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. <u>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</u>

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. <u>The maximum obstacle detection range for LIDAR sensors is limited by reflectivity</u>

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. Stopping distance

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. Unknown Videre Design stereo camera pair and unknown cameras

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. Unknown long-range RADAR

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. SICK LMS 200-30106

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. <u>Cohu 1330 cameras</u>

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. <u>Stopping distance</u>

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. <u>Unknown SICK LIDAR sensor</u>

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. <u>Stopping distance</u>

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. <u>Unknown SICK LIDAR sensors</u>

The Team 2005-07 challenge vehicle stopping distance:

- exceeded the maximum effective range of short-range LIDAR sensors.

VIII.B.32.a.ii. <u>Unknown stereo camera pairs</u>

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 40º. 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. Riegl LMS-Q120i

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. Point Grey Dragonfly cameras

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. Field-of-view limitations

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. <u>Field-of-view limitations</u>

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 40º 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.