.01
2004-22	60	111.1	Proprietary video system	243.8	N	0.46
2004-23	50	77.1	Unknown SICK LIDAR sensors	40.0	Y	1.93
			Unknown Eaton RADAR sensors	150.0	N	0.51
			Unknown cameras	75.0	Y	1.03

2004-24	25	19.3	Unknown cameras	[a]	N/A	N/A
			Unknown LIDAR sensor	[a]	N/A	N/A
			Unknown Eaton RADAR	[a]	N/A	N/A
2004-25	35	37.8	Unknown camera	[a]	N/A	N/A
			Unknown SICK LIDAR sensors	[a]	N/A	N/A
			Unknown Eaton RADAR	[a]	N/A	N/A

Note:

[a] Maximum obstacle detection range for this sensor was not reported.

Table LVI. Comparison of stopping distance to maximum effective range for VISION, STEREO, LIDAR, and RADAR sensors (2004 QID and GCE participants).

Team	Speed, mph	Stopping distance, m	Sensor	Maximum effective range, m	Exceeded	Range ratio
2004-01	45	62.5	Unknown cameras	70.0	N	0.89
			Unknown SICK LIDAR sensors	20.0	Y	3.13
2004-02	50	77.1	SICK LMS 211-30206	20.0	Y	3.86
			Point Grey Bumblebee stereo camera pairs	70.0	Y	1.10
			FLIR A20M camera	70.0	Y	1.10
			Unknown AVT cameras	70.0	Y	1.10
			Epsilon Lambda ELSC71-1A RADAR	50.0	Y	1.54
2004-03	25	19.3	Unknown Cognex cameras	70.0	N	0.28
			Unknown other camera	70.0	N	0.28
			Epsilon Lambda ELSC71-1A RADAR	50.0	N	0.39
2004-04	50	77.1	Unknown Videre Design stereo camera pair	70.0	Y	1.10
			Unknown other cameras	70.0	Y	1.10
			Unknown long-range RADAR	50.0	Y	1.54
			SICK LMS 200-30106	20.0	Y	3.86
2004-05	55	93.3	Unknown SICK LIDAR sensors	20.0	Y	4.67
			Unknown Eaton RADAR	50.0	Y	1.87
			Point Grey Bumblebee stereo camera pair	70.0	Y	1.33
2004-06	60	111.1	Proprietary stereo camera pair	70.0	Y	1.59
2004-07	45	62.5	Unknown SICK LIDAR sensor	20.0	Y	3.13

			Epsilon Lambda ELSC71-1A RADAR	50.0	Y	1.25
			FLIR Omega camera	70.0	N	0.89
			Sony DFW-VL500 cameras	70.0	N	0.89
2004-08	55	93.3	Laseroptronix LDM 800-RS232	20.0	Y	4.67
			Laseroptronix Sea-Lynx	70.0	Y	1.33
			Laseroptronix Sea-Lynx	40.0	Y	2.33
			Cohu 1330 cameras	70.0	Y	1.33
2004-09	60	111.1	Unknown SICK LIDAR sensor	20.0	Y	5.56
			Unknown camera	70.0	Y	1.59
2004-10	36	40.0	Unknown SICK LIDAR sensors	20.0	Y	2.00
			Riegl LMS-Q140i	40.0	N	1.00
2004-11	60	111.1	Unknown long-range laser ranger	40.0	Y	2.78
			Unknown scanning laser range finder	20.0	Y	5.56
			Unknown Omnivision sensor	70.0	Y	1.59
2004-12	40	49.4	SICK LMS 291-S05	20.0	Y	2.47
2004-13	60	111.1	Unknown SICK LIDAR sensors	20.0	Y	5.56
			Unknown camera	70.0	Y	1.59
			Epsilon Lambda ELSC71-1A RADAR	50.0	Y	2.22
2004-14	40	49.4	Unknown cameras	70.0	N	0.71
			Unknown SICK LIDAR sensors	20.0	Y	2.47
			Epsilon Lambda ELSC71-1A RADAR	50.0	N	0.99
2004-15	50	77.1	SICK LMS 211-30206	20.0	Y	3.86
			Eaton EVT-300 RADAR	50.0	Y	1.54

2004-16	30	27.8	Unknown cameras	70.0	N	0.40
			Unknown RADAR	50.0	N	0.56
			Unknown SICK LIDAR sensors	20.0	Y	1.39
2004-17	40	49.4	Point Grey Dragonfly stereo camera pair	70.0	N	0.71
			SICK LMS 221-30206	20.0	Y	2.47
2004-18	60	111.1	Unknown RADAR	50.0	Y	2.22
			SICK LMS 220-30106	20.0	Y	5.56
			Unknown stereo camera pair	70.0	Y	1.59
2004-19	30	27.8	Unknown stereo camera pair	70.0	N	0.40
			SICK DME 2000	20.0	Y	1.39
2004-20	40	49.4	SICK LMS 221-30206	20.0	Y	2.47
			Eaton EVT-300 RADAR	50.0	N	0.99
			Unibrain Fire-i 400 camera	70.0	N	0.71
2004-21	60	111.1	Epsilon Lambda ELSC71-1A RADAR	50.0	Y	2.22
2004-22	60	111.1	Proprietary video system	70.0	Y	1.59
2004-23	50	77.1	Unknown SICK LIDAR sensors	20.0	Y	3.86
			Unknown Eaton RADAR	50.0	Y	1.54
			Unknown cameras	70.0	Y	1.10
2004-24	25	19.3	Unknown cameras	70.0	N	0.28
			Unknown LIDAR sensor	20.0	N	0.97
			Unknown Eaton RADAR	50.0	N	0.39
2004-25	35	37.8	Unknown camera	70.0	N	0.54
			Unknown SICK LIDAR sensors	20.0	Y	1.89

			Unknown Eaton RADAR	50.0	N	0.76

Table LVII. Field-of-view limitations for VISION, STEREO, LIDAR, and RADAR sensors (2004 QID and GCE participants).							
Team	**Challenge vehicle width, m**	**Sensor**	**Field-of-view, degrees**	**Lane width, m**	**Maximum allowed turn radius, m**	**Number of turns exceeding**	**Lateral obstacle detection distance, m**
2004-01	1.8	Unknown cameras	[a]				
		Unknown SICK LIDAR sensors	[a]				
2004-02	1.8	SICK LMS 211-30206	[a]				
		Point Grey Bumblebee stereo camera pairs	[a]				
		FLIR A20M camera	[a]				
		Unknown AVT cameras	[a]				
		Epsilon Lambda ELSC71-1A RADAR (wide-scan mode)	[a]				
		Epsilon Lambda ELSC71-1A RADAR (narrow-scan mode)	±8	21.7	93.9	41	0.40
2004-03	0.5	Unknown Cognex cameras	[b]				
		Unknown other camera	[b]				
		Epsilon Lambda ELSC71-1A RADAR (wide-scan mode)	[a]				
		Epsilon Lambda ELSC71-1A RADAR (narrow-scan mode)	±8	11.2	23.5	0	[c]
2004-04	1.6	Unknown Videre Design stereo camera pair	[a]				
		Unknown other cameras	[b]				
		Unknown long-range RADAR	[b]				
		SICK LMS 200-30106	[a]				
2004-05	2.2	Unknown SICK LIDAR sensors	[a]				
		Unknown Eaton RADAR	±6	19.2	203.9	182	0.25

		Point Grey Bumblebee stereo camera pair	b				
2004-06	1.9	Proprietary stereo camera pair	b				
2004-07	2.0	Unknown SICK LIDAR sensor	a				
		Epsilon Lambda ELSC71-1A RADAR (wide-scan mode)	a				
		Epsilon Lambda ELSC71-1A RADAR (narrow-scan mode)	±8	17.6	103.0	53	0.40
		FLIR Omega camera	b				
		Sony DFW-VL500 cameras	b				
2004-08	2.2	Laseroptronix LDM 800-RS232	d				
		Laseroptronix Sea-Lynx	±3.75	13.0	508.7	474	0.10
		Cohu 1330 cameras	b				
2004-09	2.0	Unknown SICK LIDAR sensor	a				
		Unknown camera	a				
2004-10	2.1	Unknown SICK LIDAR sensors	a				
		Riegl LMS-Q140i	a				
2004-11	2.4	Unknown long-range laser ranger	d				
		Unknown scanning laser range finder	a				
		Unknown Omnivision sensor	b				
2004-12	1.3	SICK LMS 291-S05	a				
2004-13	1.5	Unknown SICK LIDAR sensors	a				
		Unknown camera	b				
		Epsilon Lambda ELSC71-1A RADAR (wide-scan mode)	a				
		Epsilon Lambda ELSC71-1A RADAR (narrow-scan mode)	±8	30.9	78.3	31	0.40
2004-14	1.8	Unknown cameras	b				

		Unknown SICK LIDAR sensors	[a]				
		Epsilon Lambda ELSC71-1A RADAR (wide-scan mode)	[a]				
		Epsilon Lambda ELSC71-1A RADAR (narrow-scan mode)	±8	30.9	91.5	40	0.40
2004-15	1.8	SICK LMS 211-30206	[a]				
		Eaton EVT-300 RADAR	±6	16.2	163.4	124	0.25
2004-16	1.5	Unknown cameras	[b]				
		Unknown RADAR	[b]				
		Unknown SICK LIDAR sensors	[a]				
2004-17	2.1	Point Grey Dragonfly stereo camera pair	[a]				
		SICK LMS 221-30206	[a]				
2004-18	1.4	Unknown RADAR	±6	23.4	125.3	76	0.25
		SICK LMS 220-30106	[a]				
		Unknown stereo camera pair	[b]				
2004-19	1.8	Unknown stereo camera pair	[a]				
		SICK DME 2000	[d]				
2004-20	2.0	SICK LMS 221-30206	[a]				
		Eaton EVT-300 RADAR	±6	10.4	182.5	147	0.25
		Unibrain Fire-i 400 camera	[b]				
2004-21	1.2	Epsilon Lambda ELSC71-1A RADAR (wide-scan mode)	[a]				
		Epsilon Lambda ELSC71-1A RADAR (narrow-scan mode)	±8	30.9	62.5	19	0.40
2004-22	1.3	Proprietary video system	[a]				
2004-23	2.5	Unknown SICK LIDAR sensors	[a]				
		Unknown Eaton RADAR sensors	±6	16.2	227.1	206	0.25

		Unknown cameras	b				
2004-24	1.8	Unknown cameras	b				
		Unknown LIDAR sensor	a				
		Unknown Eaton RADAR	±6	4.1	166.8	128	0.25
2004-25	1.4	Unknown camera	b				
		Unknown SICK LIDAR sensors	a				
		Unknown Eaton RADAR	±7	9.3	95.3	42	0.34

Notes:

[a] The field-of-view of this sensor equaled or exceeded 40º. As a result, there was no field-of-view limitation. "Lane width", "Maximum allowed turn radius", "Number of turns exceeding", and "Lateral obstacle detection distance" were not calculated.

[b] The field-of-view of this sensor was not reported.

[c] "Lateral obstacle detection distance" exceeded one-half the challenge vehicle width. As a result, there was no field-of-view limitation.

[d] This sensor has no field-of-view.

Table LVIII. Comparison of stopping distance to maximum obstacle detection range for VISION, STEREO, LIDAR, and RADAR sensors (2005 GCE participants).

Team	Speed, mph	Stopping distance, m	Sensor	Maximum obstacle detection range, m	Exceeded	Range ratio
2005-01	50[a]	77.1	Unknown AVT camera	45.7	Y	1.69
			FLIR A20M camera	45.7	Y	1.69
			Point Grey Bumblebee stereo camera pairs	45.7	Y	1.69
			Unknown Eaton RADAR	100.6	N	0.77
			Unknown RADAR	100.6	N	0.77
			Amphitech OASys RADAR	182.9	N	0.42
			SICK LMS 211-30206	82.3	N	0.94
			Unknown SICK LIDAR sensors	82.3	N	0.94
2005-02	50[a]	77.1	SICK LMS 291-S05	[b]		
			Unknown camera	[b]		
2005-03	50[a]	77.1	Proprietary LIDAR sensor	[b]		
2005-04	50[a]	77.1	SICK LMS 221-30206	80.0	N	0.96
			Eaton EVT-300 RADAR	110.0	N	0.70
			Proprietary RADAR	50.0	Y	1.54
			Unknown stereo camera pair	45.0	Y	1.71
2005-05	50[a]	77.1	Unknown SICK LIDAR sensors	80.0	N	0.96
			Mobileye ACP5 camera	[b]		
2005-06	50[a]	77.1	Unknown SICK LIDAR sensors	50.0	Y	1.54
2005-07	50[c]	77.1	Unknown SICK LIDAR sensors	[b]		

			Unknown stereo camera pair	[b]		
2005-08	50[a]	77.1	Riegl LMS-Q120	30.0	Y	2.57
			SICK LMS 291-S14	[b]		
			SICK LMS 211-30106	[b]		
			Delphi Forewarn ACC3 RADAR	152.4	N	0.51
			Sony DFW-VL500 stereo camera pair	[b]		
			Unknown cameras	[b]		
2005-09	50[a]	77.1	Unknown SICK LIDAR sensors	40.0	Y	1.93
2005-10	50	77.1	Unknown SICK LIDAR sensors	30.0	Y	2.57
			Cognex DVT 542C cameras	40.0	Y	1.93
			Unknown stereo camera pair	35.0	Y	2.20
			Optech ILRIS-3D	500.0	N	0.15
2005-11	50[a]	77.1	Unknown SICK LIDAR sensors	[b]		
2005-12	50[a]	77.1	Point Grey Bumblebee stereo camera pair	15.2	Y	5.07
2005-13	35	37.8	Riegl LMS-Q140i	150.0	N	0.25
			Unknown SICK LIDAR sensors	50.0	N	0.76
			Navtech DS2000 RADAR	70.0	N	0.54
2005-14	35	37.8	Riegl LMS-Q140i	150.0	N	0.25
			Unknown SICK LIDAR sensors	50.0	N	0.76
			Navtech DS2000 RADAR	70.0	N	0.54
2005-15	50	77.1	Unknown SICK LIDAR sensors	80.0	N	0.96
			Proprietary stereo camera pair	25.0	Y	3.08
2005-16	35	37.8	Unknown SICK LIDAR sensors	25.0	Y	1.51

			Unknown camera	[b]		
2005-17	25	19.3	Unknown SICK LIDAR sensors	25.0	N	0.77
2005-18	25	19.3	SICK LMS 221-30206	80.0	N	0.24
			SICK LMS 291-S14	80.0	N	0.24
			SICK LMS 291-S05	80.0	N	0.24
			Riegl LMS-Q120i	65.0	N	0.30
			Point Grey Dragonfly cameras	[b]		
2005-19	50[a]	77.1	Unknown SICK LIDAR sensors	80.0	N	0.96
2005-20	50	77.1	Unknown LIDAR sensor(s)	61.0	Y	1.26
			Unknown RADAR	121.9	N	0.63
			Unknown stereo camera pair(s)	61.0	Y	1.26
2005-21	50	77.1	Unknown SICK LIDAR sensors	[b]		
			Unknown Ibeo LIDAR sensor	80.0	N	0.96
			Unknown cameras	[b]		
2005-22	25	19.3	Unknown SICK LIDAR sensor	40.0	N	0.48
			Point Grey Bumblebee stereo camera pair	40.0	N	0.48
2005-23	25	19.3	Unknown SICK LIDAR sensors	[b]		
			Point Grey Bumblebee stereo camera pair	[b]		

Notes:

[a] Challenge vehicle top speed was not reported. The 2005 GCE course-wide speed limit of 50 mph is used herein.

[b] Maximum obstacle detection range for this sensor was not reported.

[c] The Team 2005-07 technical proposal was not available for review. As a result, the 2005 GCE course-wide speed limit of 50 mph is used herein.

Table LIX. Comparison of stopping distance to maximum effective range for VISION, STEREO, LIDAR, and RADAR sensors (2005 GCE participants).

Team	Speed, mph	Stopping distance, m	Sensor	Maximum effective range, m	Exceeded	Range ratio
2005-01	50[a]	77.1	Unknown AVT camera	70.0	Y	1.10
			FLIR A20M camera	70.0	Y	1.10
			Point Grey Bumblebee stereo camera pairs	70.0	Y	1.10
			Unknown Eaton RADAR	50.0	Y	1.54
			Unknown RADAR	50.0	Y	1.54
			Amphitech OASys RADAR	50.0	Y	1.54
			SICK LMS 211-30206	20.0	Y	3.86
			Unknown SICK LIDAR sensors	20.0	Y	3.86
2005-02	50[a]	77.1	SICK LMS 291-S05	20.0	Y	3.86
			Unknown camera	70.0	Y	1.10
2005-03	50[a]	77.1	Proprietary LIDAR sensor	20.0	Y	3.86
2005-04	50[a]	77.1	SICK LMS 221-30206	20.0	Y	3.86
			Eaton EVT-300 RADAR	50.0	Y	1.54
			Proprietary RADAR	50.0	Y	1.54
			Unknown stereo camera pair	70.0	Y	1.10
2005-05	50[a]	77.1	Unknown SICK LIDAR sensors	20.0	Y	3.86
			Mobileye ACP5 camera	70.0	Y	1.10
2005-06	50[a]	77.1	Unknown SICK LIDAR sensors	20.0	Y	3.86
2005-07	50[b]	77.1	Unknown SICK LIDAR sensors	20.0	Y	3.86

			Unknown stereo camera pair	70.0	Y	1.10
2005-08	50[a]	77.1	Riegl LMS-Q120	40.0	Y	1.93
			SICK LMS 291-S14	20.0	Y	3.86
			SICK LMS 211-30106	20.0	Y	3.86
			Delphi Forewarn ACC3 RADAR	50.0	Y	1.54
			Sony DFW-VL500 stereo camera pair	70.0	Y	1.10
			Unknown cameras	70.0	Y	1.10
2005-09	50[a]	77.1	Unknown SICK LIDAR sensors	20.0	Y	3.86
2005-10	50	77.1	Unknown SICK LIDAR sensors	20.0	Y	3.86
			Cognex DVT 542C cameras	70.0	Y	1.10
			Unknown stereo camera pair	70.0	Y	1.10
			Optech ILRIS-3D	40.0	Y	1.93
2005-11	50[a]	77.1	Unknown SICK LIDAR sensors	20.0	Y	3.86
2005-12	50[a]	77.1	Point Grey Bumblebee stereo camera pair	70.0	Y	1.10
2005-13	35	37.8	Riegl LMS-Q140i	40.0	N	0.95
			Unknown SICK LIDAR sensors	20.0	Y	1.89
			Navtech DS2000 RADAR	50.0	N	0.76
2005-14	35	37.8	Riegl LMS-Q140i	40.0	N	0.95
			Unknown SICK LIDAR sensors	20.0	Y	1.89
			Navtech DS2000 RADAR	50.0	N	0.76
2005-15	50[a]	77.1	Unknown SICK LIDAR sensors	20.0	Y	3.86
			Proprietary stereo camera pair	70.0	Y	1.10
2005-16	35	37.8	Unknown SICK LIDAR sensors	20.0	Y	1.89

			Unknown camera	70.0	N	0.54
2005-17	25	19.3	Unknown SICK LIDAR sensors	20.0	N	0.97
2005-18	25	19.3	SICK LMS 221-30206	20.0	Y	2.47
			SICK LMS 291-S14	20.0	Y	2.47
			SICK LMS 291-S05	20.0	Y	2.47
			Riegl LMS-Q120i	40.0	Y	1.24
			Point Grey Dragonfly cameras	70.0	N	0.71
2005-19	50[a]	77.1	Unknown SICK LIDAR sensors	20.0	Y	3.86
2005-20	50	77.1	Unknown LIDAR sensor(s)	20.0	Y	3.86
			Unknown RADAR	50.0	Y	1.54
			Unknown stereo camera pair(s)	70.0	Y	1.10
2005-21	50	77.1	Unknown SICK LIDAR sensors	20.0	Y	3.86
			Unknown Ibeo LIDAR sensor	40.0	Y	1.93
			Unknown cameras	70.0	Y	1.10
2005-22	25	19.3	Unknown SICK LIDAR sensor	20.0	N	0.97
			Point Grey Bumblebee stereo camera pair	70.0	N	0.28
2005-23	25	19.3	Unknown SICK LIDAR sensors	20.0	N	0.97
			Point Grey Bumblebee stereo camera pair	70.0	N	0.28

Notes:

[a] Challenge vehicle top speed was not reported. The 2005 GCE course-wide speed limit of 50 mph is used herein.

