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Vehicle Road Runoff – Active Steering Control for Shoulder Induced Accidents

J. Black†, J. Wagner†, Ph.D., P.E., K. Alexander‡, Ed.D., P. Pidgeon‡, Ed.D.
†Department of Mechanical Engineering and ‡Automotive Safety Research Institute
Clemson University, Clemson, South Carolina 29634

Abstract

The safe operation of a passenger/commercial ground vehicle requires continual judgment, mission planning, and driving skills by the operator. The departure of the tires from the prescribed road surface, labeled road runoff, represents a hazardous situation that must be properly handled to prevent unintended consequences. In this instance, the recommended actions are for the driver to recognize the situation, reduce vehicle speed, and then return to the road way in a safe manner. However, drivers may command a large steering wheel angle to immediately return to the paved road surface which can result in vehicle yaw angles which precipitate accidents. In this paper, the potentially dangerous dynamics for a vehicle recovering from road runoff will be explored with an opportunity for steering system intervention. First, a basis for the importance of the problem will be established. Second, the vehicle dynamics and tire/road interface will be examined to demonstrate the "cause and effect" of large steer angles when returning to the road. Finally, the integration of a road runoff recovery strategy algorithm into a steer-by-wire control system will be discussed. Representative numerical results will be presented and discussed.

1. Introduction

A run-off-road (ROR) accident occurs when one or more tires of a ground vehicle leave the road surface, resulting in the driver losing control and/or colliding with an object. The reasons for road departure can be excessive speed, obstacle avoidance, lack of attention (fatigue, cabin distraction), or other outside influences (alcohol, drugs). A specific subset of ROR accidents are the result of the driver losing vehicle control while attempting to return to the roadway from a soft shoulder. These events will be identified as shoulder induced accidents (SIA). SIAs are primarily due to the difference in elevation between the paved roadway and the soft road shoulder. Excessive steering may be required to negotiate the sharp change in elevation, and this steering input can cause the driver to lose control if the vehicle speed is too high. These accidents are largely attributed to driver error and can be minimized with proper training and/or steering intervention.

Previous research on ROR has primarily focused on road design and construction. Some of the measures to provide driver warnings include rumble strips for lane deviation [1,2]. Extended hard shoulders have been incorporated into road designs where space allows giving drivers more time to react before encountering an ROR situation [3]. To compliment these activities, the circle of safety may be closed with efforts to prevent SIAs after an ROR condition has been reached. This can be accomplished with a mixture of driver training and active steering to eliminate preventable SIAs.

The traditional hydraulic power steering system provides passive torque assistance to the driver while directly channeling the steering input from the steering wheel via the driver to the road wheels. Electric power steering systems, refer to Figure 1a, provide similar passive assistance with greater efficiency. However, this steering system can also be programmed with smart algorithms for active torque feedback. The inclusion of a planetary gear set allows an electric power steering system to have limited angular control to improve the driver's steering input as necessary (i.e., active assistance). A steer-by-wire system, refer to Figure 1b, provides the opportunity for full torque and road wheel angle intervention. Hence, various levels of active steering can be implemented in either electric power steering or steer-by-wire configurations depending on the required level of control.

This paper reviews the literature associated with road runoff, discusses vehicle behavior, and methods of mitigation. Section 2 provides an overview of the vehicle safety database to illustrate that this accident type occurs frequently. The vehicle behavior in Section 3 describes an SIA in full detail. In Section 4, the governing equations for vehicle and steering dynamics are presented to further explain run-off-road events. In the mitigation section, driver training and active control systems will be presented. Section 6 presents the summary.

