CHAPTER II. COURSE DIFFICULTY

II.A. Discussion

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Based on a review of information published by DARPA:

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

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

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

- The 2004 GCE course was too difficult.

Alternately:

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

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

II.B. Analysis

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

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

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

II.B.1. RDDF revision

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

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

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

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

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

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

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

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

```
Phase Line Waypoints are those Waypoints that have
been assigned a Maximum Crossing Time.
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DARPA defined the "Maximum Crossing Time" as ([1] and [6]):

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

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

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

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

II.B.1.c. 2005 GCE RDDF

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

II.C. Results

II.C.1. Course length

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

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

II.C.1.a. Error in distance calculations

II.C.1.a.i. Error in distance calculations based on the WGS84 Ellipsoid

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

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

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

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

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

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

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

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

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

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

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

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

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

II.C.2. Average course segment length

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

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

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

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

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

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

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

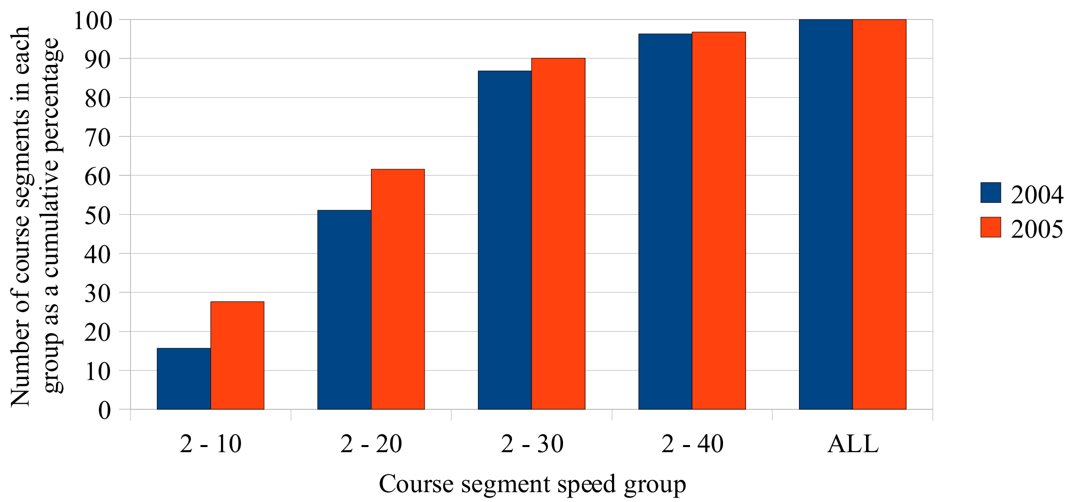

Figure 1. Number of course segments in each group versus cumulative percentage.

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

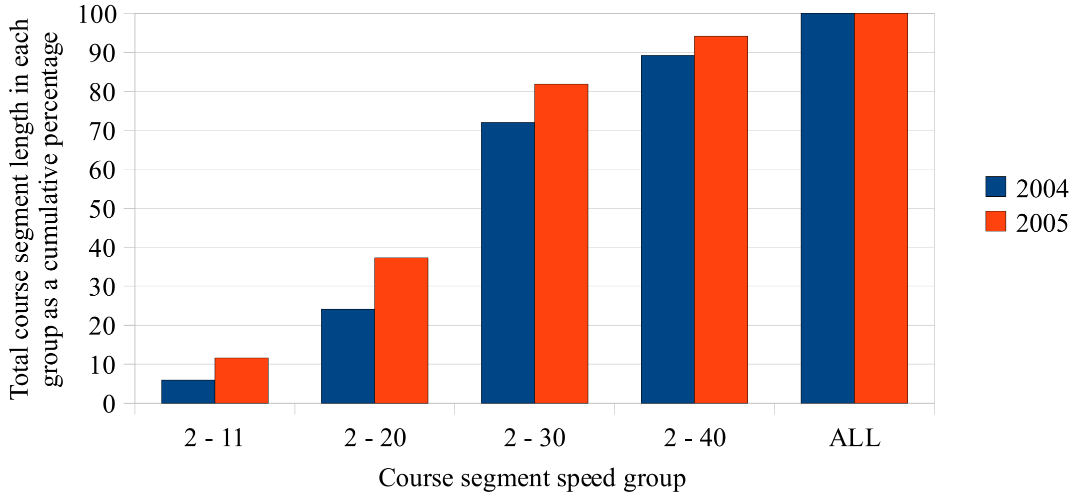

Figure 2. Total course segment length in each group versus cumulative percentage.

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

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

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

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

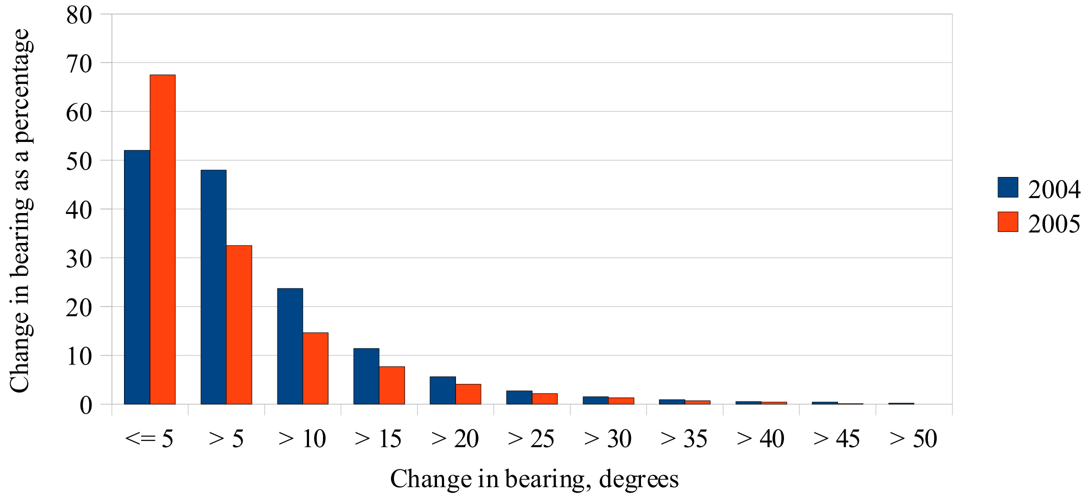

Figure 3. Change in bearing versus percentage.

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

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

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