[b] The Team 2005-07 technical proposal was not available for review. As a result, the 2005 GCE course-wide speed limit of 50 mph is used herein.

Table LX. Field-of-view limitations for VISION, STEREO, LIDAR, and RADAR sensors (2005 GCE participants).						
Team	**Challenge vehicle width, m**	**Sensor**	**Field-of-view, degrees**	**Lane width, m**	**Maximum allowed turn radius, m**	**Number of turns exceeding**
2005-01	1.8	Unknown AVT camera	[a]			
		FLIR A20M camera	[a]			
		Point Grey Bumblebee stereo camera pairs	[a]			
		Unknown Eaton RADAR	[a]			
		Unknown RADAR	[a]			
		Amphitech OASys RADAR	[a]			
		SICK LMS 211-30206	[a]			
		Unknown SICK LIDAR sensors	[a]			
2005-02	[c]	SICK LMS 291-S05	[a]			
		Unknown camera	[b]			
2005-03	1.9	Proprietary LIDAR sensor	[a]			
2005-04	1.5	SICK LMS 221-30206	[a]			
		Eaton EVT-300 RADAR	±6	16.2	139.1	142
		Proprietary RADAR	[a]			
		Unknown stereo camera pair	[a]			
2005-05	2.0	Unknown SICK LIDAR sensors	[a]			
		Mobileye ACP5 camera	[a]			
2005-06	1.8	Unknown SICK LIDAR sensors	±15	21.4	26.4	7
2005-07	[d]	Unknown SICK LIDAR sensors	[a]			

		Unknown stereo camera pair	d			
2005-08	2.0	Riegl LMS-Q120	a			
		SICK LMS 291-S14	a			
		SICK LMS 211-30106	a			
		Delphi Forewarn ACC3 RADAR	a			
		Sony DFW-VL500 stereo camera pair	a			
		Unknown cameras	a			
2005-09	1.8	Unknown SICK LIDAR sensors	a			
2005-10	1.8	Unknown SICK LIDAR sensors	a			
		Cognex DVT 542C cameras	±15	21.4	26.4	7
		Unknown stereo camera pair	a			
		Optech ILRIS-3D	a			
2005-11	1.2	Unknown SICK LIDAR sensors	a			
2005-12	1.7	Point Grey Bumblebee stereo camera pair	a			
2005-13	2.1	Riegl LMS-Q140i	a			
		Unknown SICK LIDAR sensors	a			
		Navtech DS2000 RADAR	a			
2005-14	2.1	Riegl LMS-Q140i	a			
		Unknown SICK LIDAR sensors	a			
		Navtech DS2000 RADAR	a			
2005-15	1.5	Unknown SICK LIDAR sensors	a			
		Proprietary stereo camera pair	b			
2005-16	1.9	Unknown SICK LIDAR sensors	a			

		Unknown camera	[b]			
2005-17	2.1	Unknown SICK LIDAR sensors	[a]			
2005-18	2.0	SICK LMS 221-30206	[a]			
		SICK LMS 291-S14	[a]			
		SICK LMS 291-S05	[a]			
		Riegl LMS-Q120i	[b]			
		Point Grey Dragonfly cameras	[b]			
2005-19	[c]	Unknown SICK LIDAR sensors	[a]			
2005-20	1.0[e]	Unknown LIDAR sensor(s)	[a]			
		Unknown RADAR	±6	16.2	182.5	193
		Unknown stereo camera pair(s)	[a]			
2005-21	2.5	Unknown SICK LIDAR sensors	[a]			
		Unknown Ibeo LIDAR sensor	[a]			
		Unknown cameras	[b]			
2005-22	1.5	Unknown SICK LIDAR sensor	[a]			
		Point Grey Bumblebee stereo camera pair	[b]			
2005-23	1.5	Unknown SICK LIDAR sensors	[a]			
		Point Grey Bumblebee stereo camera pair	[b]			

Notes:

[a] The field-of-view of this sensor equaled or exceeded 40º. As a result, there was no field-of-view limitation. “Lane width”, “Maximum allowed turn radius”, “Number of turns exceeding”, and “Lateral obstacle detection distance” were not calculated.

[b] The field-of-view of this sensor was not reported. As a result, “Lane width”, “Maximum allowed turn radius”, “Number of turns exceeding”, and “Lateral

obstacle detection distance" were not calculated.

[c] Challenge vehicle width was not reported.

[d] The Team 2005-07 technical proposal was not available for review. As a result, "Lane width", "Maximum allowed turn radius", "Number of turns exceeding", and "Lateral obstacle detection distance" were not calculated.

[e] Challenge vehicle width was not reported. The author estimated the width of the Team 2005-20 challenge vehicle as 2.0 m.

Table LXI. Number of sensors for which stopping distance exceeded maximum obstacle detection range.

	2004 (71 sensors)	2005 (60 sensors)
Number of sensors	34 (48 percent)	16 (27 percent)
Average safety factor	1.61[a]	1.16[b]

Notes:

[a] Maximum obstacle detection ranges for 14 sensors were not reported. Average safety factor was calculated for 57 sensors for which the maximum obstacle detection range was reported.

[b] Maximum obstacle detection ranges for 17 sensors were not reported. Average safety factor was calculated for 43 sensors for which the maximum obstacle detection range was reported.

Table LXII. Number of sensors for which stopping distance exceeded maximum effective range.

	2004 (66 sensors)	2005 (60 sensors)
Number of sensors	46 (70 percent)	49 (82 percent)
Average safety factor	1.88	2.31

Table LXIII. Number of teams for which stopping distance exceeded the maximum obstacle detection range of sensors in use.

Number of teams	2004[a]	2005[b]
All sensors	10 (43 percent)	4 (22 percent)
One or more sensors	7 (30 percent)	6 (33 percent)
No sensors	6 (26 percent)	8 (44 percent)

Notes:

[a] Teams 2004-24 and 2004-25 did not report maximum obstacle detection range for any sensors in use by the team.

[b] Teams 2005-02, 2005-03, 2005-07, 2005-11, and 2005-23 did not report maximum obstacle detection range for any sensors in use by the team.

Table LXIV. Number of teams for which stopping distance exceeded the maximum effective range of sensors in use.

Number of teams	2004	2005
All sensors	14 (56 percent)	16 (70 percent)
One or more sensors	9 (36 percent)	4 (17 percent)
No sensors	2 (8 percent)	3 (13 percent)

Table LXV. Average ratio of stopping distance to range for sensors in use by teams which participated in both the 2004 and 2005 GCE.

Team	Average ratio		Team	Average ratio	
	Maximum obstacle detection range	Maximum effective range		Maximum obstacle detection range	Maximum effective range
2004-10	1.07	1.50	2005-13	0.52	1.20
2004-23	1.16	2.17	2005-21	0.96[a]	2.30
2004-18	1.74	3.12	2005-20	1.05	2.17
2004-02	1.74	1.74	2005-01	1.11	1.96
2004-25	[b]	1.06	2005-22	0.48	0.63
2004-06	1.22	1.59	2005-03	[b]	3.86
2004-08	0.48	2.42	2005-07	[b]	2.48
2004-07	3.30	1.54	2005-05	0.96[a]	2.48
2004-16	0.29	0.78	2005-17	0.77	0.97
2004-13	1.80	3.12	2005-15	2.02	2.48
2004-04	2.55	1.90	2005-02	[b]	2.48
2004-17	1.65	1.59	2005-18	0.26[a]	1.87
AVERAGE	1.55	1.88	AVERAGE	0.90	2.07

Notes:

[a] The team did not report the maximum obstacle detection range for one or more sensors in use by the team.

[b] The team did not report the maximum obstacle detection range for all sensors in use by the team.

Table LXVI. Primary group identity and sponsorship of teams participating in the 2004 QID and GCE.

Team	Primary group identity	Sponsorship						GCE
		Corporate			Academic			
		L	M	E	L	M	E	
2004-10	Academic			X			X	7.4
2004-14	Corporate		X					6.7
2004-06	Individual	X						6.0
2004-07	Individual	X						5.2
2004-17	Academic		X			X		1.3
2004-23	Corporate			X	X			1.2
2004-13	Corporate		X					0.75
2004-04	Academic		X				X	0.45
2004-18	Corporate		X					0.20
2004-02	Individual	X						0.0
2004-09	Academic		X		X			0.0
2004-16	Academic		X			X		0.0
2004-25	Academic		X			X		0.0
2004-03	Academic	X			X			WD
2004-24	Individual							WD
2004-01	Individual	X						–
2004-05	Individual	X						–
2004-08	Individual	X						–
2004-11	Individual	X						–
2004-12	Individual							–
2004-15	Academic	X			X			–
2004-19	Individual	X						–
2004-20	Individual		X					–
2004-21	Individual	X						–
2004-22	Individual							–

Table LXVII. Primary group identity and sponsorship of teams participating in the 2005 GCE.

Team	Primary group identity	Sponsorship						GCE
		Corporate			Academic			
		L	M	E	L	M	E	
2005-16	Academic		X				X	131.7
2005-13	Academic			X			X	131.7
2005-14	Academic			X			X	131.7
2005-06	Individual		X					131.7
2005-21	Corporate			X	X			131.7
2005-20	Corporate		X					81.2
2005-01	Individual	X						66.2
2005-22	Academic		X			X		43.5
2005-23	Academic		X			X		39.4
2005-04	Academic	X					X	29.0
2005-03	Individual	X						26.2
2005-07	Individual	X						25.6
2005-10	Individual	X						23.0
2005-05	Individual	X			X			22.4
2005-17	Academic		X			X		17.2
2005-15	Corporate		X			X		15.9
2005-08	Individual		X					14.0
2005-02	Academic		X				X	13.6
2005-12	Academic	X				X		9.5
2005-19	Academic		X			X		8.9
2005-18	Academic		X			X		8.0
2005-11	Individual	X						7.2
2005-09	Corporate		X					0.7

Table LXVIII. Sponsorship of teams which participated in both the 2004 and 2005 GCE.

Team	Sponsorship						Team	Sponsorship					
	Corporate			Academic				Corporate			Academic		
	L	M	E	L	M	E		L	M	E	L	M	E
2004-10			X			X	2005-13			X			X
2004-23			X	X			2005-21			X	X		
2004-18		X					2005-20		X				
2004-02	X						2005-01	X					
2004-25		X			X		2005-22		X			X	
2004-06	X						2005-03	X					
2004-08	X						2005-07	X					
2004-07	X						2005-05	X			X		
2004-16		X			X		2005-17		X			X	
2004-13		X					2005-15		X			X	
2004-04		X				X	2005-02		X				X
2004-17		X			X		2005-18		X			X	

Table LXIX. Number of preventable failures reported by teams participating in the 2005 GCE.				
Team	**Number of failures reported**			**Preventable failures**
	Controlling intelligence	**System integration**	**Other**	
2005-02		1	1	1
2005-05	1	2		3
2005-06		2	2	2
2005-09		2		2
2005-12		4	1	4
2005-13/14		1	1	1
2005-15		2		1
2005-17		4	1	4
2005-18	2	2		2
2005-19		2		2
2005-22/23		1		1
TOTAL	3	23	6	23

Table LXX. Reported ranges of 2004 challenge vehicles.	
Team	**Range (miles)**
2004-01	350
2004-02	400
2004-03	230
2004-04	300
2004-05	320
2004-06	700[a]
2004-07	500
2004-08	460
2004-09	300
2004-10	"... in excess of 300km..." ([77], p. 4)[b]
2004-11	350
2004-12	250
2004-13	300
2004-14	400
2004-15	300 – 350
2004-16	200
2004-17	250
2004-18	256[c]
2004-19	250
2004-20	250 – 350
2004-21	300
2004-22	350
2004-23	600
2004-24	400
2004-25	300

Notes:

[a] Team 2004-06 did not report the range of the Team 2004-06 challenge vehicle. Team 2004-06 stated: "The vehicle will be retrofitted with an extra fuel cell to provide an additional 50-gallon capacity." ([114], p. 3). Team 2004-06 selected a 2003 Toyota

Tundra (SR5 V8 Access Cab) as challenge vehicle platform. See Table XV. The manufacturer minimum "mileage estimate" for this vehicle is 14 miles per gallon ([258]). The author estimated the range of the Team 2004-06 challenge vehicle was 700 miles.

[b] 300 km is approximately 186.4 miles. Team 2004-10 reported the range of the Team 2004-10 challenge vehicle was "...in excess of [the] prescribed course..." ([77], p. 7). However, the proposed 2004 GCE course length was "approximately 250 miles" ([261]) on October 14, 2003, the date technical proposals were required to be submitted to DARPA, and DARPA did not report the proposed 2004 GCE course length via revision "5 January 2004" of the 2004 GCE rules. See Appendix C. Team 2004-10 submitted several revisions of their technical proposal. The revision published by DARPA was dated April 8, 2004, approximately six months after technical proposals were required to be submitted to DARPA on October 14, 2003.

[c] Team 2004-18 stated: "The vehicle is estimated to get an average of 16 mpg and the 16 gallons of fuel will provide approximately 2560 miles of total range." ([48], p. 10). However, this is in error.

Table LXXI. Electrical power generation strategies for teams which participated in the 2004 GCE.						
Team	**Alternator**	**Alternator and batteries**	**Generator**	**Generator and batteries**	**Platform type[a]**	**GCE**
2004-10				X	4	7.4
2004-14		X			3	6.7
2004-06	X				2	6.0
2004-07				X	2	5.2
2004-17				X	1	1.3
2004-23[b]	X				4	1.2
2004-13			X		3	0.75
2004-04			X		1	0.45
2004-18[c]	X				3	0.20
2004-02		X			1	0.0
2004-09	X				1	0.0
2004-16[d]				X	3	0.0
2004-25				X	3	0.0
2004-03		X			[e]	WD
2004-24				X	5	WD

Notes:

[a] See Table XIV for a description of challenge vehicle platform type.

[b] Team 2004-23 stated: "The diesel engine will supply both driveline power and electrical power for instrumentation and drive-by-wire components." ([159], p. 3). Team 2004-23 did not report a generator or batteries were in use by the team. The author concluded an alternator was in use by Team 2004-23 to generate electrical power.

[c] Team 2004-18 did not report the electrical power generation strategy in use by the team. Team 2004-18 stated: "The stock 649cc single cylinder four-stroke engine running with high-octane pump fuel will supply the power." and "The engine will supply all the power." ([48], p. 2). Team 2004-18 did not report a generator was in use by the team. Team 2004-18 also stated: "Seven sealed lead acid batteries (20 amp-hr) or equivalent are used to operate the engine starter motor and lights when the engine is not running, and the steering, throttle and the choke when the engine is running." ([48],

p. 2). The author concluded an alternator was in use by Team 2004-18 to generate electrical power.

[d] Via Figure 6 ("E-Power Subsystem") of the team technical proposal ([138], p. 9), Team 2004-16 reported one "2300W Generator" was in use by the team to generate electrical power through an UPS separate from the challenge vehicle battery.

[e] Team 2004-03 selected a motorcycle as challenge vehicle platform. See Table XV.

Table LXXII. Electrical power generation strategies for teams which participated in the 2005 GCE.

Team	Alternator	Alternator and batteries	Generator	Generator and batteries	Platform type[a]	GCE[43]
2005-16	X				1	131.7
2005-13			X		4	131.7
2005-14			X		1	131.7
2005-06[b]					1	131.7
2005-21[c]	X				4	131.7
2005-20[d]	X				5	81.2
2005-01		X			1	66.2
2005-22[e]				X	3	43.5
2005-23[e]				X	3	39.4
2005-04			X		3	29.0
2005-03[f]	X				2	26.2
2005-07[g]					1	25.6
2005-10[h]	X				1	23.0
2005-05[i]	X				2	22.4
2005-17			X		3	17.2
2005-15			X		3	15.9
2005-08		X			2	14.0
2005-02[j]		X			5	13.6
2005-12		X			2	9.5
2005-19			X		4	8.9
2005-18				X	[k]	8.0
2005-11		X			3	7.2
2005-09	X				1	0.7

Notes:

[a] See Table XIV for a description of challenge vehicle platform type.

[b] Team 2005-06 was the only team which participated in either the 2004 or 2005 GCE to

select a commercially-available hybrid vehicle as challenge vehicle platform. See Table XVI. This vehicle is therefore unique. See paragraph XIV.B.1.b.i.

[c] Team 2005-21 did not report the electrical power generation strategy in use by the team ([160]). Team 2005-21 participated in the 2005 GCE as Team 2004-23. Team 2004-23 stated: "The diesel engine will supply both driveline power and electrical power for instrumentation and drive-by-wire components." ([159], p. 3). The author considers it likely a similar strategy was in use by Team 2005-21 to generate electrical power and concluded an alternator was in use by the team.

[d] Team 2005-20 did not report the electrical power generation strategy in use by the team ([56]). The author considers it likely an alternator was in use by Team 2005-20 to generate electrical power.

[e] Teams 2005-22 and Team 2005-23 did not report the electrical power generation strategy in use by the teams ([58] and [164]). Although Teams 2005-22 and 2005-23 later stated: "This section includes the details of the base vehicles, power system, drive-by-wire conversion, and network architecture..." ([59], p. 710), the teams did not report the electrical power generation strategy in use by the teams. However, Team 2005-23 failed to complete the 2005 GCE because the challenge vehicle's "on-board generator shut down due to a suspected false low-oil reading.". See paragraph XIII.B.14. In addition, Team 2004-25 reported a generator and batteries were in use by the team. As a result, the author considers it likely a similar strategy was in use by Teams 2005-22 and 2005-23 to generate electrical power, and concluded a generator and batteries were in use by the teams.

[f] Team 2005-03 stated: "The vehicle will be stock except for desert racing tires and a retrofitted extra fuel cell to provide a total fuel capacity of approximately 40 gallons." ([33], p. 4). Throughout their technical proposal, Team 2005-03 reported selecting low-power components. The author concluded an alternator was in use by Team 2005-03 to generate electrical power.

[g] The hyperlink to the Team 2005-07 technical paper hosted by the Archived Grand Challenge 2005 website ([19]) is a hyperlink to the team website, and the author was unable to locate a copy of the Team 2005-07 technical paper on the team website. As a result, the author concluded the technical paper was unavailable for review. See paragraph V.C.32.

[h] Team 2005-10 did not report the electrical power generation strategy in use by the team ([176]). Team 2005-10 stated: "Our vehicle is a commercially available 2001 Nissan Xterra SUV... The rational for this choice was that we didn't want to spend time designing and building a vehicle. We wanted to spend time on the sensory and navigation systems, so we bought a commercial vehicle that was as close as possible to what was needed and modified it in the ways described above." ([176], p. 2). The author concluded an alternator was in use by Team 2005-10 to generate electrical power.

[i] Team 2005-05 did not report the electrical power generation strategy in use by the team ([34]). Team 2005-05 later stated: “Each of our vehicles was a commercially available pickup truck, fitted with electrically actuated steering and throttle, and pneumatically actuated brakes.” ([170], p. 529). Team 2005-05 did not report a generator or batteries were in use by the team. The author concluded an alternator was in use by Team 2005-05 to generate electrical power.

[j] Team 2005-02 did not report the electrical power generation strategy in use by the team ([167]). Team 2005-02 later stated: “The power system consists of two independent 140 A 28 V alternator systems... Each alternator drives a 2400 W continuous, 4800 W peak inverter and is backed up by four deep-cell batteries.” ([50], p. 604).

[k] Team 2005-18 selected a 2005 Ford E-350 Van as challenge vehicle platform. See Table XVI.

Table LXXIII. Manufacturer index[a].