2. Run-Off-Road Literature

Despite efforts to improve motor vehicle safety and decrease driver error, vehicle crashes continue to be an important public health concern in the United States [4]. According to the National Highway Traffic Safety Administration (NHTSA), motor vehicle crashes were the leading cause of death in the United States in 2004 for persons between the ages of 2-34 [5]. In 2005, there were 43,443 highway fatalities in the estimated 6,159,000 police reported motor vehicle traffic crashes, 2,699,000 people were injured, and 4,304,000 crashes involved property damage only [6]. NHTSA estimated the total economic impact of motor vehicle crashes to be $230.6B in 2000 [7].

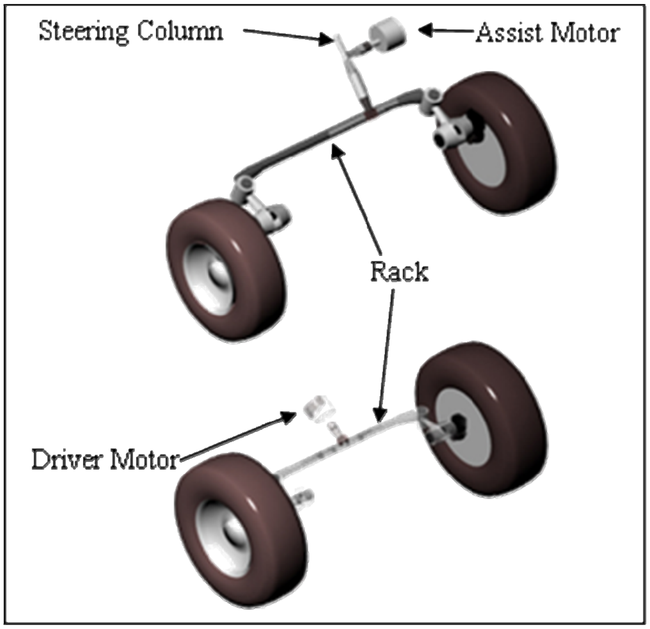

Figure 1: Configuration diagrams for an (a) electric power steering, and (b) steer-by-wire system in a ground vehicle.

Rarely is there a single causal factor for motor vehicle crashes. In fact, there are often multiple, interrelated factors which combine to produce a collision. The three primary contributing factors leading to traffic crashes are human, vehicle, and infrastructure [4]. Human factors refer to the driver behavior which might include decision errors, distraction, inattention, speeding, not wearing seat belts, and impaired driving. Vehicle factors include vehicle design issues as well as mechanical failure. Infrastructure factors involve roadway conditions and design. According to recent studies, of the contributing factors to traffic crashes, human factors are the most important [4].

Run-off-road collisions, also known as single vehicle road departures (SVRD), are among the more serious types of the crashes. The U.S. Department of Transportation (USDOT) reported that of the 42,643 fatalities in 2003 there were 25,231 road departure fatalities (59%), 9,213 intersection fatalities (21%), and 4,749 pedestrian fatalities (11%) [5]. ROR crashes are dangerous for the driver and passenger(s) since the vehicles involved often roll over or strike stationary objects. Furthermore, there are two major categories of ROR collisions which account for about half of the police-reported crashes: traveling too fast in a curve and drift-off-road (DOR) crashes [8,9]. Neuman *et al.* [10] note that ROR crashes involve vehicles that leave the travel lane and encroach onto the shoulder and beyond and hit one or more of any number of natural or artificial objects, such as bridge walls, poles, embankments, guardrails, parked vehicles, and trees. A single vehicle is usually involved in ROR crashes. An ROR crash, which typically consists of a vehicle encroaching onto the right shoulder and roadside, can also occur on the median side where the highway is separated or on the opposite side when the vehicle crosses the opposing lanes of a non-divided highway [10].

