CHAPTER IV. TEAM EVALUATION OF VEHICLE RISK OF ROLLOVER

IV.A. Discussion

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

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

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

IV.B. Analysis

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

- Team 2004-01

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

- Team 2004-04

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

- Team 2004-05

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

- Team 2004-07

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

- Team 2004-09

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

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

- Team 2004-18

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

- Team 2004-25

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

- Team 2005-02

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

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

- Team 2005-04

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

- Team 2005-06

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

- Team 2005-09

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

- Teams 2005-13 and 2005-14

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

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

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

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

- Team 2005-15

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

- Team 2005-18

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

- Team 2005-19

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

- Team 2005-20

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

- Team 2005-21

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

- Team 2005-22

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

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

- Teams 2005-22 and 2005-23

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

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

IV.C. Results

- 2004

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

- 2005

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

IV.C.1. Mitigation of rollover risk

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

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

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

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

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

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

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

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

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

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

IV.D. Conclusion

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

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

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

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