Manufacturer name	Short name
Advanced Micro Devices, Inc.	AMD
ALK Technologies, Inc.	ALK
Allied Vision Technologies GmbH	AVT
AM General, LLC	AM General
American GNC Corp.	AGNC
Amphitech Systems, Inc.	Amphitech
Analog Devices, Inc.	Analog Devices
Applanix Corp.	Applanix
Basler AG	Basler
BEI Technologies, Inc.	BEI
Bendix Commercial Vehicle Systems, LLC	Bendix
Bodine Electric Co.	Bodine Electric
Boeing Co.	Boeing
C&C Technologies, Inc.	C&C Technologies
Caterpillar, Inc.	Caterpillar
Cognex Corp.	Cognex
Cohu, Inc.	Cohu
Crossbow Technology, Inc.	Crossbow
CSI Wireless, Inc.	CSI Wireless
Delphi Corp.	Delphi
DICKEY-john Corp.	DICKEY-john
DVT Corp.	DVT
Eaton Corp.	Eaton
Edmunds, Inc.	Edmunds
The Eigenpoint Co.	Eigenpoint
Electro Switch Corp.	Electro Switch
Epsilon Lambda Electronics Corp.	Epsilon Lambda
FLIR Systems, Inc.	FLIR
Ford Motor Co.	Ford

Garmin, Ltd.	Garmin
General Electric Co.	GE
General Motors Co.	GM
American Honda Motor Co.	Honda
Honeywell International, Inc.	Honeywell
Ibeo Automotive Sensor GmbH	Ibeo
Indigo Systems Corp.	Indigo
Inertial Science, Inc.	ISI
Intel Corp.	Intel
Japan Servo Co.	Japan Servo
Kearfott Corp.	Kearfott
KVH Industries, Inc.	KVH
Laseroptronix AB	Laseroptronix
Litton Industries, Inc.	Litton
Microbotics, Inc.	Microbotics
MiTAC International Corp.	MiTAC
Mobileye, Ltd.	Mobileye
Motion Systems Corp.	Motion Systems
MotorTrend Magazine	MotorTrend
NavCom Technology, Inc.	NavCom
Navtech RADAR, Ltd.	Navtech
Northrop Grumman Corp.	Northrop Grumman
NovAtel, Inc.	NovAtel
OmniSTAR, Inc.	OmniSTAR
Omnivision Technologies, Inc.	Omnivision
Omron Corp.	Omron
Optech, Inc.	Optech
Oshkosh Corp.	Oshkosh
Oxford Technical Solutions, Ltd.	Oxford
PNI Sensor Corp.	PNI
Point Grey Research, Inc.	Point Grey
Preco Electronics	Preco

Recreative Industries, Inc.	Recreative Industries
RIEGL Laser Measurement Systems GmbH	Riegl
Rockwell Automation, Inc.	Rockwell Automation
Rotomotion, LLC	Rotomotion
Science Applications International Corp.	SAIC
SensComp, Inc.	SensComp
SICK AG	SICK
Smart Microwave Sensors GmbH	Smart Microwave
SpaceAge Control, Inc.	SpaceAge
SRI International	SRI
Systron Donner Inertial	Systron Donner
Thales Navigation	Thales Navigation
TOMCAR USA, Inc.	Tomcar
Toyota Motor Corp.	Toyota
Trimble Navigation, Ltd.	Trimble
u-blox AG	u-blox
Ultra Motion	Ultra Motion
Unibrain, Inc.	Unibrain
Vansco Electronics, Inc.	Vansco
Videre Design, LLC	Videre Design

Notes:

[a] Manufacturers are referred to herein by short name. For example, Inertial Sciences, Inc. is referred to as "ISI". In general, the author selected the short name based on manufacturer custom, i.e., the short name by which the manufacturer refers to itself, and not the short names selected by the teams, which were frequently in error.

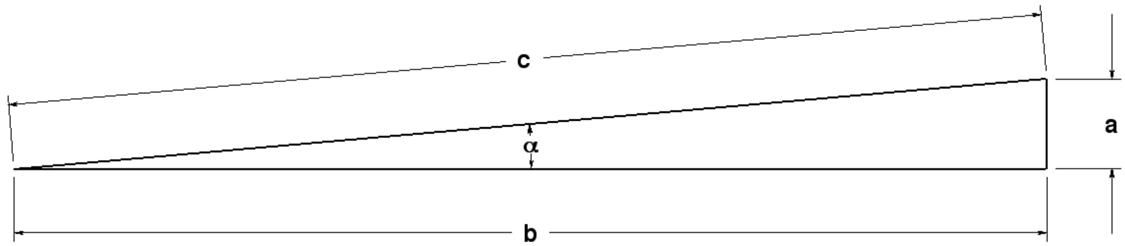

Figure 4. Slope contribution to error in course length.

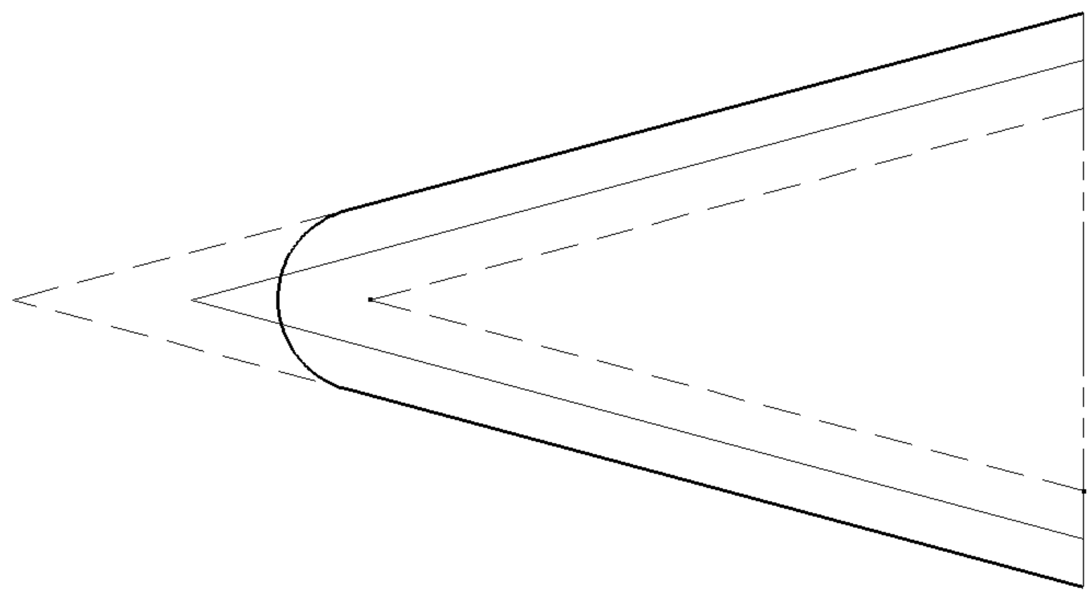

Figure 5. Minimum turn radius based on outside lateral boundary offset.

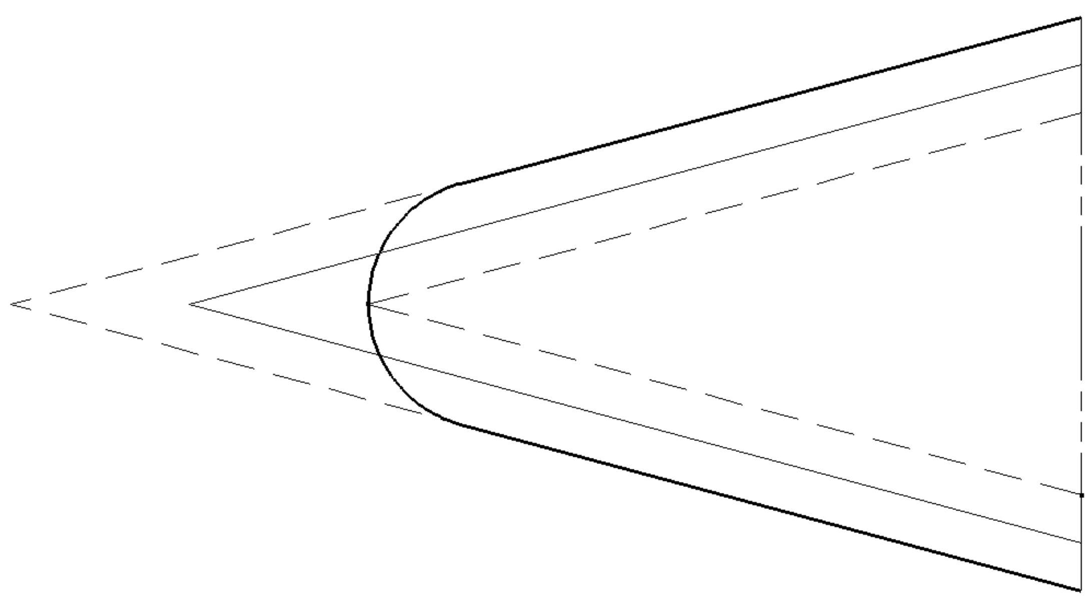

Figure 6. Maximum turn radius based on inside lateral boundary offset.

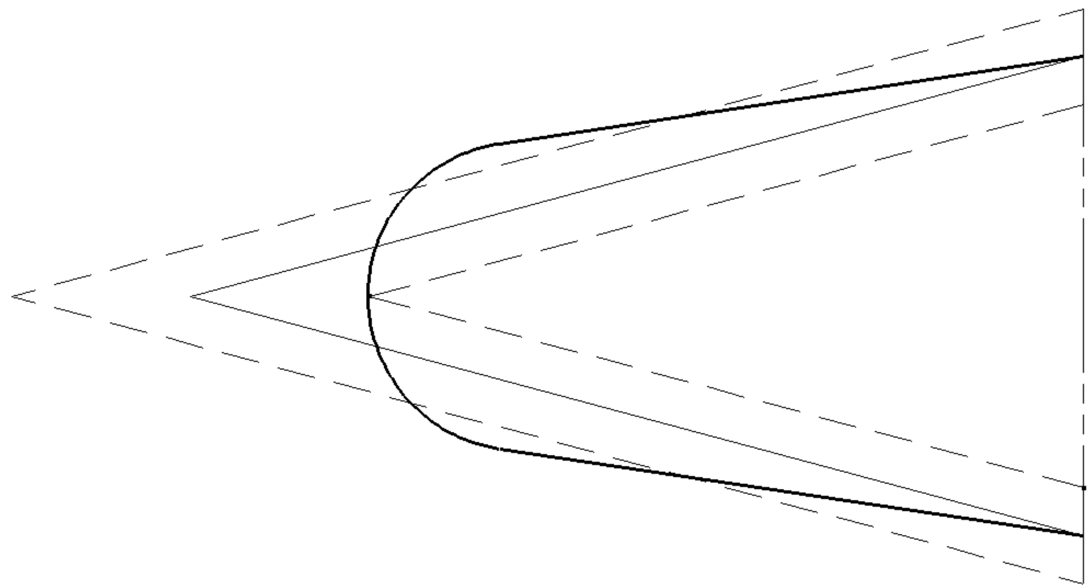

Figure 7. Vehicle exceeds the outside lateral boundary offset to make a turn.

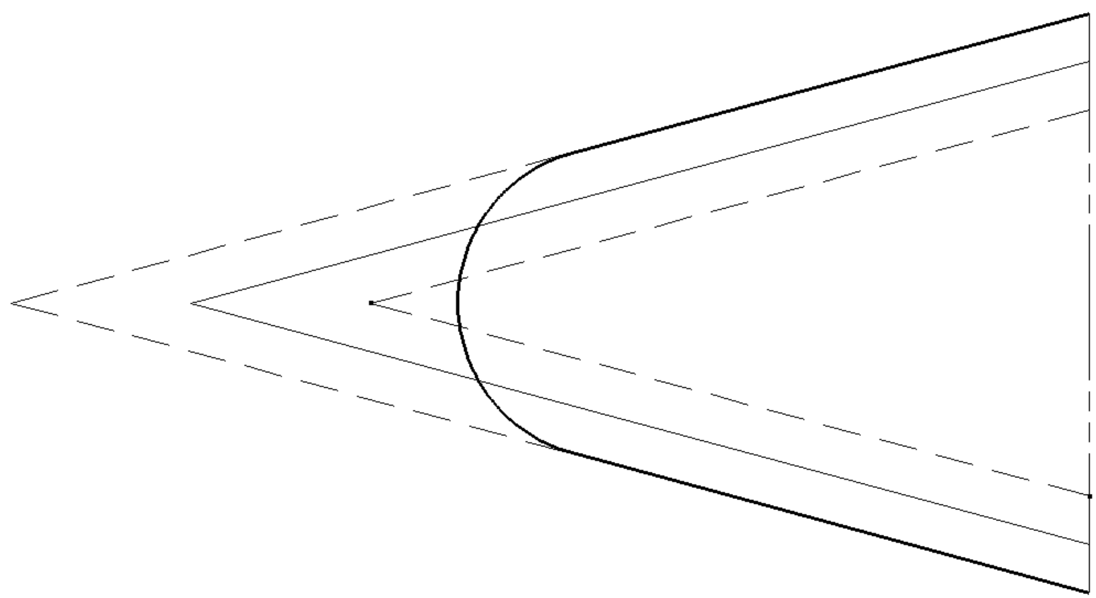

Figure 8. Vehicle exceeds the inside lateral boundary offset to make a turn.

Figure 9. 2004 GCE course superimposed on map view.

Figure 10. 2004 GCE course superimposed on map and satellite view.

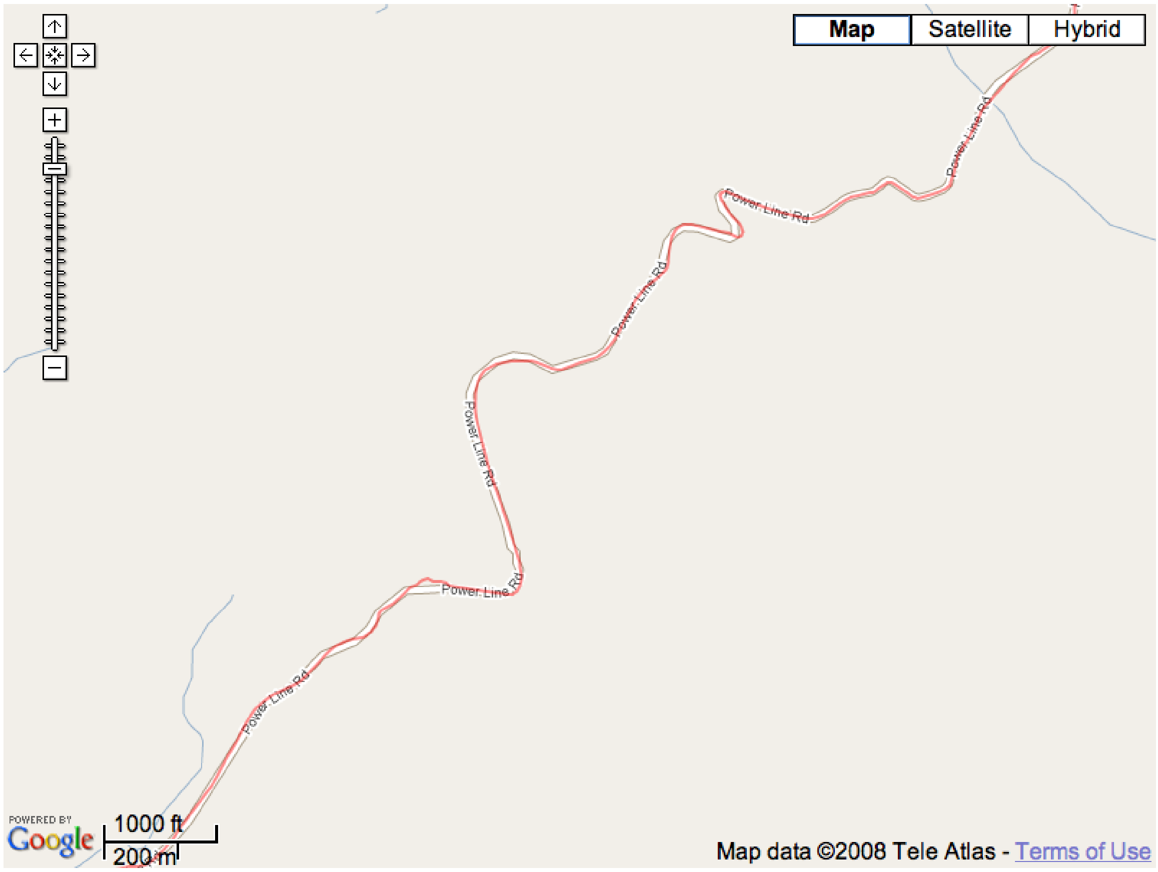

Figure 11. 2004 GCE course superimposed on map view (Powerline Road 1).

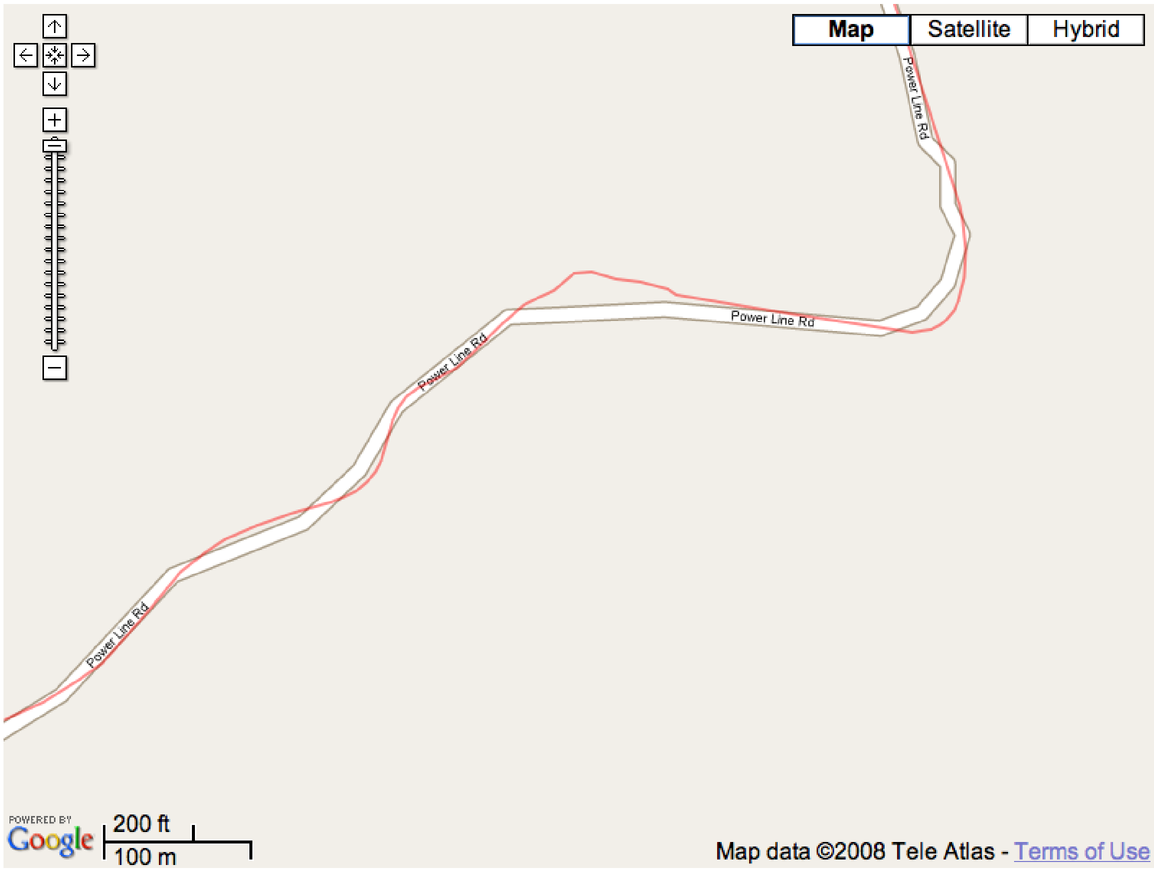

Figure 12. 2004 GCE course superimposed on map view (Powerline Road 1 at increased zoom level).

Figure 13. 2004 GCE course superimposed on map and satellite view (Powerline Road 1 at increased zoom level).

Figure 14. 2004 GCE course superimposed on map view (Interstate 40).