Research has shown that the causes for ROR crashes may include “excessive vehicle speed, driver incapacitation, loss of directional control on the road surface, evasive maneuvers, and driver inattention” [11]. More recently, the Virginia Crash Investigation Team studied driver inattention and distraction in single vehicle ROR crashes. The most common means of prevention depends on an infrastructure approach. Edgeline rumble strips provide noise and vibration to the vehicle as an alarm to warn drivers who are leaving the roadway. Bahar *et al.* [12] present roadway design strategies to reduce the number of ROR fatality crashes. Similarly, Bahar and Parkhill [13] noted three key objectives of infrastructure design to reduce ROR crashes: keep the vehicle in the travel lane, assist drivers that encroach onto the roadside to regain control of the vehicle, and return safely to the correct travel lane, and reduce the severity of run-off road collisions if the first two objectives were not met. The vehicle’s recovery must be controlled, so that the driver does not over-correct and cross into the opposing travel lane or median of a divided highway. Morena [14] focused on 1,887 drift-off-road crashes in Michigan as a subset of ROR crashes. This research found that DOR crashes are 3-to-5 times as severe as other ROR crashes, and that milled design rumble strips were an effective (39% reduction) countermeasure.

A number of recent research studies have emphasized preventing ROR through a vehicle dynamics approach. Pape *et al.* [15] discussed the effectiveness of in-vehicle crash avoidance active safety systems as a countermeasure for ROR crashes through on-road, test track, and simulator experiments designed to improve driver lane-keeping models. The authors reported that numerical studies demonstrated improved driver models for passenger vehicles and tractor trailers; however, heavy trucks present a greater challenge for improved lane-keeping technology due to instability in recovery maneuvers. Second, Deram [16] studied lane departure crashes, specifically focusing on two research questions. First, can vehicle based parameters detect driver inattention? Second, how can such detection be integrated into a lane departure warning system (LDWS)? The findings suggested that an adaptive lane departure warning system was a viable tool for detection. The accompanying simulation studies were able to suppress up to 70% of redundant warnings. Finally, Pohl *et al.* [17] studied a lane-keeping support system which was designed to provide assistance to a distracted driver. The authors utilized a video-based monitoring system to estimate the level of a visual distraction for distracted drivers. On-road tests indicated initial success in terms of a lane-keeping device which only intervened when a lane departure event was detected.

Recently, studies have shown an interest in a human factors approach to ROR crashes. First, Campbell *et al.* [4] provided an extensive analysis of primary contributing human factors for crashes. In analyzing single vehicle ROR crashes, the authors found that the “2 leading crash contributing factors involved speeding in 43% of crashes and resulting in a control loss in 41% of crashes". Furthermore, the study demonstrated other primary contributing human factors for single vehicle ROR crashes including inattention (35%), driving under the influence (21%), drowsy/sleepy drivers (8%), vision obstruction for driver (3%), and driver sickness or blacking out (2%). Second, Janssen *et al*. [18] found that that there were not many studies conducted to investigate driver behavior in ROR crashes. Furthermore, the authors found that the available studies are largely field observation studies and do not delineate best practices for reducing risk-taking behaviors. Third, LeBlanc *et al*. [19] investigated a road departure crash warning (RDCW) system focusing on drivers that either drift off the road or take a turn too quickly. Researchers developed, validated, and field-tested the driver warning system in real time utilizing video and audio data. Findings suggested that the RDCW system improved driver lane keeping and therefore reducing the number of ROR incidents. Additionally, data on driver perception was collected through post-drive questionnaires, debriefing sessions, and focus groups. Interestingly, the authors found that "drivers who rated themselves as not prone to inattention or slips in memory found the RDCW system easier to use (Factor 2) than drivers with higher lapse scores" (pp. 9-15 in [19]). Finally, Sayer *et al*. [9] conducted a field operational test to determine driver acceptance and perceived utility of a ROR crash warning system. The study found that drivers were generally positive regarding the use of the in-vehicle warning systems, and they determined lane departure warning (LDW) to be more helpful than curve speed warning (CSW). Furthermore, the subjects tended to rate the warning systems higher for utility rather than satisfaction. Findings suggested that drivers perceived the overall warning system to increase safety regarding ROR crashes.

