CHAPTER III. VEHICLE RISK OF ROLLOVER

III.A. Discussion

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

The author formulated the following hypothesis:

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

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

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

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

v = vehicle speed,

r = turn radius, and

g = acceleration due to gravity

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

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

where

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

h = height of vehicle CG above the road surface

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

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

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

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

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

III.B. Analysis

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

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

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

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

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

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

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

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

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

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

III.B.1. Law of Sines approach

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

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

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

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

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

III.C. Results

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

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

III.D. Conclusion

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

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

and

> Segments with unspecified maximum speed are indicated by 999.

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

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

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

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

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Speed limits will be mandatory for certain segments of
the Challenge Route for safety and environmental
reasons.  Speed limits will be specified in the RDDF
in miles per hour, and will apply from the associated
Waypoint to the next sequential Waypoint.  A specified
speed limit does not imply that it has been tested or
that it is a safe or achievable speed.  Exceeding a
speed limit will be cause for disqualification.
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A speed of 48.0 mph was within the course-wide speed limit of 50 mph imposed by DARPA for the 2005 GCE. Available sources ([1] and [6]) did not report a course-wide speed limit was imposed by DARPA for the 2004 GCE. The 2004 GCE RDDF defined speeds up to, and including, 60 mph.

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

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

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

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

and:

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

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

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

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

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

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

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

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

v = vehicle speed,

r = turn radius,

g = acceleration due to gravity, and

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

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

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

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

III.D.1.b. Effect of friction

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

$$SSF < \mu_k$$

where SSF = the Static Stability Factor, and

μ_k = the kinetic coefficient of friction

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

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

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

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

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

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

III.D.1.d. Safety factor

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

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

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

III.D.2. Minimum design turn radius

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

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

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

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

III.D.3. Confirmation of forced deceleration lanes

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

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

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

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

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

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