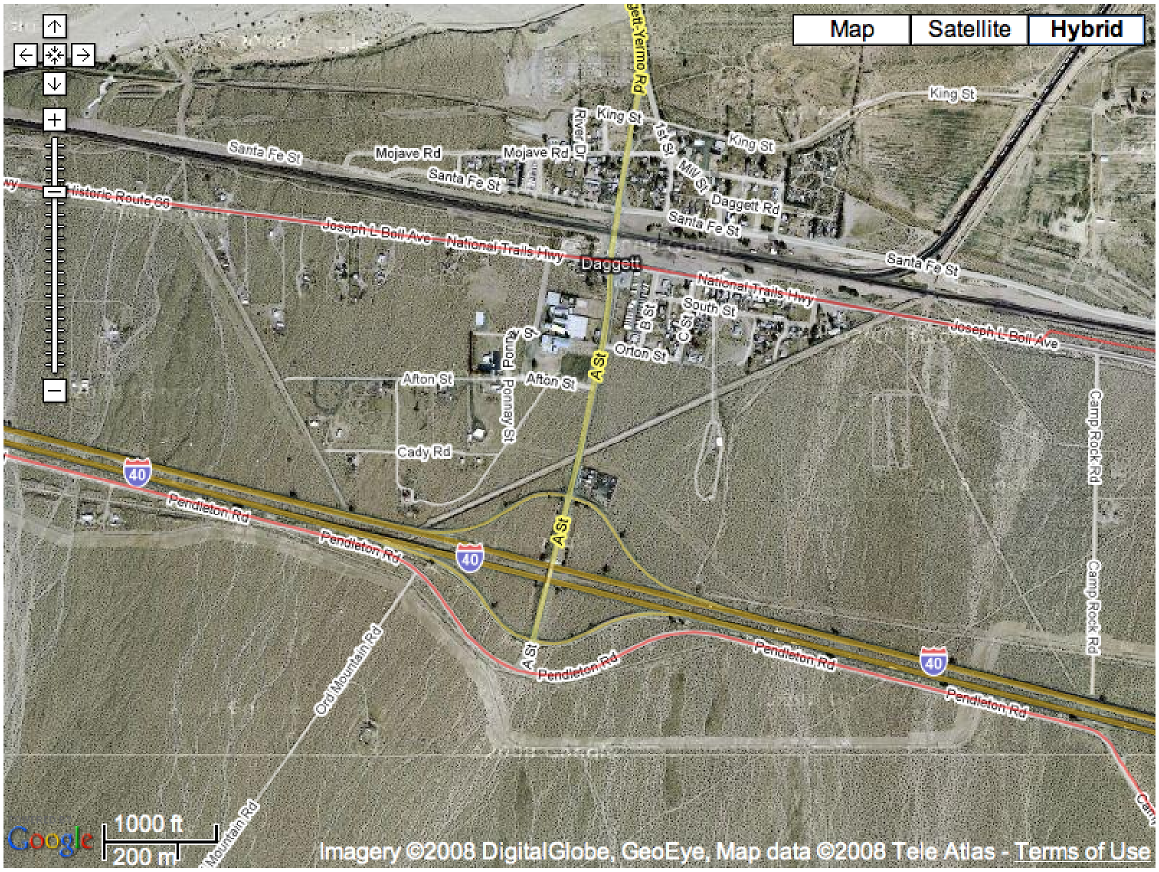

Figure 15. 2004 GCE course superimposed on map and satellite view (Interstate 40).

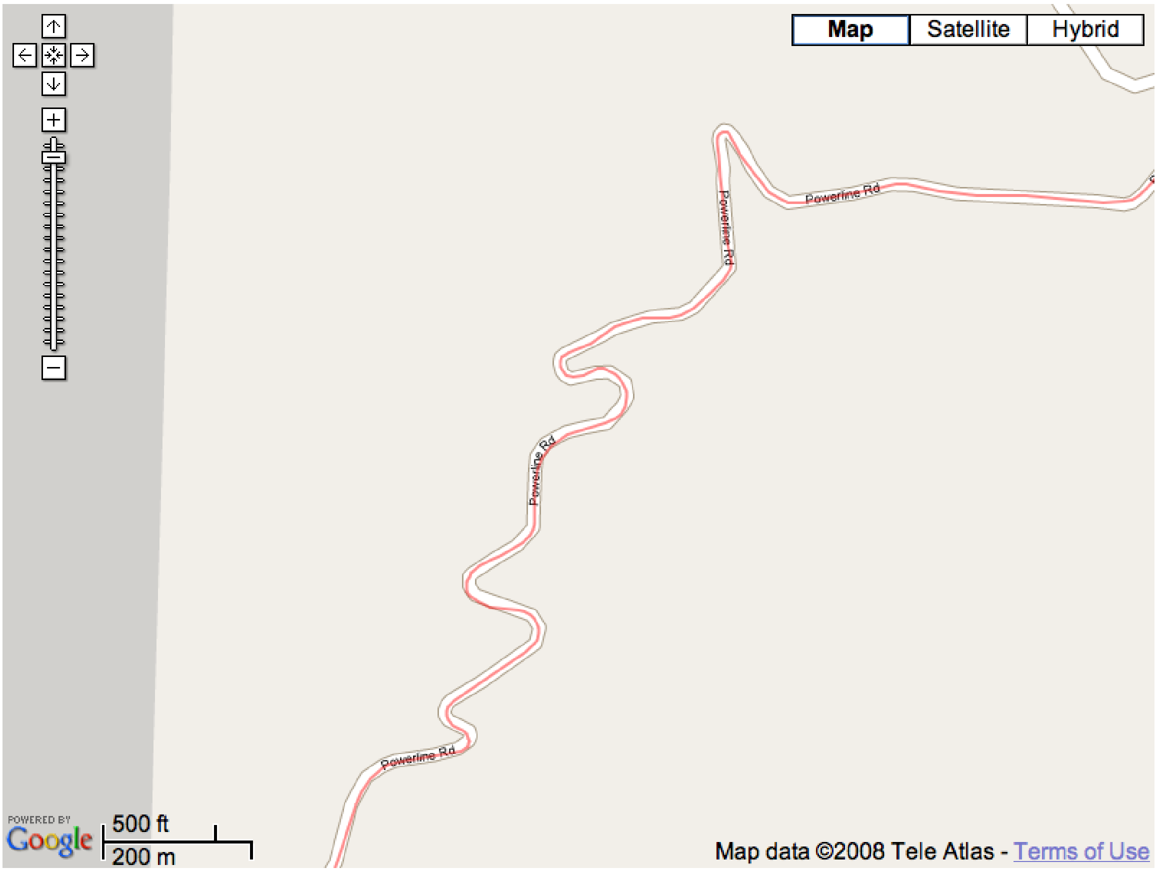

Figure 16. 2004 GCE course superimposed on map view (Powerline Road 2).

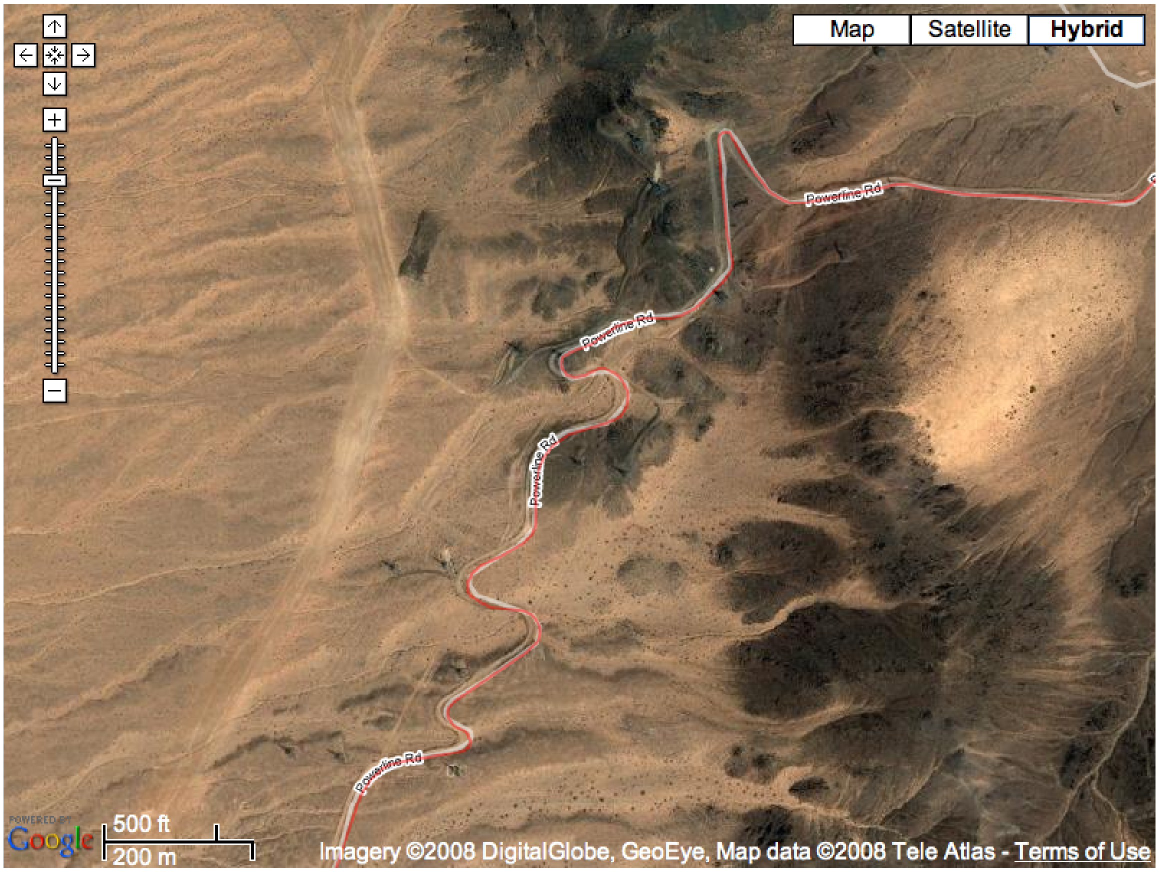

Figure 17. 2004 GCE course superimposed on map and satellite view (Powerline Road 2).

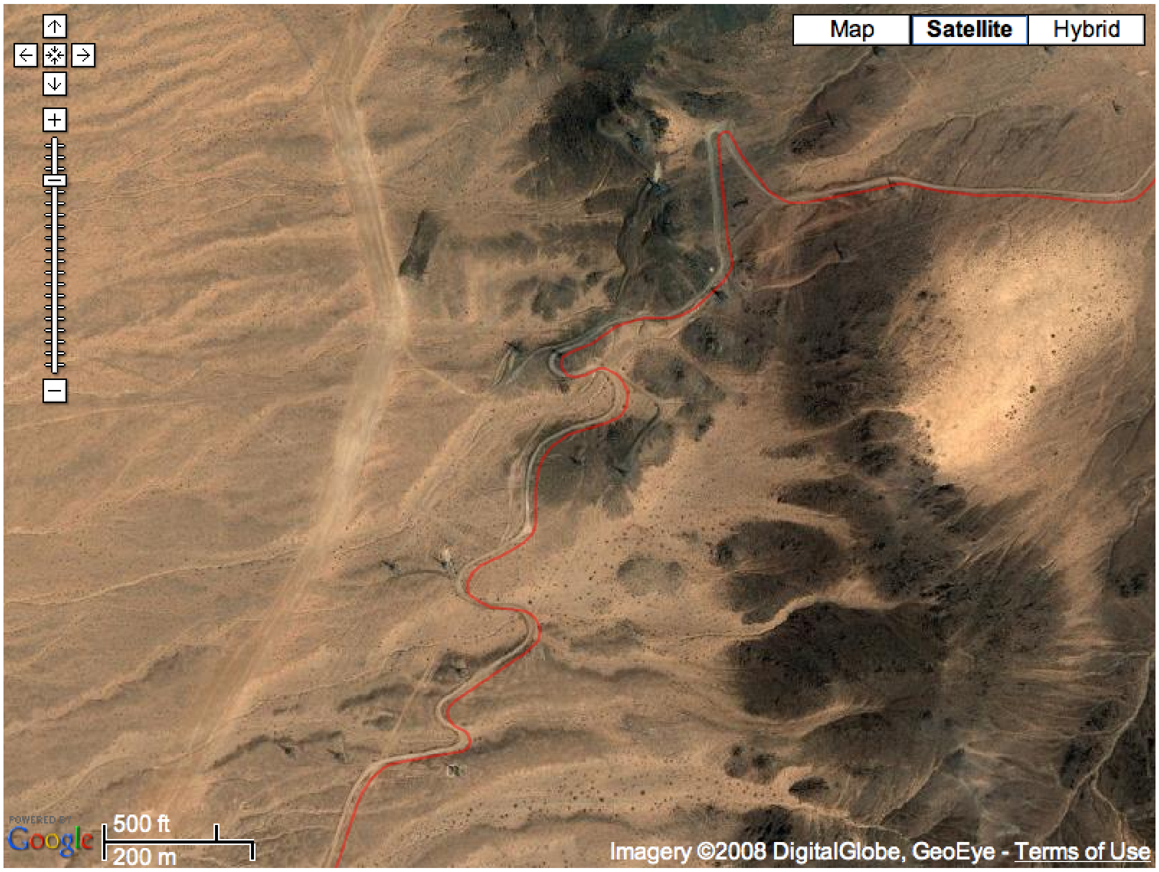

Figure 18. 2004 GCE course superimposed on satellite view (Powerline Road 2).

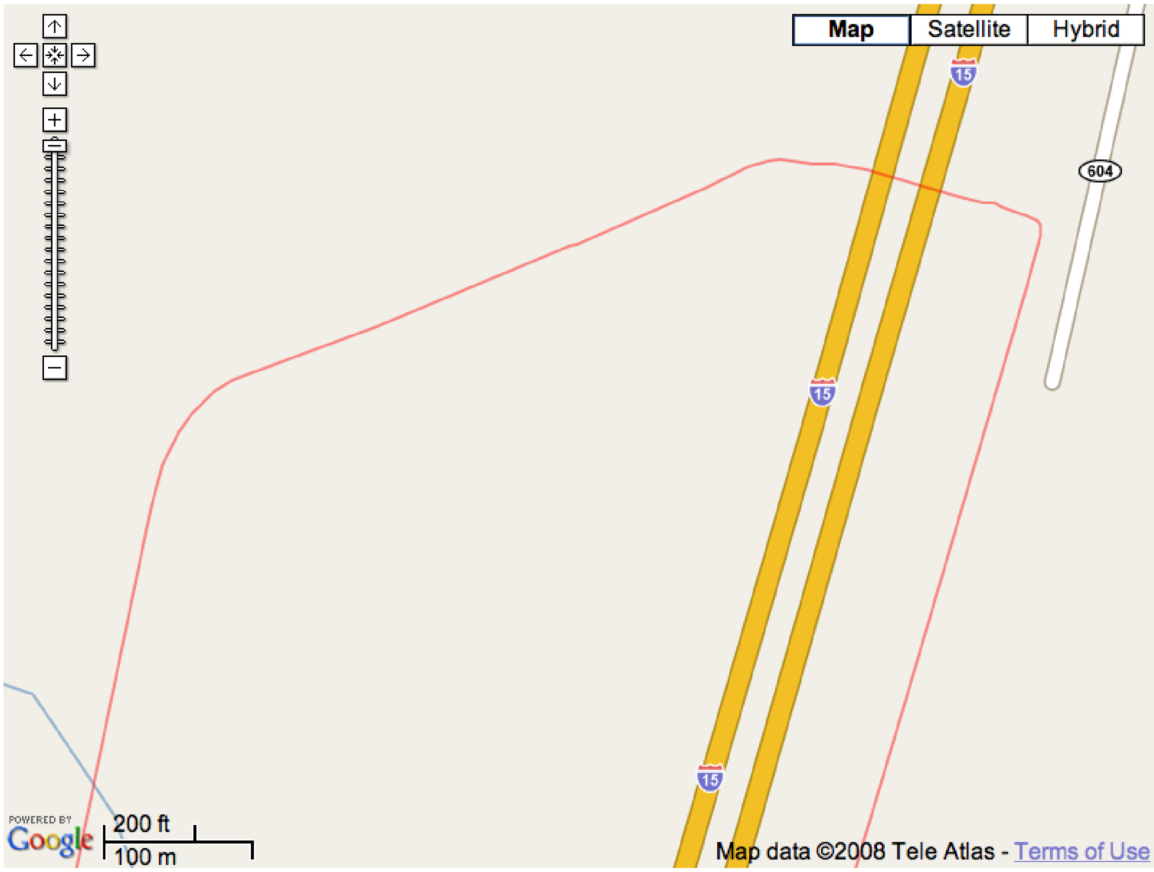

Figure 19. 2004 GCE course superimposed on map view (Interstate 15).

Figure 20. 2004 GCE course superimposed on map and satellite view (Interstate 15).

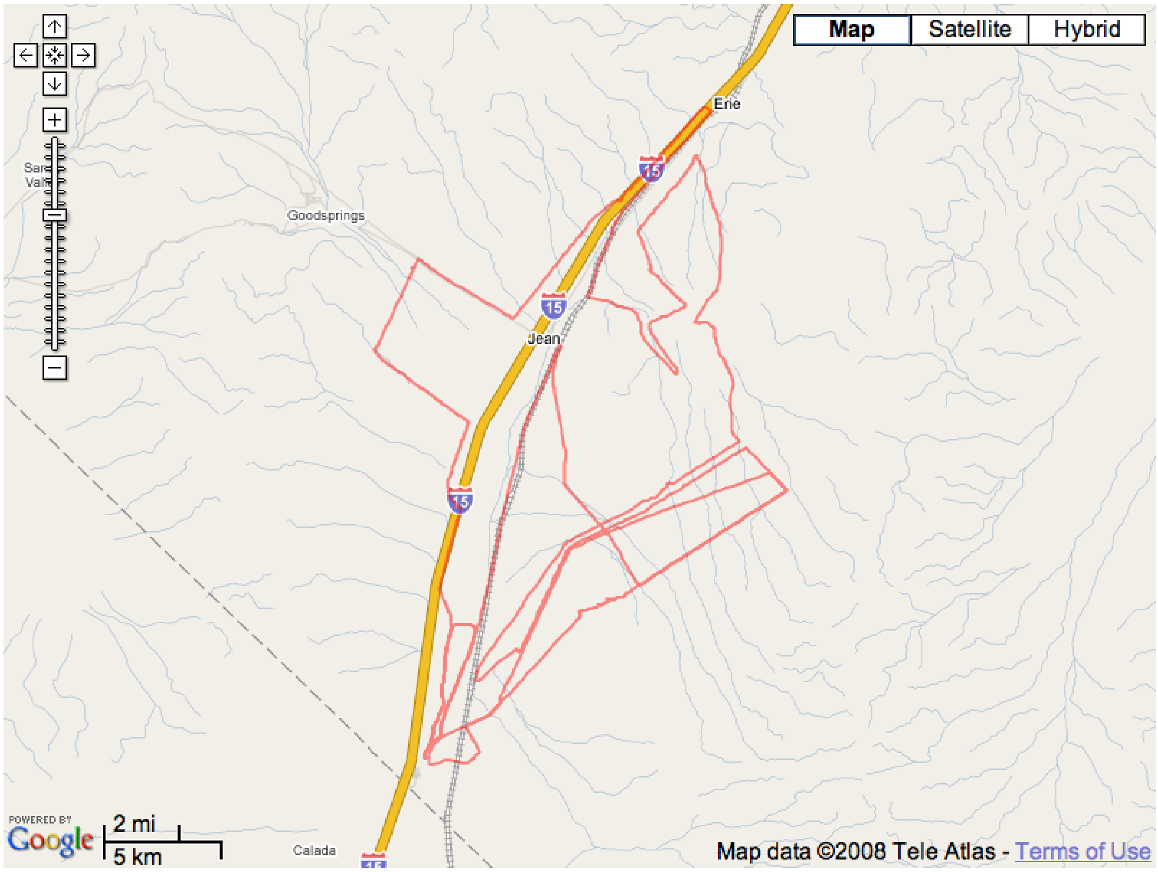

Figure 21. 2005 GCE course superimposed on map view.