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

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

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

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

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

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

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

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

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

II.C.7. Evidence of course grooming

II.C.7.a. <u>"Taming"</u>

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

II.C.7.c. Changes in maximum course segment length from 2004 to 2005

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

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

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

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The distance between successive waypoints will never
exceed 1,000 feet and will never be less than 3 feet.
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The maximum course segment length of 305 m defined by the 2005 RDDF, above, is approximately equal to 1000 feet. DARPA did not limit the distance between successive waypoints defined by the 2004 GCE RDDF ([1] and [6]).

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

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

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

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

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

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

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

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

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

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

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

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

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

II.D. Conclusion

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

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

- Increased the number of waypoints from 2586 to 2934.

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

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

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

In addition, the evidence supports a conclusion that:

- DARPA provided well-defined berms for the 2005 GCE course to make it easier for challenge vehicles to identify the edges of the path.
- DARPA groomed washouts, eliminating areas that would otherwise have been high risk.
- The location DARPA selected for the 2005 GCE course resulted in a decrease in the number of miles of observed slope greater than 5 degrees from 17.5 miles to less than two miles, which resulted in more effective obstacle detection at long range and provided a sensing advantage to teams which were able to effectively use long-range sensors.
- DARPA engineered the 2005 GCE course to eliminate the extreme course segment lengths and lateral boundary offsets defined by the 2004 GCE RDDF.
- DARPA engineered the 2005 GCE course to decrease the number of significant changes in bearing.
- DARPA engineered the 2005 GCE course to introduce deceleration lanes to force vehicles to decelerate to significantly lower speeds before negotiating areas which were high risk.

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

- Team 2005-02

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

- Team 2005-03

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

- Team 2005-16

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

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

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