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.