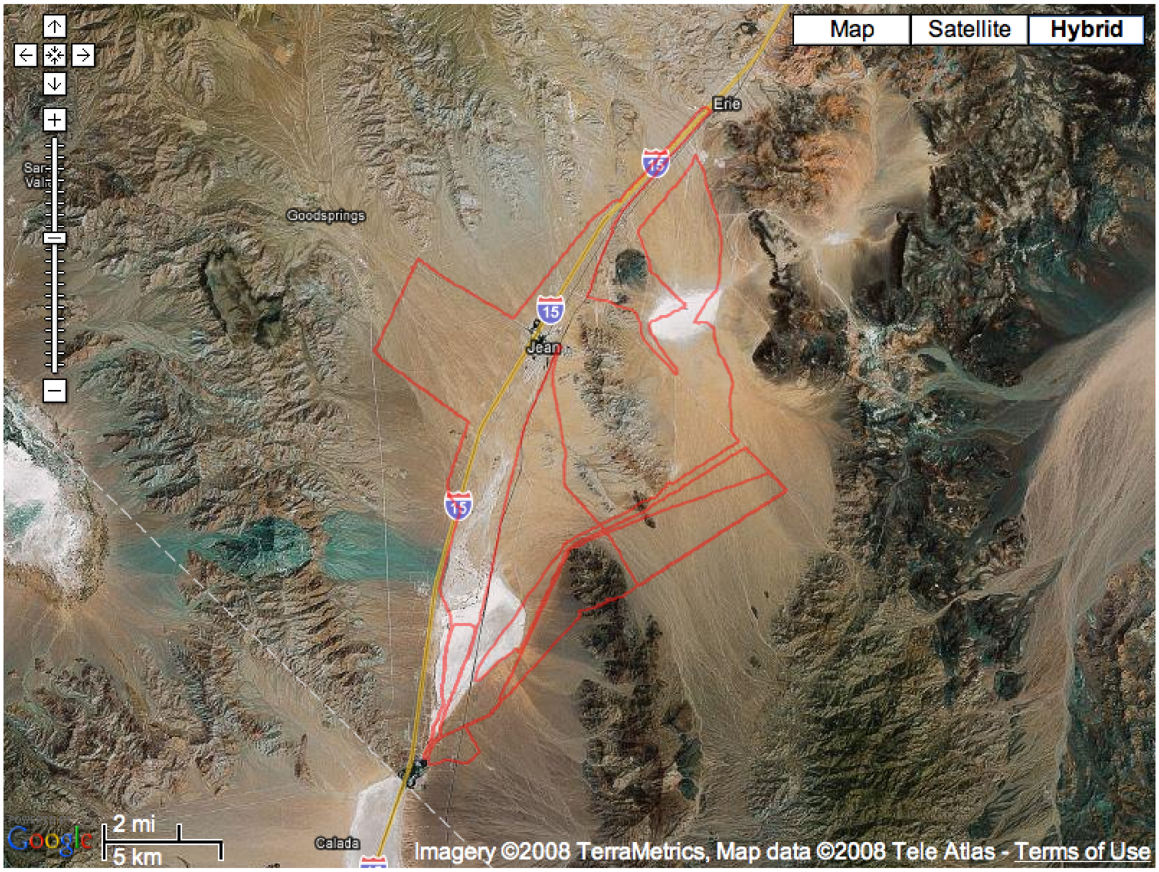

Figure 22. 2005 GCE course superimposed on map and satellite view.

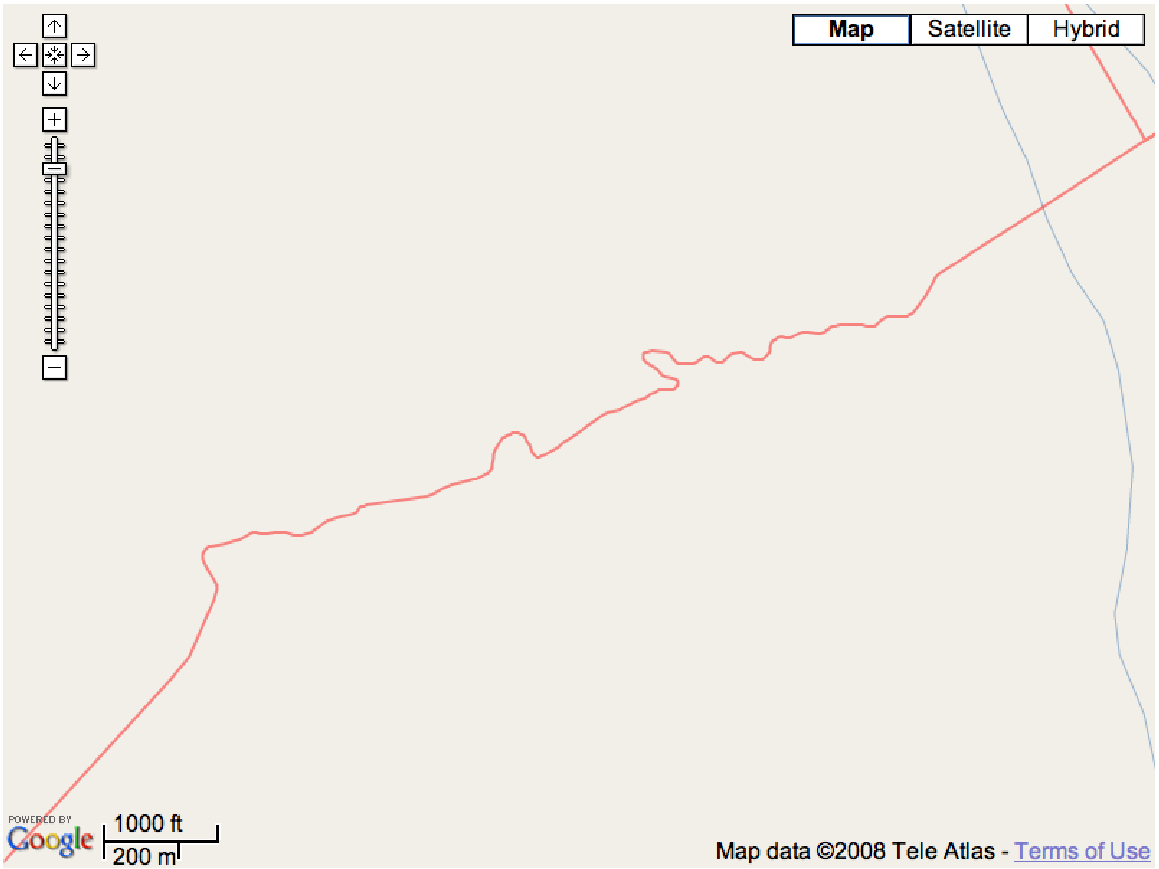

Figure 23. 2005 GCE course superimposed on map view (unnamed road).

Figure 24. 2005 GCE course superimposed on map and satellite view (unnamed road).

Figure 25. 2005 GCE course superimposed on map and satellite view (unnamed road at increased zoom).

Figure 26. 2005 GCE course superimposed on map view (Sandy Valley Road).

Figure 27. 2005 GCE course superimposed on map and satellite view (Sandy Valley Road).

Figure 28. 2005 GCE course superimposed on map view (Interstate 15).

Figure 29. 2005 GCE course superimposed on map and satellite view (Interstate 15).

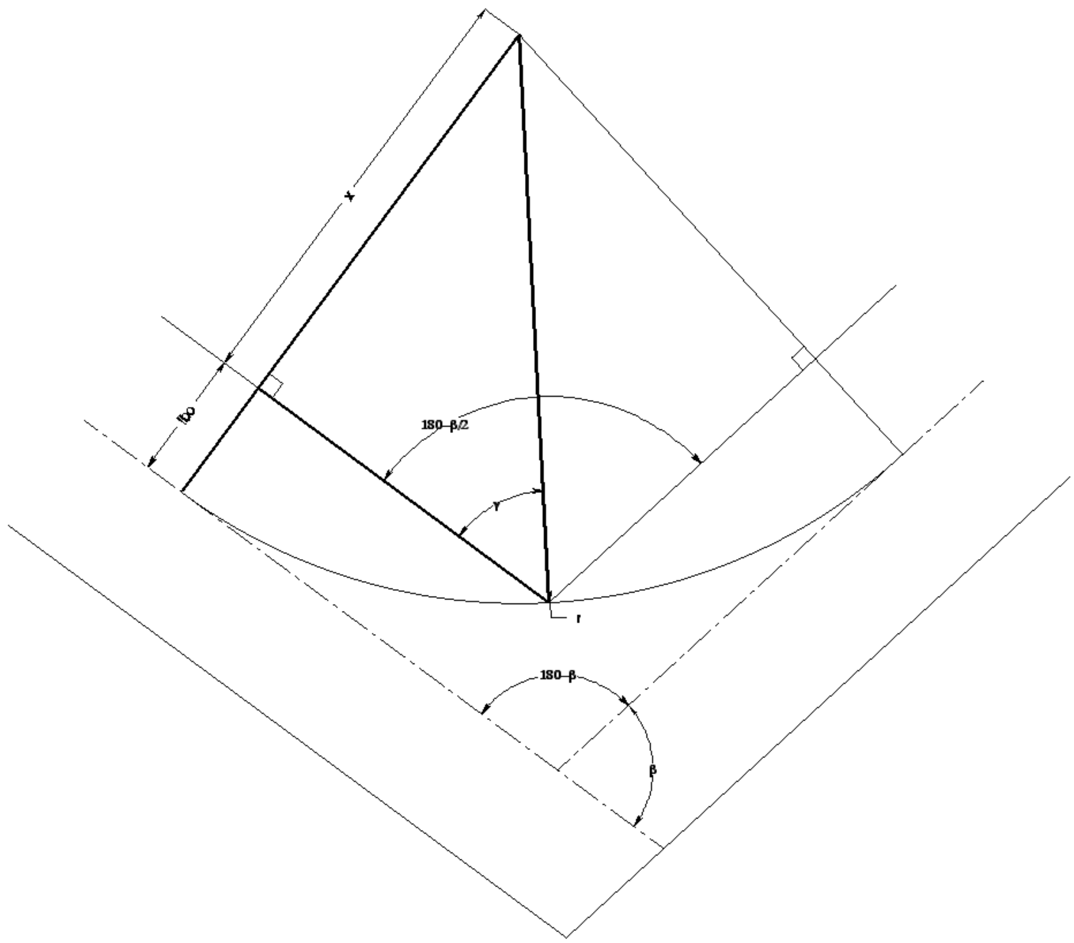

Figure 30. Calculation of minimum allowable turn radius based on change in bearing and lateral boundary offset.

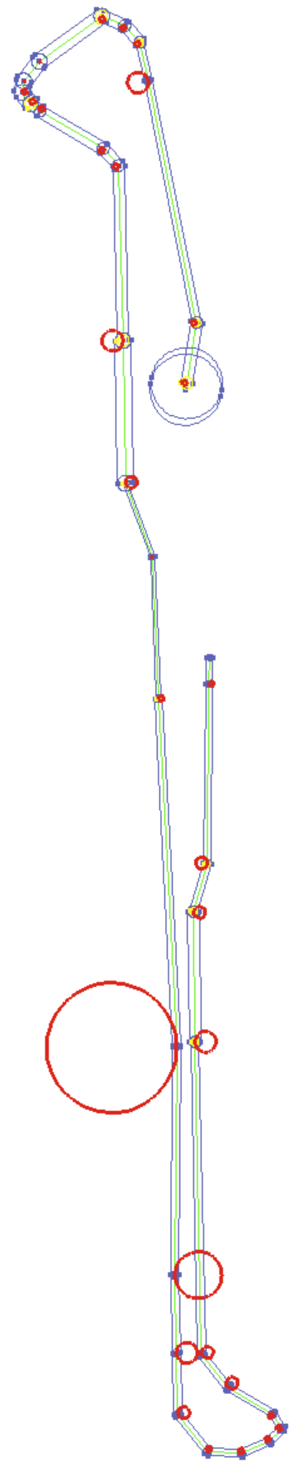

Figure 31. 2004 QID course with RDDF-allowed turn radius based on course segment speed.

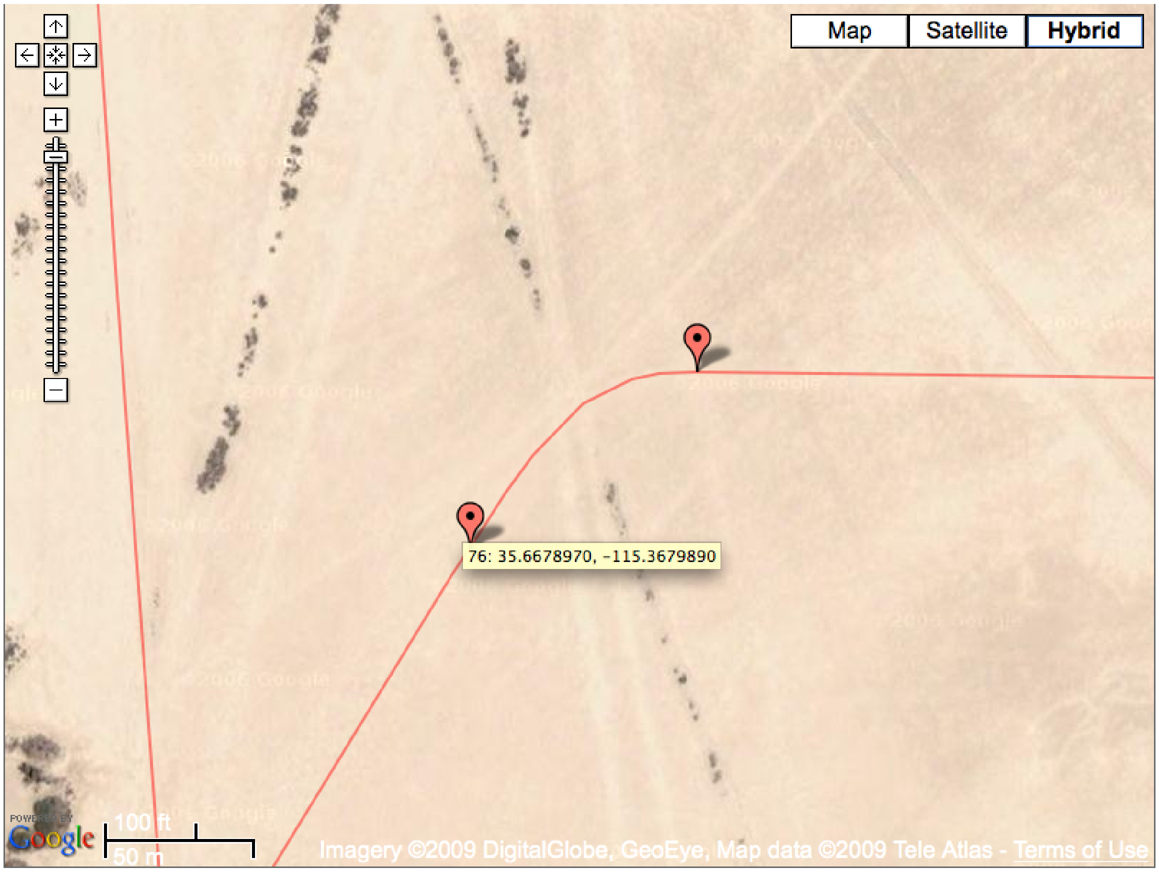

Figure 32. Deceleration lane (waypoints 76 to 84).

Figure 33. Deceleration lane (waypoints 1177 to 1184).

Figure 34. Deceleration lane (waypoints 1805 to 1809).

Figure 35. Deceleration lane (waypoints 2277 to 2290).

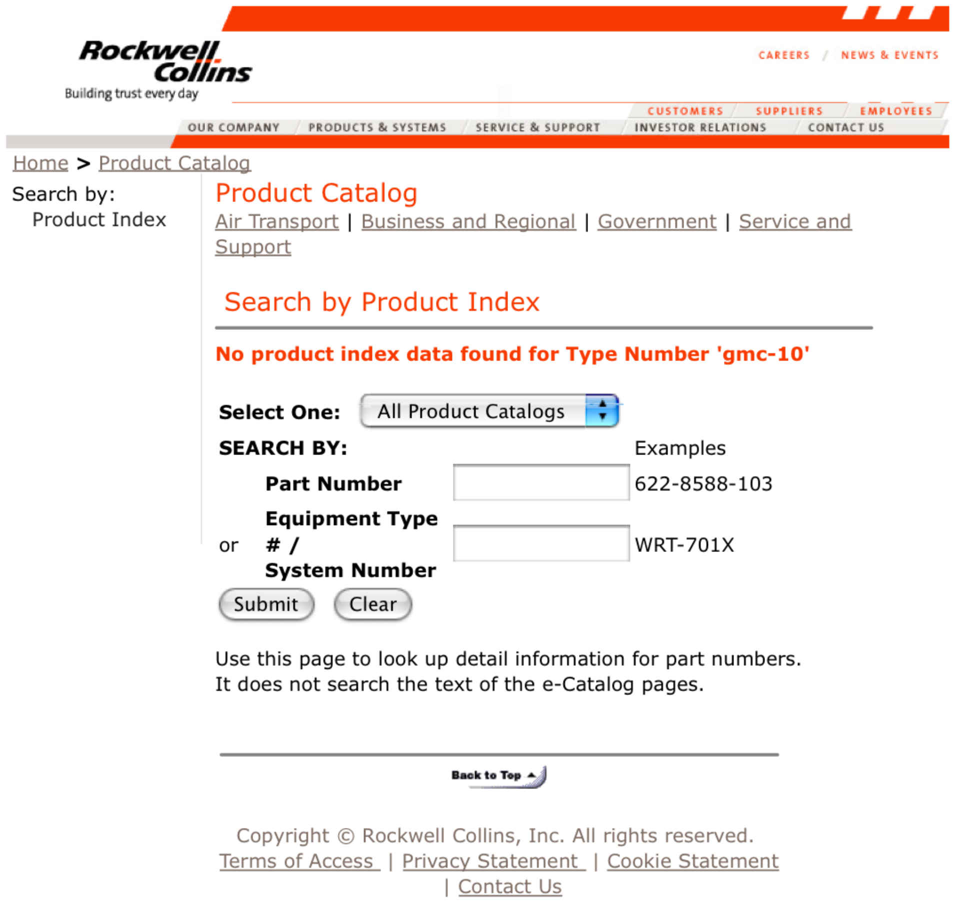

Figure 36. Rockwell Collins product search for “GMC-10”.

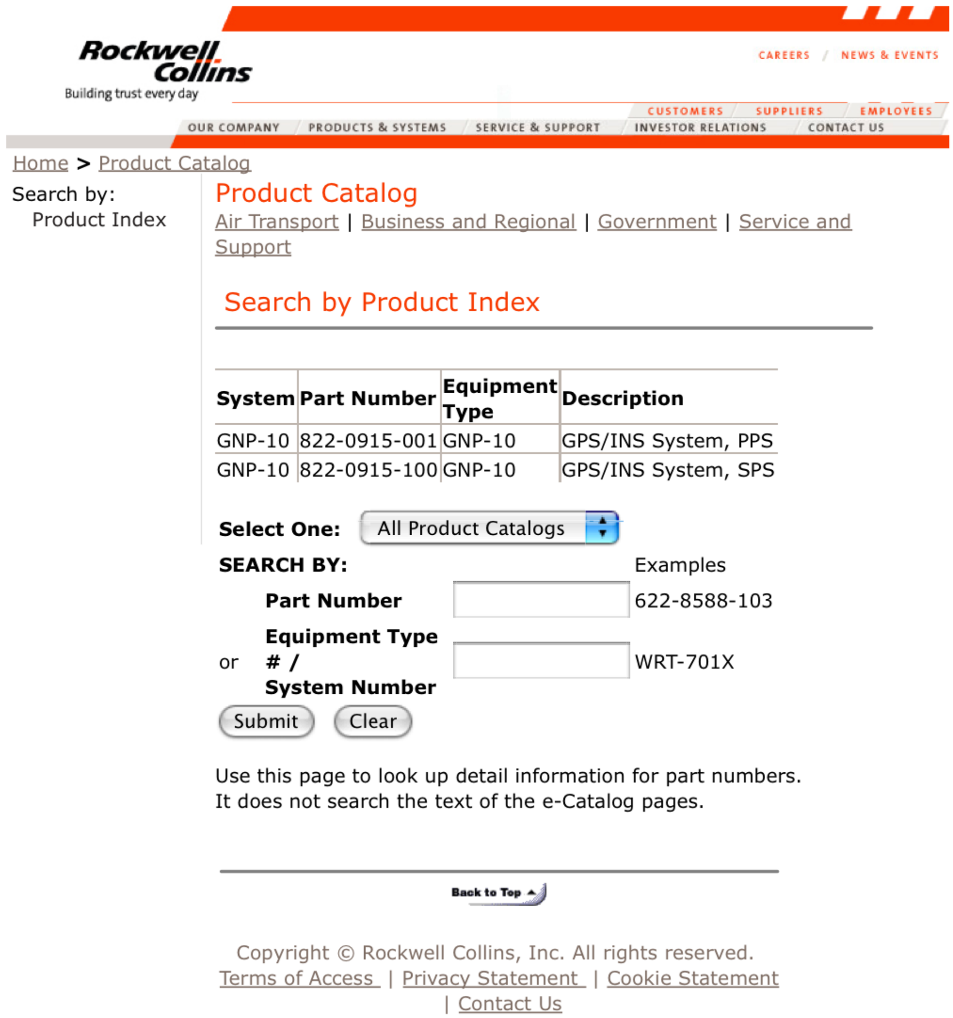

Figure 37. Rockwell Collins product search for “GNP-10”.

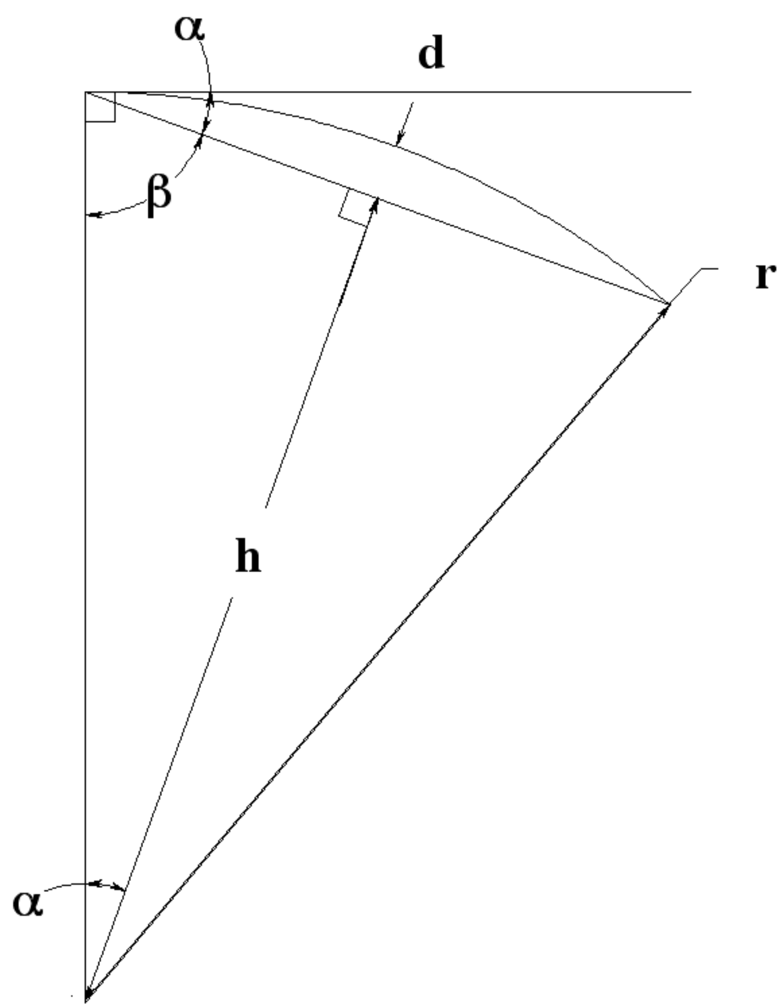

Figure 38. Maximum distance between the path of travel in a constant-radius turn and the left- or right-limit of field-of-view.

1. $\cos\alpha = \frac{h}{r}, \qquad h = r\cos\alpha$

2. $d = r - h$

3. $d = r - r\cos\alpha$ or $d = r(1 - \cos\alpha)$

Appendix A: RDDF Analysis Application

```
<!--Calculate the geodesic distance (in meters) between adjacent
waypoints in the 2004 and 2004 QID and RACE Route Data Definition File
(RDDF).-->
<?php
//PHP include statements and the author's Google Maps™ key were deleted
// from the source code prior to inclusion in this technical report.
// This comment does not appear in the original source code.

  $map = $_POST['map'];
  if ($map == "Yes")
    $debug = TRUE;
  else
    $debug = FALSE;

  $temp = $_FILES['file']['tmp_name']; //temporary file name
  if (is_uploaded_file($temp))
  {
//Create primary input table (RDDF), if it does not exist:
    $connectionID = get_mysql_connectionID("thesis", "f");
    $sql = "CREATE TABLE IF NOT EXISTS RDDF (
    Waypoint INT NOT NULL,
    Latitude DOUBLE(9,7) NOT NULL,
    Longitude DOUBLE(10,7) NOT NULL,
    LBO INT NOT NULL,
    Speed INT NOT NULL,
    PRIMARY KEY(Waypoint))";
    mysql_query($sql);
//Create primary output table (RDDF_OUT), if it does not exist:
    $sql = "CREATE TABLE IF NOT EXISTS RDDF_OUT (
    waypoint1 INT NOT NULL,
    latitude1 DOUBLE(9,7) NOT NULL,
    longitude1 DOUBLE(10,7) NOT NULL,
    lbo1 INT NOT NULL,
    speed1 INT NOT NULL,
    waypoint2 INT NOT NULL,
    latitude2 DOUBLE(9,7) NOT NULL,
    longitude2 DOUBLE(10,7) NOT NULL,
    lbo2 INT NOT NULL,
    speed2 INT NOT NULL,
    s DOUBLE (7,3) NOT NULL,
    alpha1 DOUBLE (6,3) NOT NULL,
    alpha2 DOUBLE (6,3) NOT NULL,
    beta DOUBLE (6,3) NOT NULL,
    speedm DOUBLE (6, 3) NOT NULL,
    radiusm DOUBLE (10, 3) NOT NULL,
    lbom DOUBLE (10, 3) NOT NULL,
    radius DOUBLE (10, 3) NOT NULL,
    rollover TEXT NOT NULL,
    PRIMARY KEY(waypoint1))";
    mysql_query($sql);
//Delete all data in the primary input and output tables, if they
exist:
    $sql = "TRUNCATE TABLE RDDF";
    mysql_query($sql);
```

```
    $sql = "TRUNCATE TABLE RDDF_OUT";
    mysql_query($sql);
//Load primary data table (RDDF):
    $sql = "LOAD DATA LOCAL INFILE '$temp'
    REPLACE INTO TABLE RDDF
    FIELDS TERMINATED BY ','
    ENCLOSED BY ''
    ESCAPED BY '\\\\'
    LINES TERMINATED BY '\\n'";
    mysql_query($sql);
//Map header.
    echo
"<!DOCTYPE html PUBLIC \"-//W3C//DTD XHTML 1.0
Strict//EN\" \"http://www.w3.org/TR/xhtml1/DTD/xhtml1-strict.dtd\">
<html xmlns=\"http://www.w3.org/1999/xhtml\">
  <head>
    <meta http-equiv=\"content-type\" content=\"text/html; charset=utf-
8\" />
    <link rel=\"stylesheet\" href=\"../css/style.css\" type=\"text/css;
charset=utf-8\" />
    <title>
      Route Data Definition File (RDDF) Analysis
    </title>";

    if ($debug)
    {
      echo
    "
    <script src=\"http://maps.google.com/maps?
file=api&amp;v=2&amp;key=\"
      type=\"text/javascript\"></script>
    <script type=\"text/javascript\">

    function initialize() {
      if (GBrowserIsCompatible()) {
        var map = new GMap2(document.getElementById(\"content-map\"));
        map.addControl(new GLargeMapControl());
        map.addControl(new GMapTypeControl());
        map.addControl(new GScaleControl());
        var polyLine = new GPolyline ([";
    }
//End map header.
//Read primary data table (RDDF):
    $sql = "SELECT Waypoint, Latitude, Longitude, LBO, Speed
    FROM RDDF";
    $result = mysql_query($sql);
    $first = TRUE;
    while ($row = mysql_fetch_array($result))
    {
      if ($first)
      {
        $waypoint2 = $row['Waypoint'];
        $latitude2 = $row['Latitude'];
        $longitude2 = $row['Longitude'];
```

```
        $lbo2 = $row['LBO'];
        $speed2 = $row['Speed'];

  //////Static Stabilty Factor (SSF).
  ////// Minimum possible value is 0.95 (1992-2000 Mitsubishi Montero).
  ////// Maximum possible value is 1.30 (2003 Honda Pilot 4-DR 4x4,
2003 Nissan Murano 4-DR 4x2/4x4, and 1980 Plymouth Arrow).
  ////// "Trends in the Static Stability Factor of Passenger Cars,
Light Trucks, and Vans"
        $ssf = $_POST['ssf'];
        if (is_numeric($ssf))
        {
          if ($ssf < 0.95)
            $ssf = 0.95;
          if ($ssf > 1.30)
            $ssf = 1.30;
        }
        else
        {
          $ssf = 1.30;
        }
  //////Reportable speed, in miles per hour (mph).
  ////// Minimum possible value is 5 mph.
  ////// Maximum possible value is 50 mph.
  ////// "DARPA Grand Challenge 2005 Route Data Definition File"
        $mph = $_POST['mph'];
        if (is_numeric($mph))
        {
          if ($mph < 5)
            $mph = 5;
          if ($mph > 50)
            $mph = 50;
        }
        else
        {
          $mph = 20;
        }
  //////Reportable change in bearing.
  ////// Minimum possible value is 5 degrees.
  ////// Maximum possible value is 90 degrees.
        $angle = $_POST['angle'];
        if (is_numeric($angle))
        {
          if ($angle < 5)
            $angle = 5;
          if ($angle > 90)
            $angle = 90;
        }
        else
        {
          $angle = 10;
        }
        $first = FALSE;
  //////Set initial course boundaries:
```

```
        $latitude_min = $latitude2;
        $latitude_max = $latitude2;
        $longitude_min = $longitude2;
        $longitude_max = $longitude2;
  //////Set initial aggregate values:
        $number = 1; //first waypoint: number of waypoints = 1.
        $length = 0; //first waypoint: total course length = 0.
        $agg_mph = 0; //first waypoint: number of waypoints at which
the speed is reportable = 0.
        $agg_angle = 0; //first waypoint: number of waypoints at which
the angle is reportable = 0.
        $agg_risk = 0; //first waypoint: number of waypoints at which
there is a rollover risk = 0.
  //////First waypoint.
        if ($debug)
        {
          echo
                                                "
          new GLatLng($latitude2, $longitude2)";
        }
  //////End first waypoint.
      }
      else
      {
        $waypoint1 = $waypoint2;
        $latitude1 = $latitude2;
        $longitude1 = $longitude2;
        $lbo1 = $lbo2;
        $speed1 = $speed2;
        $waypoint2 = $row['Waypoint'];
        $latitude2 = $row['Latitude'];
        $longitude2 = $row['Longitude'];
        $lbo2 = $row['LBO'];
        $speed2 = $row['Speed'];
  //////Adjust course boundaries, if necessary:
        if ($latitude2 > $latitude_max)
        {
          $latitude_max = $latitude2;
        }
        if ($latitude2 < $latitude_min)
        {
          $latitude_min = $latitude2;
        }
        if ($longitude2 > $longitude_max)
        {
          $longitude_max = $longitude2;
        }
        if ($longitude2 < $longitude_min)
        {
          $longitude_min = $longitude2;
        }
  //////Waypoint.
        if ($debug)
        {
```

```
          echo
                                                        ",
          new GLatLng($latitude2, $longitude2)";
        }
   //////End waypoint.
        $return = inverse($waypoint1, $latitude1, $longitude1,
$waypoint2, $latitude2, $longitude2);
   //////Increment number of waypoints by one.
        $number++;
//   //////Calculate reduced latitudes.
//         $a = 6378137.0;
//         $b = 6356752.3142;
//         $f = 1/298.257223563;
//         $Usub1 = rad2deg(atan((1 - $f) * tan(deg2rad($latitude1))));
//         $Usub2 = rad2deg(atan((1 - $f) * tan(deg2rad($latitude2))));

        $s = $return[0];
   //////Total course length += s.
        $length += $s;

        if ($return[1] < 0)
        {
          $alpha1 = rad2deg($return[1] + 2*pi());
        }
        else
        {
          $alpha1 = rad2deg($return[1]);
        }

        if ($return[2] < 0)
        {
          $alpha2 = rad2deg($return[2] + 2*pi());
        }
        else
        {
          $alpha2 = rad2deg($return[2]);
        }

      if ($number < 3)
      { //Three waypoints are required to determine the angle at which
route segments intersect.
        $alpha2p = $alpha2;
        $beta = 0;
      }
      else
      {
        if (abs($alpha2p - $alpha1) > 180)
        {
          if ($alpha2p > $alpha1)
            $beta = ($alpha2p - 360) - $alpha1;
          else
            $beta = $alpha2p - ($alpha1 - 360);
        }
        else
```

```
        {
          $beta = $alpha2p - $alpha1;
        }
        $alpha2p = $alpha2;
      }

      $return = rollover($latitude1, $lbo1, $speed1, $beta, $ssf,
$angle);

      $speedm = $return[0];
      $radiusm = $return[1];
      $lbom = $return[2];
      $radius = $return[3];
      $rollover = $return[4];

      if ($speed1 > $mph)
      {
        $agg_mph++;
      }

      if (abs($beta) > $angle)
      {
        $agg_angle++;
      }

      if ($rollover == "Y")
      {
        $agg_risk++;
      }

      $sql = "INSERT INTO RDDF_OUT (waypoint1, latitude1, longitude1,
lbo1, speed1,
                                    waypoint2, latitude2, longitude2,
lbo2, speed2,
                                    s, alpha1, alpha2, beta,
                                    speedm, radiusm, lbom, radius,
rollover)
                            VALUES ($waypoint1, $latitude1,
$longitude1, $lbo1, $speed1,
                                    $waypoint2, $latitude2,
$longitude2, $lbo2, $speed2,
                                    $s, $alpha1, $alpha2, $beta,
                                    $speedm, $radiusm, $lbom,
$radius, \"$rollover\")";
      mysql_query($sql);
      }
    }
  $latitude_center = ($latitude_max + $latitude_min) / 2;
  $latitude_bounds = $latitude_max - $latitude_min;
  $longitude_center = ($longitude_max + $longitude_min) /2;
  $longitude_bounds = $longitude_max - $longitude_min;
//Map footer.
  if ($debug)
  {
```

```
    echo
        "
          ], \"#ff0000\", 2);
          map.setCenter(new GLatLng($latitude_center,
$longitude_center), 8);
          map.addOverlay(polyLine);
        }
      }
    </script>
  </head>
  <body onload=\"initialize()\" onunload=\"GUnload()\">
    <div id=\"content-top\"></div>
    <div id=\"content-map\"></div>
    <div id=\"content-middle\">";
  }
  else
  {
    echo
 "
  </head>
  <body>
    <div id=\"content-top\"></div>
    <div id=\"content-middle\">";
  }
  echo
    "
      <h1>
        Form values:
      </h1>
      <p>
        Static Stability Factor (SSF) [default = 1.02]: $ssf
      </p>
      <p>
        Reportable speed, in miles per hour (mph) [default = 20]: $mph
      </p>
      <p>
        Reportable change in bearing [default = 10]: $angle
      </p>
      <h1>
        Map boundaries:
      </h1>
      <p>
        Latitude (maximum, minimum, map center, bounds): $latitude_max,
$latitude_min, $latitude_center, $latitude_bounds
      </p>
      <p>
        Longitude (maximum, minimum, map center, bounds):
$longitude_max, $longitude_min, $longitude_center, $longitude_bounds
      </p>
      <h1>
        Aggregate data:
      </h1>
      <p>
        Number of waypoints: $number.
```

```
      </p>
      <p>
        Overall course length: $length (meters).
      </p>
      <p>
        Total number of course segments for which the speed exceeds the
reportable speed: $agg_mph.
      </p>
      <p>
        Total number of intersections at which the change in bearing
exceeds the reportable change in bearing: $agg_angle.
      </p>
      <p>
        Total number of waypoints at which there is a rollover risk:
$agg_risk.
      </p>
    </div>
    <div id=\"content-bottom\"></div>
  </body>
</html>\n";
//End map footer.
  }
  else
  {
    echo "Error: " . $_FILES['nameFile']['error'];
    die("<p>The file upload was unsuccessful</p>");
  }
  exit();

        function inverse($waypoint1, $latitude1, $longitude1,
$waypoint2, $latitude2, $longitude2) {
//////////Apply the Vincenty formula to determine the distance between
waypoint1 and waypoint2, above.
//////////Constants for WGS84 ellipsoid:
          $a = 6378137.0;
          $b = 6356752.3142;
          $f = 1/298.257223563; //this is a deviation from the Vincenty
formula, for which: f, flattening = (a - b) / a = 1/298.257222933.
//////////Calculate derived variables from given variables:
          $L = deg2rad(($longitude2 - $longitude1));
          $Usub1 = atan((1 - $f) * tan(deg2rad($latitude1)));
          $Usub2 = atan((1 - $f) * tan(deg2rad($latitude2)));
          $sinUsub1 = sin($Usub1);
          $cosUsub1 = cos($Usub1);
          $sinUsub2 = sin($Usub2);
          $cosUsub2 = cos($Usub2);
//////////Step 13:
          $lambda = $L; //first approximation
          $lambdaprime = 2 * pi();
          $iterations = 0;

//          echo print_constants($waypoint1, $waypoint2, $a, $b, $f,
$L, $latitude1, $latitude2, $Usub1, $Usub2, $sinUsub1, $cosUsub1,
$sinUsub2, $cosUsub2, $lambda);
```

```
          while (abs($lambda - $lambdaprime) > 1.0e-12) {
//////////Step 14:
            $sin2sigma = ($cosUsub2 * sin($lambda)) * ($cosUsub2 *
sin($lambda)) + ($cosUsub1 * $sinUsub2 - $sinUsub1 * $cosUsub2 *
cos($lambda)) * ($cosUsub1 * $sinUsub2 - $sinUsub1 * $cosUsub2 *
cos($lambda));
            $sinsigma = sqrt($sin2sigma);
            if ($sinsigma == 0) {
              echo _p("Warning: co-incident points (sin &#x03C3; =
$sinsigma).");//Warn on co-incident points.
              break;
            }
//////////Step 15:
            $cossigma = $sinUsub1 * $sinUsub2 + $cosUsub1 * $cosUsub2 *
cos($lambda);
//////////Step 16:
            $tansigma = $sinsigma / $cossigma;
            $sigma = atan2($sinsigma, $cossigma);
//////////Step 17:
            $sinalpha = $cosUsub1 * $cosUsub2 * sin($lambda) /
$sinsigma;
            $sin2alpha = $sinalpha * $sinalpha;
//////////Step 18:
            $cos2alpha = 1 - $sin2alpha;
            if (is_infinite($cossigma - 2 * $sinUsub1 * $sinUsub2 /
$cos2alpha)) // equatorial line: $cos2alpha = 0.
              $costwosigmasubm = 0;
            else
              $costwosigmasubm = $cossigma - 2 * $sinUsub1 *
$sinUsub2 / $cos2alpha;
//////////Step 10:
            $C = ($f / 16) * $cos2alpha * (4 + $f * (4 - 3 *
$cos2alpha));
//////////Step 11:
            $lambdaprime = $lambda;
            $lambda = $L + (1 - $C) * $f * $sinalpha * ($sigma + $C *
$sinsigma * ($costwosigmasubm + $C * $cossigma * (-1 + 2 *
$costwosigmasubm * $costwosigmasubm)));
            $iterations++;

//            echo print_intermediates($iterations, $sin2sigma,
$sinsigma, $cossigma, $tansigma, $sigma, $sin2alpha, $sinalpha,
$cos2alpha, $costwosigmasubm, $C, $lambdaprime, $lambda);
          }
//////////Step 03:
          $u2 = $cos2alpha * ($a * $a - $b * $b) / ($b * $b);
          $A = 1 + $u2 / 16384 * (4096 + $u2 * (-768 + $u2 * (320 - 175
* $u2)));
//////////Step 04:
          $B = $u2 / 1024 * (256 + $u2 * (-128 + $u2 * (74 - 47 *
$u2 )));
//////////Step 06:
```

```
          $deltasigma = $B * $sinsigma * ($costwosigmasubm + 1 / 4 * $B
* ($cossigma * (-1 + 2 * $costwosigmasubm * $costwosigmasubm) - 1 / 6 *
$B * $costwosigmasubm * (-3 + 4 * $sin2sigma) * (-3 + 4 *
$costwosigmasubm * $costwosigmasubm)));
//////////Step 19:
          $s = $b * $A * ($sigma - $deltasigma);
//////////Step 20:
          $alpha1 = atan2(($cosUsub2 * sin($lambda)), ($cosUsub1 *
$sinUsub2 - $sinUsub1 * $cosUsub2 * cos($lambda)));
//////////Step 21:
          $alpha2 = atan2(($cosUsub1 * sin($lambda)), (-$sinUsub1 *
$cosUsub2 + $cosUsub1 * $sinUsub2 * cos($lambda)));
//////////Output the result:
//          echo print_intermediate_results($waypoint1, $waypoint2,
$u2, $A, $B, $deltasigma);
//          echo print_results($waypoint1, $waypoint2, $s, $alpha1,
$alpha2);
          return array($s, $alpha1, $alpha2);
        }

        function rollover ($latitude1, $lbo1, $speed1, $beta, $ssf,
$angle) {
          $a = 6378137.0;
          $b = 6356752.3142;
          $f = 1/298.257223563;

          $gamma = deg2rad(90 - abs($beta / 2)); //convert beta, in
degrees, to gamma (beta complementary angle) in radians
          $lbom = $lbo1 / 3.2808399; //convert lbo, in feet, to meters
          $speedm = ($speed1 * 5280) / (3600 * 3.2808399); //convert
speed, in miles per hour, to meters per second

//////////Calculate acceleration due to gravity.
          $phi = deg2rad($latitude1); //convert latitude, in degrees,
to radians
          $gammae = 9.7803253359; //theoretical (normal) gravity at the
equator (on the ellipsoid)
          $gammap = 9.8321849378; //theoretical (normal) gravity at the
pole (on the ellipsoid)
          $k = ($b * $gammap) / ($a * $gammae) - 1;
          $gravity = $gammae * (1 + $k * sin($phi) * sin($phi)) / sqrt
(1 - (1 - ($b * $b) / ($a * $a)) * sin($phi) * sin($phi));

          $radiusm = ($speedm * $speedm) / ($gravity * $ssf);
//required turn radius at speedm

          if (sin($gamma) == 1) {
            $radius = 0;
            $rollover = "N";
          } else {
            $radius = -$lbom / (sin($gamma) - 1); //maximum allowable
turn radius

            if ($radiusm > $radius)
```

```
          $rollover = "Y";
        else
          $rollover = "N";
      }
      return array($speedm, $radiusm, $lbom, $radius, $rollover);
    }
  ?>
  </div>
 </body>
</html>
```

Appendix B: Vincenty's Inverse Solution

Notation:

a, *b*, major and minor semiaxes of the ellipsoid.

f, flattening = (*a* - *b*) / *a*.

, geodetic latitude, positive north of the equator.

L, difference in longitude, positive east.

s, length of the geodesic.

$_1$, $_2$, azimuths of the geodesic, clockwise from north; $_2$ in the direction $P_1 P_2$ produced.

, azimuth of the geodesic at the equator.

u^2 = $\cos^2$ $(a^2 - b^2) / b^2$.

U, reduced latitude, defined by tan *U* = (1 - *f*) tan .

, difference in longitude on an auxiliary sphere.

, angular distance $P_1 P_2$ on the sphere.

$_1$, angular distance on the sphere from the equator to P_1.

$_m$, angular distance on the sphere from the equator to the midpoint of the line.

Inverse Formula:

$$= L \text{ (first approximation)} \tag{13}$$

$$\sin^2\sigma = (\cos U_2 \sin\lambda)^2 + (\cos U_1 \sin U_2 - \sin U_1 \cos U_2 \cos\lambda)^2 \tag{14}$$

$$\cos\sigma = \sin U_1 \sin U_2 + \cos U_1 \cos U_2 \cos\lambda \tag{15}$$

$$\tan\sigma = \sin\sigma / \cos\sigma \tag{16}$$

$$\sin\alpha = \cos U_1 \cos U_2 \sin\lambda / \sin\sigma \tag{17}$$

$$\cos 2\sigma_m = \cos\sigma - 2\sin U_1 \sin U_2 / \cos^2\alpha \tag{18}$$

is obtained by equations (10) and (11). This procedure is iterated starting with equation (14) until the change in is negligible.

$$s = bA(\sigma - \Delta\sigma), \tag{19}$$

where $\Delta\sigma$ comes from equations (3), (4), and (6):

$$A = 1 + \frac{u^2}{16384}\{4096 + u^2[-768 + u^2(320 - 175u^2)]\} \tag{3}$$

$$B = \frac{u^2}{1024}\{256 + u^2[-128 + u^2(74 - 47u^2)]\} \tag{4}$$

$$\Delta\sigma = B\sin\sigma\{\cos 2\sigma_m + \frac{1}{4}B[\cos\sigma(-1 + 2\cos^2 2\sigma_m) - \frac{1}{6}B\cos 2\sigma_m(-3 + 4\sin^2\sigma)(-3 + 4\cos^2 2\sigma_m)]\} \tag{6}$$

$$\tan\alpha_1 = \frac{\cos U_2 \sin\lambda}{\cos U_1 \sin U_2 - \sin U_1 \cos U_2 \cos\lambda} \tag{20}$$

$$\tan\alpha_2 = \frac{\cos U_1 \sin\lambda}{-\sin U_1 \cos U_2 + \cos U_1 \sin U_2 \cos\lambda} \tag{21}$$

Appendix C: DARPA Grand Challenge 2004 and 2005 Timeline

I. DARPA GRAND CHALLENGE 2004 AND 2005 TIMELINE

The author compiled the following list of important dates and milestones for the 2004 and 2005 GCE (herein referred to as "the timeline") based on review of the published record:

I.A. 2004 GCE

I.A.1. February 22, 2003

DARPA held a "Competitor's Conference" as the official start of the 2004 GCE. DARPA stated: "Conference goals were to provide information about the upcoming event to potential participants, sponsors, and the media; provide a forum in which interested individuals, teams, and sponsors could meet to exchange ideas and set up partnerships leading to eventual entry in the event; and give DARPA a sense of the number of participants interested in competing in the Grand Challenge. The conference attracted over 400 attendees." ([3], p. 3).

An "Overview Presentation" hosted by DARPA via the "Team Resources" hyperlink on the Archived Grand Challenge 2004 website ([17]) established a proposed 2004 GCE course length of 300 miles. DARPA stated the proposed 2004 GCE course was a "300-mile course of off- and on-road terrain between Los Angeles and Las Vegas" ([263]).

The "Overview Presentation" is undated[44], and did not establish a maximum corrected time. As a result, the author considers it likely this presentation pre-dates revision "April 1.2" of the 2004 GCE rules, which established a maximum corrected time of 10 hours, and was probably given during the Competitor's Conference on February 22, 2003. In addition, the author concluded the maximum corrected time exceeded 10 hours at the time this presentation was given.

I.A.2. April 1, 2003

DARPA published revision "April 1.2" of the 2004 GCE rules ([1]).

The "April 1.2" revision of the 2004 GCE rules established a proposed 2004 GCE course length of 360 +/- 60 miles. DARPA stated: "The Checkpoint Area is a mandatory stop between the Departure and Arrival Lines." ([1]) and "The location of the Checkpoint Area will be approximately 180 +/- 30 miles from the Departure Line." ([1]). Because the Checkpoint Area was "that area that has been designated as such by DARPA for the purpose of automated maintenance and servicing of Challenge Vehicles." ([1]) the author considers it likely the Checkpoint Area was located near the midway point of the proposed 2004 GCE course, and that the proposed 2004 GCE course length was less than twice the distance from the Departure Line to the Checkpoint Area Entry Waypoint, or 360 +/- 60 miles.

The “April 1.2” revision of the 2004 GCE rules also established a maximum corrected time of 10 hours. DARPA stated: “The maximum corrected time to receive the Grand Challenge Prize is now ten hours.” ([1]) and “The Winner is the Participant whose Challenge vehicle has completed the prescribed Route in the least corrected time at or under ten hours.” ([1]).

April 1, 2003 was the first day of the application period for the 2004 GCE. DARPA stated: “The period of application begins on April 1, 2003...” ([1]).

I.A.3. June 18, 2003

DARPA stated the proposed 2004 GCE course length was: “approximately 250 miles” ([261]).

DARPA also stated: “As of June 18, 2003, 27 teams had submitted applications to enter the Grand Challenge.” ([261]).

I.A.4. October 14, 2003

October 14, 2003 was the last day of the application period for the 2004 GCE. DARPA stated: “The period of application... ends on the application deadline at noon, Eastern Daylight Time, on October 14, 2003.” ([1]).

DARPA inconsistently used the words “applicant” and “application”. Although DARPA stated: “A complete application consists of several documents that need not be submitted simultaneously. These documents include the application form, application addenda (if required), the technical paper, and technical paper addenda (if required).” ([1]), DARPA later stated: “The Grand Challenge attracted 106 applicants, 86 of which submitted technical papers by the October 14 deadline.” ([83]). The author concluded 86 teams, not 106, submitted applications by the October 14, 2003 deadline because the technical proposal was a required submission for the team application to be considered complete.

I.A.5. November 5, 2003

Of the 86 teams which submitted complete applications by the October 14, 2003 application deadline, DARPA selected 19 whose technical proposals were “completely acceptable” and invited those teams “to participate in the Grand Challenge Qualification, Inspection and Demonstration (QID) event at the California Speedway, March 8-12, 2004.” ([83]). DARPA stated: “An additional 26 teams were evaluated as 'possibly acceptable' and eligible for a site visit that could qualify them for the final 6 slots at the QID.” ([83])

The list of teams whose technical proposals were evaluated as “completely acceptable” by DARPA included many teams which submitted proposals with a large number of technical mistakes, or otherwise reported confusing or inadequate technical detail. See paragraph V.E. In addition, review of submitted technical proposals indicated several of the technical proposals evaluated as “completely acceptable” were revised continuously between November 5, 2003 and the 2004 QID and GCE, and that they referred to future actions, in particular planned test and evaluation. See paragraph XIV.D.1.

Although DARPA established requirements for technical proposal accuracy and stated: “Challenge Vehicles presented for the Qualification Inspections and Demonstration (QID) that deviate substantially from the description in the approved technical paper (including approved addenda) will be disqualified.” (see paragraph V.E.1.a.), the author was unable and unwilling to conclude, based on a comprehensive review of team technical proposals, that DARPA refused to allow teams, which were not in compliance with requirements DARPA itself established, to participate in either the 2004 QID or GCE. The author concluded DARPA attempted to maintain an appearance of objectivity, but selected some teams on the basis of a novel technology in use by the team (see paragraph X.D.1.) or a desire to stimulate good public relations. Based on the general quality of team technical proposals and the performance of some teams during the 2004 QID and GCE, the author questions whether it was appropriate for DARPA to allow teams which little or no chance of successfully completing the 2004 GCE to participate in the 2004 QID and GCE.

I.A.6. November 26, 2003

DARPA published responses to questions asked by teams participating in the 2004 QID and GCE on or around November 26, 2003, and which was not hosted by DARPA via the Archived Grand Challenge 2004 website ([17]). A copy of DARPA's responses was downloaded from the Team 2004-20 website ([20]), a repository of records independent of DARPA. The copy ([264]) is undated[45]. DARPA stated: “There will no longer be a Checkpoint or Checkpoint area. The total route length will be less than the published maximum distance to the Checkpoint Area (approximately 210 miles).” ([264]).

I.A.7. December 19, 2003

DARPA announced 25 teams were selected to participate in the 2004 QID. DARPA stated: “Twenty-five teams from a wide variety of backgrounds, organizations and areas of the country have been selected to participate in the Qualification, Inspection and Demonstration (QID) Event...” ([254]).

I.A.8. December, 2003 or January, 2004

DARPA distributed an “information package” in December, 2003 or January, 2004 which contained “QID information/slides” among other resources ([265]), and which was not hosted by DARPA via the Archived Grand Challenge 2004 website ([17]). A copy of the “QID information/slides” was downloaded from the Team 2004-20 website

([20]), a repository of records independent of DARPA. The "QID Process Description" presentation ([266]) is undated[46].

I.A.9. January 5, 2004

DARPA published revision "5 January 2004" of the 2004 GCE rules ([6]), and which was not hosted by DARPA via the Archived Grand Challenge 2004 website ([17]). A copy of the "5 January 2004" revision of the 2004 GCE rules was downloaded from the Team 2004-20 website ([20]), a repository of records independent of DARPA. The "5 January 2004" revision of the 2004 GCE rules did not establish a proposed 2004 GCE course length. However, DARPA stated: "There is no longer a checkpoint on the route." ([6]).

The "5 January 2004" revision of the 2004 GCE rules established a maximum corrected time of 10 hours. DARPA stated: "The Winner is the Participant whose Challenge vehicle has completed the prescribed Route in the least corrected time at or under ten hours." ([6]).

I.A.10. March 8 - 12, 2004

The 2004 QID was held March 8 - 12, 2004. DARPA stated ([3], p. 5):

> The QID was used to determine the final 20 participants for the Grand Challenge. The 25 teams that passed the technical paper review process were invited (21 actually participated) to the QID at the California Speedway in Fontana, California, March 8-12, 2004... The QID comprised several distinct activities: a static, safety, and technical inspection of the robotic vehicles and their systems; a separate practice area; and a demonstration course of approximately 1.4 miles that the vehicles were required to traverse.
>
> The technical inspection ensured that each vehicle complied with all rules and was safe to operate. The demonstration course ensured that each vehicle could demonstrate intelligent autonomous sensing and navigational capabilities around a series of static and movable obstacles designed to represent those that might be found on the actual course... The course also provided an opportunity to test the electronic-stop (E-stop) systems of each vehicle and other equipment and procedures that would be used during the actual event.

> Each vehicle was ranked according to its overall time to complete the course, and point deductions were taken for impacting obstacles, exceeding established speed limits, or deviating from the established course. Over the 5-day period, eight teams completely finished the course, nine teams partially finished the course, two teams terminated within the starting area, and two teams officially withdrew from the event. On March 12, 2004, DARPA announced that 15 of the 21 teams at the QID qualified for the Grand Challenge event.

I.A.11. March 13, 2004

The 2004 GCE was held March 13, 2004. No team successfully completed the 2004 GCE. No team completed more than 7.4 miles of the 2004 GCE course.

I.B. 2005 GCE

I.B.1. June 8, 2004

DARPA announced a "Participant's Conference" would be held on August 14, 2004 ([267]).

DARPA announced the 2005 GCE would be held on October 8, 2005 ([3], p. 11).

I.B.2. August 14, 2004

Although DARPA did not state the "Participant's Conference" was the official start of the 2005 GCE, the author selected the date of the "Participant's Conference" as the official start of the 2005 GCE because of the similarity to the "Competitor's Conference" held on February 22, 2003 which was the official start of the 2004 GCE.

I.B.3. October 8, 2004

DARPA published the 2005 GCE rules ([2]).

The 2005 GCE rules established a proposed 2005 GCE course length of "no longer than 175 miles" ([2], p. 4).

The 2005 GCE rules also established a maximum corrected time of 10 hours. DARPA stated: "DARPA will award a prize ... of $2 million to the team ... whose vehicle completes the route with the shortest corrected time ... under 10 hours..." ([2], p. 5).

I.B.4. February 11, 2005

Parts 1 and 2 of the 2005 GCE application were required to be submitted by February 11, 2005 ([2], p. 6).

I.B.5. March 11, 2005

Parts 3 (“Vehicle Specification Sheet”), 4 (“Video Demonstration”), and 5 of the 2005 GCE application were required to be submitted by March 11, 2005 ([2], p. 6).

I.B.6. April 4, 2005

DARPA stated the “Announcement of teams selected for site visits” would take place on April 4, 2005 based on the “Results from review of vehicle specification sheet and video demonstration” ([2], p. 6).

I.B.7. May 2 - 15, 2005

DARPA stated site visits would take place May 2 - 15, 2005 ([2], p. 6).

I.B.8. June 1, 2005

DARPA stated the “Announcement of 40 teams selected for National Qualification Event (semifinalists)” would take place on June 1, 2005 based on “results from site visits” ([2], p. 7). DARPA selected 43 teams to participate in the 2005 NQE ([268]).

I.B.9. August 15, 2005

Team technical proposals were required to be submitted by August 15, 2005 ([2], p. 7).

I.B.10. September 27 - October 6, 2005

DARPA announced the 2005 NQE would be held between September 27 and October 6, 2005 ([2], p. 7). DARPA stated 20 teams would be selected to participate in the 2005 GCE ([2], p. 7).

The 2005 NQE was held September 28 - October 5, 2005 ([242]). DARPA selected 23 teams to participate in the 2005 GCE ([242]).

I.B.11. October 8, 2005

The 2005 GCE was held October 8, 2005. Four teams successfully completed the 2005 GCE ([5]).

II. TIMEFRAMES AND OBSERVATIONS

II.A. 2004 GCE

- Time between the official start of the 2004 GCE on February 22, 2003 and the last day of the application period for the 2004 GCE on October 14, 2003: 234 days.
- Time between the official start of the 2004 GCE on February 22, 2003 and the first day of the 2004 QID on March 8, 2004: 380 days.
- Time between the last day of the application period for the 2004 GCE on October 14, 2003 and the first day of the 2004 QID on March 8, 2004: 146 days.
- DARPA published at least two revisions of the 2004 GCE rules, one before and one after the last day of the application period for the 2004 GCE on October 14, 2003. The earliest revision of the 2004 GCE rules the author is aware of is the "April 1.2" revision of the 2004 GCE rules. The version number implies there were prior revisions, which may not have been published.
- DARPA revised the proposed course length continuously in the months prior to the 2004 GCE: on February 22, 2003 (300 miles), April 1, 2003 (360 +/- 60 miles), June 18, 2003 (250 miles), November 26, 2003 (210 miles), and January 5, 2004, when the proposed course length was deleted from the "5 January 2004" revision of the 2004 GCE rules.
- DARPA revised the maximum corrected time from greater than 10 hours to 10 hours on April 1, 2003.

II.B. 2005 GCE

- Time between the official start of the 2005 GCE on August 14, 2004 and the last day of the application period on March 11, 2005: 209 days.
- Time between the official start of the 2005 GCE on August 14, 2004 and the first day of the 2005 NQE on September 28, 2005: 410 days.
- Time between the last day of the application period for the 2005 GCE on March 11, 2005 and the first day of the 2005 NQE on September 28, 2005: 201 days.
- DARPA published one revision of the 2005 GCE rules on October 8, 2004 before the last day of the application period for the 2005 GCE on March 11, 2005.
- DARPA did not revise the course length (175 miles) or maximum corrected time (10 hours) after the 2005 GCE rules were published on October 8, 2004.

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1. The text of the footnote reported by DARPA differs slightly from the text of the Fiscal Year 2001 National Defense Authorization Act, which stated: “It shall be a goal of the Armed Forces to achieve the fielding of unmanned, remotely controlled technology such that... by 2015, one-third of the operational ground combat vehicles are unmanned.” ([4], p. 46).

2. Teams are referred to by the unique combination of year and identifier throughout this technical report. For example, Axion Racing is referred to as “Team 2004-02” for the 2004 QID and GCE, and “Team 2005-01” for the 2005 GCE. See Table III for a list of team reference numbers.

3. Many teams which participated in the 2004 QID or GCE or 2005 GCE reported pre-mapping was in use by the team. See Chapter XI. Several teams reported pre-mapping prior to the race effectively eliminated from consideration for the controlling intelligence all terrain but the actual course defined by the RDDF. The task of the controlling intelligence was therefore made simpler, and became one of distinguishing the course from terrain which had been eliminated from consideration by the team, and avoiding unintended obstacles.

   Statements similar to those made by Teams 2004-01 and 2004-02 were typical:

   - Team 2004-01 stated: “Terrain outside of Challenge route boundaries is written to the local map as completely impassable. The AI will not consider traversing these areas under any circumstances” ([8], p. 5).

   - Team 2004-02 stated: “At the beginning of the DARPA Grand Challenge race, the participants are provided with GPS waypoints and error margin information. [The challenge vehicle] recognizes these boundaries in its mapping engine, and makes all decisions based upon the knowledge that it should not pass these boundaries.” ([9], p. 10).

4. Several teams referred to the key components or technologies in use by the team as well-known. Statements similar to those made by Teams 2004-02, 2005-01, 2005-13, and 2005-14 were typical:

   - Team 2004-02 stated: “An autonomous vehicle race through the desert such as the DARPA Grand Challenge presents tremendous technical challenges that push the limit of existing individual technologies, as well as their synthesis into an integrated system. The challenges can be broken down into the following distinct components: goal identification, map assessment and planning to define a path to the goal, real time sensing of the environment to avoid obstacles, selection of the optimal route, and transmission of commands to mechanically move the vehicle. Separately, each of these components has been solved by existing technology.” ([9], p. 2).

Team 2004-02 participated in the 2005 GCE as Team 2005-01. Team 2005-01 stated: “The DARPA Grand Challenge provides tremendous technical challenges that push the limit of existing individual technologies, as well as their synthesis into an integrated system. The Challenge can be broken down into distinct components: goal identification, map assessment and planning to define a path to the goal, real time sensing of the environment to avoid obstacles, selection of the optimal route, and transmission of commands to mechanically move the vehicle. Separately, each of these components has been solved by existing technology.” ([10], p. 2).

- When describing their general approach to the Grand Challenge, Teams 2005-13 and 2005-14 stated: “These distinctive technologies, combined with solid implementation of well-known basics like pose estimation, waypoint following and path tracking drive [the challenge vehicle].” ([11], p. 2 and [12], p. 2).

In addition, the author considers the following observations support this conclusion:

- References describing or documenting key components or technologies in use by teams participating in the 2004 QID or GCE or 2005 GCE generally pre-date the Grand Challenge by several years, as a minimum, indicating they were known at the time of the Grand Challenge. Several teams cite these references in their technical papers and results published via the Journal of Field Robotics.

- Teams participating in the 2004 QID or GCE or 2005 GCE made extensive use of COTS components, with successful teams and most potentially disruptive teams being integrators of existing COTS components. In general, teams which attempted to re-implement existing technologies were not successful. This will be discussed in detail throughout this technical report.

5. It is unclear what DARPA intended by the phrase “average minimum speed”. The phrase is interpreted herein as “average speed”.

6. DARPA stated: “No vehicle was able to complete the 142-mile Grand Challenge route.” ([3], p. 7).

7. DARPA stated: “The Defense Advanced Research Projects Agency (DARPA) today announced that five autonomous ground vehicles successfully completed the DARPA Grand Challenge...” ([5]). The use of “success” to mean “completed the Grand Challenge”, does not conform to criteria published by DARPA prior to the event, and is not used herein.

8. The author's lack of familiarity with PHP at the beginning of this research, specifically, the use of “$” for identifiers, including variable names, resulted in manual calculation to determine the cause of a 0.1 - 12.5% variance in distance calculated using Vincenty's Inverse Formula.

   While attempting to determine the cause of the variance, several errors in current PHP and Javascript references were identified which made diagnosis difficult:

   - Descriptions provided for PHP functions `sin()` ([14], p. 441), `tan()` ([14], p. 451), `asin()` ([14], p. 383), and `atan()` ([14], p. 384) were identical. The description provided for `sin()` was reported as “corrected” by the publisher as of the April, 2006 printing; the description provided for `tan()` was reported as “unconfirmed”.

   - A reference incorrectly gives the concatenation assignment operator “ `.=`” as “ `.+`” ([14], p. 478). This had not been reported by the publisher as a known error as of the April, 2006 printing, and was reported to the publisher by the author.

   - A reference stated: “...M specifies the number of digits before the decimal point, while D gives the number of places after the decimal point.” ([15], p. 147). However, both versions “5.0” and “6.0” of the MySQL Reference Manual state: “'(M,D)' means that values can be stored with up to M digits in total, of which D digits may be after the decimal point.” ([16]). Therefore, M gives the number of digits total, including those before and after the decimal point. Review of the third edition of this reference indicated this error is still present on page 144. Based on the author's personal experience, the author proposes this may be a translation error.

9. DARPA stated that latitudes and longitudes are given as type FLOAT ([13], p. 1). However, when attempting to read latitude and longitude values from the 2004 QID, 2004 GCE, and 2005 GCE RDDF into a MySQL database using the RDDF analysis application, specifying FLOAT in lieu of DOUBLE caused errors in the values of the latitudes and longitudes in the 5th, 6th, and 7th position after the decimal place.

10. DARPA made resources and references available to teams participating in the 2004 QID or GCE or 2005 GCE via the Grand Challenge website, such as several revisions of the 2004 GCE rules, a “description of the mandatory subjects to be addressed” in the team technical proposal, and the 2004 QID and GCE RDDF. The Grand Challenge website was substantially redesigned prior to the 2005 GCE. DARPA re-published portions of the Grand Challenge website as the Archived Grand Challenge 2004 website ([17]), but did not retain all published records. As a result, the Archived Grand Challenge 2004 website is an incomplete record of events.

11. Analysis of the 2004 GCE RDDF revealed that the Maximum Crossing Time does not correspond to the “time by which a Challenge Vehicle must pass that Phase Line Waypoint in order to remain in the Challenge.” ([1]). The Maximum Crossing Time for waypoint 2024 (“16:30:00”) was ten hours after the first vehicle departed the starting chute on the day of the race: “At 6:30 AM on Saturday, March 13, 2004, [the Team 2004-10 challenge vehicle] sped from the starting chute at the Slash X Ranch in Barstow, California, marking the start of the DARPA Grand Challenge” ([3], p. 7).

    The other challenge vehicles participating in the 2004 GCE began the course over the next two hours ([3], p. 7). Vehicles not having completed the course by the Maximum Crossing Time for waypoint 2024, the final Phase Line Waypoint, or any waypoint between waypoint 2024 and waypoint 2585, the final waypoint, could not have successfully completed the course in ten hours (see Table IV). As a result, the author was unable to determine what DARPA intended by specifying Phase Line Waypoints with a Maximum Crossing Time.

12. Vincenty stated ([21]):

    ```
    Distances obtained from the inverse solution and
    rounded off to the millimeter may be in error by up to
    0.5 mm, which represents 0.000015″ in the direction of
    the line.
    ```

13. According to paragraph 2 (“Notation”) of Vincenty, *f* is a function of *a* and *b* ([21]). However, *a* and 1/*f* are considered “Defining Parameters” with “adopted values” by the National Imagery and Mapping Agency (NIMA), and the value of *b* is a “Derived Geometric Constant” ([22]). As a result, the RDDF analysis application does not calculate *f* in accordance with Vincenty ([21]), but uses the values for *a*, *b*, and *f* reported by NIMA ([22]).

14. NIMA stated ([22]):

    ```
    In common practice the geoid is expressed at a given
    point in terms of the distance above (+N) or below
    (-N) the ellipsoid.  For practical reasons, the geoid
    has been used to serve as a vertical reference surface
    for mean sea level (MSL) heights.  In areas where
    elevation data are not available from conventional
    leveling, an approximation of mean sea level heights,
    using orthometric heights, can be obtained from the
    following equation:

    H = h - N

    where:
    ```

```
h  = geodetic height (height relative to the
ellipsoid)

N = geoid undulation

H = orthometric height (height relative to the geoid)
```

15. DARPA reported at least two different 2005 GCE course lengths. DARPA stated: "At least three robots successfully completed a grueling 131.2-mile course in the Mojave Desert today..." ([26]).

    The next day, DARPA stated: "...five autonomous ground vehicles successfully completed the DARPA Grand Challenge, a tough, 131.6-mile course in the Mojave Desert." ([27]).

    The latter length, from a source published after the 2005 GCE, is used herein.

    This was a relatively common error. Course length and average course segment length were variously and incorrectly reported by both DARPA and some teams which participated in the 2004 and 2005 GCE. For example, Team 2005-06 stated: "[The course] consisted of a series of GPS waypoints which were an average of 275 feet apart." ([28], p. 510). The 2005 GCE RDDF defines 2934 course segments. See paragraph II.C.2. An average course segment length of 275 ft would have resulted in a course length of 152.8 miles (245.9 km), approximately 21.2 miles greater than the 2005 GCE course.

16. The author notes the course length calculated for the "smoothed" 2005 GCE course conforms more closely to the 131.2-mile course length reported by DARPA ([26]). The error in calculated course length was less than 0.1 percent.

17. While evaluating data resulting from the 2004 and 2005 RDDF analysis, the author noted, and initially attached significance to, the fact that some of the speeds in the 2004 and 2005 RDDF naturally result in turns of diameters which match the squares of the numbers from one to 12.

    This can be explained by the fact that one mile per hour equals 0.1998 meters per second, and is essentially equivalent to one-fifth (1/5) m/s. As a result, there is a natural confluence with speeds that are multiples of five mph defined by the RDDF.

    Compounding this observation, for the SSF chosen as the reasonable lower bound in the analysis above (1.02):

$$\frac{1}{(g \cdot SSF)}$$

is equal to:

$$\frac{1}{(9.80 \cdot 1.02)}$$

which is essentially equivalent to one-tenth (1/10) m/s^2.

Therefore, calculated radii are essentially equivalent to the square of the speed, divided by five, which is in every case a multiple of five, which is then divided by ten. See Table VIII.

The author concluded this is a consequence of the selected geometry, and converting between miles per hour and meters per second using known values, i.e., the number of feet in one mile (5280), number of seconds in one hour (3600), and number of feet in one meter (3.2808399), which had no other significance but may otherwise be convenient for course designers.

18. Although commercially-available ATVs were also popular, their potential as military service vehicles is limited by reduced cargo capacity. No vehicle based on a commercially-available ATV completed the 2005 GCE course.

19. This section was amended in 2006 by Public Law 109-364, Section 212(a)(1), which substituted “Director of Defense Research and Engineering and the service acquisition executive for each military department” for “Director of the Defense Advanced Research Projects Agency” and “programs” for “a program” ([60]).

20. The FCS was canceled June 23, 2009 ([62]). Two of three planned MULE variants were cancelled following a U. S. Army review of the Army's short- and long-term modernization requirements in December, 2009: the XM1217 MULE-T and XM1218 MULE-CM ([63]).

21. Various NovAtel sensors reported to be in use by the teams included: “Anovatel Pro-Pack LB” (Team 2004-18), “Novatel ProPack LBHP GPS” (Team 2004-20), “Novatel ProPac-LB-HB” (Team 2004-22), “Novatel Propack -LB” (Team 2004-23), “Novatel ProPak-LB” (Team 2005-03), “Novatel Propak LB-L1L2” (Team 2005-04), “NovAtel Propak-LBPLus” or “Novatel ProPak LB-Plus” (Team 2005-05), “NovAtel ProPAK-LBplus” (Team 2005-08), “Novatel Pro-Pack LB dual frequency (L1/L2)” (Team 2005-20), and “Novatel Propak LBplus” (Teams 2005-22 and 2005-23).

    Neither the manufacturer website ([149]) nor “Discontinued Products List” ([150]) reported a “NovAtel ProPak-LB” product exists. However, the “Discontinued Products List” referred to a family of “NovAtel ProPak-LBplus” products with specific model numbers such as “PROPAK-LB+HP” and “PROPAK-LB+HP-L1L2”.

Unless otherwise noted, the author considers it likely a NovAtel ProPak-LBplus DGPS receiver was in use by the teams.

22. Via a “NOTE” in revision “5 January 2004” of the 2004 GCE rules, DARPA stated: “GPS data for the RDDF was collected using a NAVCOM StarFire™ GPS system...” ([6]), which may explain the popularity of NavCom DGPS receivers.

    Six teams which participated in the 2004 QID and GCE reported one or more NavCom DGPS receivers were in use by the team: Teams 2004-04, 2004-06, 2004-13, 2004-14, 2004-17, and 2004-24. See Table XXVI.

    Six teams which participated in the 2005 GCE reported one or more NavCom DGPS receivers were in use by the team: Teams 2005-01, 2005-02, 2005-03, 2005-10, 2005-15, and 2005-18. See Table XXVIII.

    All teams which reported a NavCom DGPS sensor were in use by the team were selected to participate in either the 2004 or 2005 GCE.

23. Teams 2004-05 and 2004-12 reported LIDAR sensors with capabilities similar to the SICK LMS 291 product family were in use by the team. However, neither team was selected to participate in the 2004 GCE. Eighteen unknown SICK LIDAR sensors were in use by teams which participated in the 2004 GCE, some of which may have been LIDAR sensors with capabilities similar to the SICK LMS 291 product family. See Table XLIII.

24. Both the SICK LMS 211-30206 and 221-30206 include an internal heater as a feature, allowing them to operate in temperatures to -30ºC ([75]). An internal heater is available for the SICK LMS 291 product family as an accessory. SICK does not publicly disclose pricing information. See paragraph V.E.2.d.i. However, the author considers it reasonable to conclude the price of a sensor with an internal heater exceeds the price of the same sensor without the internal heater.

25. Teams 2005-04 and 2005-21 participated in the 2004 GCE as Team 2004-23. Team 2005-04 stated: “As [Team 2005-04] were the team that developed the sensing and intelligence for [Team 2004-23], a number of aspects of [the Team 2005-04 challenge vehicle] are descendants of technology and approaches we used in 2004 and a number of individuals participated in this endeavor through its development.” ([169], p. 2).

26. The Team 2005-07 technical proposal was unavailable for review. See paragraph V.C.32. In addition, the Team 2005-11 technical proposal table of contents referred to a paragraph 2.2.2 (“Utilization of Mapping Data”), but the technical proposal contains no paragraph numbered “2.2.2” or titled “Utilization of Mapping Data”.

27. This definition of the fundamental problem of the Grand Challenge is at odds with various team definitions, including that of the team which placed first during the 2005 GCE: Team 2005-16. Team 2005-16 stated: "The strong emphasis on software and vehicle intelligence indicates [Team 2005-16's] belief that the DARPA Grand Challenge is largely a software competition." ([195], p. 2).

28. Alternately, the proposed 2005 GCE course length may have been the average of the "average minimum speed of approximately 15 - 20 mph" multiplied by a maximum corrected time of ten hours. However, a challenge vehicle completing the 2005 GCE course with a proposed length of 175 miles in ten hours would have been required to exceed a minimum speed of 15 mph to successfully complete the 2005 GCE.

29. Based on the author's personal experience, Teams 2004-10 and 2005-13 may have been able to eliminate the use of a generator and batteries by selecting the M1097A2 "heavy variant" HMMWV as challenge vehicle platform in lieu of the M998 due to its heavy duty 200 A alternator ([245]).

30. Team 2005-06 stated ([172], pp. 5 - 6):

> All of [Team 2005-06's] LADAR sensors require 24 volts. Rather than provide this power from the hybrid's 12 volt electrical system, [Team 2005-06] chose to instead provide a separate 24 volt electrical system for these sensors. This electrical system consists of two large-capacity 12 volt batteries connected together to provide 24 volts of power. These batteries alone will provide over ten hours of power. This would provide enough power for the race alone, but not if the vehicle was paused for an extended period of time...
>
> To ensure that the batteries will always be near full capacity, [Team 2005-06] installed six solar panels on top of the vehicle. These solar panels are high efficiency, and will consistently provide over 150 watts of power even in low-light conditions. Since the Grand Challenge will be run in the desert during the day, a sufficient light source is expected to be available at all times.

31. Several teams also referred to modifications to the challenge vehicle's suspension to increase ground clearance or otherwise make the challenge vehicle more suitable for off-road terrain. Those descriptions are not included herein.

32. Although vibration was implicated in failures by Teams 2005-05 (see paragraph XIII.B.3.) and 2005-12 (see paragraph XIII.B.6.), only one team reported “mil-spec” connectors (presumably similar to Amphenol-style connectors common to military hardware) were in use by the team: Team 2005-18.

33. See Appendix C for a list of important dates and milestones for the 2004 and 2005 GCE.

34. Inadequate test and evaluation was the leading cause of failure during the 2005 GCE among potentially disruptive teams, suggesting that even if a greater number of teams were potentially disruptive, inadequate test and evaluation may have prevented them from being competitive with Teams 2005-13, 2005-14, and 2005-16, all of which had prior experience and extensive corporate or academic sponsorship. See paragraph XV.E. GPS “jump” and position error was the problem most frequently reported by the teams which was preventable through adequate test and evaluation.

35. The hyperlink to the Team 2005-07 technical proposal hosted by the Archived Grand Challenge 2005 website ([19]) was a hyperlink to the team website, and the author was unable to locate a copy of the Team 2005-07 technical proposal on the team website. As a result, the author concluded the technical proposal was unavailable for review. See paragraph V.C.32.

36. Team 2005-12 later stated: “...[The challenge vehicle] suffered a communications failure between the GPS unit and the guidance computer just before Beer Bottle Pass, a mountain pass near the end of the course, that would have ended a fully autonomous attempt.” ([183], p. 753). Obviously, a similar communications failure during the 2005 GCE would have resulted in a similar outcome. However, the author is here attempting to distinguish between potentially-disruptive teams and other teams, and there is no evidence supporting a conclusion a similar communications failure would have occurred during the 2005 GCE if Team 2005-12 had not failed to complete the 2005 GCE due to the programming error reported.

37. This observation and similar observations became the basis for a recommendation to develop a process called “acclimation” whereby the challenge vehicle controlling intelligence would calibrate itself. This would make the controlling intelligence portable between vehicles. The recommendation is discussed in more detail in the thesis for which this technical report is the foundation.

38. The author also considered the possibility that lack of sponsorship was ultimately the cause of Team 2004-16 / 2005-17 failure to complete the 2005 GCE. However, although Team 2004-16 / 2005-17 did not report a 2004 or 2005 GCE budget, the team reported moderate corporate and academic sponsorship during both the 2004 and 2005 GCE.

Anecdotal evidence, specifically estimated new vehicle cost based on used vehicle sales, supports a conclusion the cost of the vehicle selected as challenge vehicle platform by Team 2004-16 / 2005-17 during the 2005 GCE would have exceeded $8000. The author asserts Team 2004-16 / 2005-17 would have been able to procure a used commercially-available SUV or truck capable of completing the 2005 GCE at this cost.

However, available estimates of the "EMC AEVIT DARPA Special Edition Package" indicated the cost of the vehicle control system was $35,000 ([215]), which would be an investment several times the cost of the challenge vehicle itself. The author was unable to independently verify either the cost of the Team 2004-16 / 2005-17 challenge vehicle platform during the 2005 GCE or the cost of the "EMC AEVIT DARPA Special Edition Package" because pricing information is not part of the published record. See Chapter XVI.

The author concluded insufficient information was available to determine if lack of sponsorship was ultimately the cause of Team 2004-16 / 2005-17 failure to complete the 2005 GCE, although he accepts it is a possibility.

39. Teams are listed in alphabetical order, based on the alphabetizing scheme used by DARPA ([254]), in which the words "a", "an", or "the" are not considered to be part of the scheme. DARPA established an alternate alphabetizing scheme, which treats the word "team" as "a", "an" or "the" ([242]). The original alphabetizing scheme was retained so that the teams would appear in the same order when referenced herein.

    In addition, to preserve alphabetical order, the occurrence of the team names "MonsterMoto" and "Mojavaton", in the order presented by DARPA ([242]), was reversed.

40. Team 2004-09 reported a "stock four-wheel drive vehicle" was in use by the team ([47], p. 2). However, the "Team Information" provided by DARPA via the Archived Grand Challenge 2005 website ([19]) reported the Team 2004-09 challenge vehicle was a purpose-modified 2004 Acura MDX.

41. Team 2004-13 reported a "4-wheel drive vehicle" was in use by the team ([232], p. 1). Team 2004-13 participated in the 2005 GCE as Team 2005-15. Team 2005-15 reported the team challenge vehicle was a purpose-modified 2003 ATV Prowler ([53], p. 4).

42. The hyperlink to the Team 2005-07 technical proposal hosted by DARPA via the Archived Grand Challenge 2005 website ([19]) was actually a hyperlink to the team website. The author was unable to locate a copy of the Team 2005-07 technical proposal on the team website. As a result, the author concluded the technical proposal was unavailable for review. See paragraph V.C.32. However,

Team 2005-07 reported the team challenge vehicle was a purpose-modified 1987 Chevrolet Suburban ([233]).

43. DARPA reported the number of miles of the 2005 GCE course completed by each team which participated in the 2005 GCE ([37]). The number of miles reported ([37]) does not conform to either the reported length of the 2005 GCE course[15] or the calculated length. See paragraph II.C.1.b. The reported length of 131.6 miles plus the smallest possible increment greater than the reported length (0.1 miles) may indicate course completion.

44. Although the presentation itself is undated, file "overview_pres.pdf" hosted by DARPA via the Archived Grand Challenge 2004 website ([17]) is dated December 12, 2003.

45. Although the copy of DARPA's responses is undated, file "darpaanswersgeneral11-26-03.pdf" hosted by Team 2004-20 via the Team 2004-20 website ([20]) is dated November 26, 2003.

46. Although the presentation itself is undated, file "qidprocessdescription.pdf" hosted by Team 2004-20 via the Team 2004-20 website ([20]) is dated January 2, 2004.

47. The title of this reference cited by Auburn University ([262]) does not match the title of the reference itself: "Development of an Autonomous Vehicle for the DARPA Grand Challenge".