This literature survey illustrates the general absence of an active technology specifically focused on run-off-road incidents that may be attributed to shoulder induced accidents. Before investigating active mitigation methods, the vehicle behavior of an SIA will be discussed.

3. Vehicle Behavior

A typical SIA begins with one or more tires leaving the road surface for a number of possible reasons (refer to Figure 2). To correct the situation, the driver commands the vehicle back towards the paved road surface. The tire sidewalls catch the lip of the shoulder as they make contact, and the vehicle's lateral motion is suddenly halted due to the elevation difference as shown in Figure 3.

As the driver increases the steering angle, the sidewalls continue to snag on the shoulder until a sufficient steering angle is provided to overcome the elevation difference and return to the road surface. The front wheels are now steered at a high angle, and if the vehicle speed is high enough, the vehicle will dart across the road with a minimal window for the driver to react (refer to Figure 4).

Figure 2: Passenger vehicle with two tires off road surface.

What happens beyond this point depends on the driver's reaction time, operating skills, experience, and road conditions. If the driver's reaction is too slow or insufficient, the vehicle will likely strike an oncoming vehicle or an object on the far side of the road (refer to Figure 5). More likely, the driver will overreact, sending the vehicle into a skid and/or leaving the road surface once again. Since the vehicle will be in an unstable mode, the driver has a much greater chance of colliding with an object once the vehicle leaves the road surface. Furthermore, the vehicle runs a high risk of overturning either from the skid (high CG vehicles) or from tripping once the vehicle leaves the road surface (all vehicles).

Figure 3: Front tire caught against the road shoulder prior to the vehicle's return to the road surface.

The primary factors that turn this seemingly mild event into a dangerous loss of vehicle control situation are the high steering angle, often excessive vehicle speed during the maneuver, and slow/improper driver reaction just after the

Figure 4: Vehicle immediately after re-entry onto the road surface with a large commanded front wheel steer angle.

vehicle returns to the road surface. The high steering angle is unavoidable in this scenario; however, it can be reduced with some countermeasures. For example, two methods are slower speeds and "getting a run" at the lip rather than approaching it gradually. Both require less steering angle to return all tires to the road surface. The proper procedure for returning to the road in this scenario is to slow down to a near stop before attempting to traverse the elevation difference. Although this sounds logical, due to shock, impatience, ignorance, and necessity (imminent obstacles), drivers attempt to return to the road surface at excessive speeds. While requiring a larger steering angle, higher speeds also give the driver less reaction time and a greater risk of losing vehicle control.

Figure 5: Vehicle less than one second after re-entry with large yaw angle and approaching roadway double solid line.

Once the vehicle returns to the road surface at speed, the driver is typically surprised by the sudden yaw rate and has a delayed overreaction. The vehicle is now in a state that is typically outside the driver's realm of experience. This is a dangerous condition for a vehicle because the driver can become a destabilizing disturbance. The key to mitigating these accidents is to prevent the vehicle from leaving the normal driver's realm of experience. This can be done through active steering/speed intervention during the incident or increasing the driver's experience through focused classroom, simulator, and test track training.

4. Vehicle and Steering Dynamics

To establish a basis to understand run-off-road events and active steering intervention, the governing equations of motion for a low order platform and a steer-by-wire system will be presented. The events immediately following the return to the road can be modeled as a J-turn steering event. To demonstrate the severity of the maneuver, a two degree-of-freedom chassis model (refer to Figure 6) has been selected with the slip angle equations stated as

$$\alpha_f = \delta - \frac{v_y + a\dot{\psi}}{v_x}, \; \alpha_r = \frac{b\dot{\psi} - v_y}{v_x} \qquad (1)$$

Using linear approximations to express the tire cornering stiffness, C_α, the front and rear lateral tire forces become

$$F_{yf} = 2C_{\alpha f}\alpha_f \, , \; F_{yr} = 2C_{\alpha r}\alpha_r \qquad (2)$$

The fundamental force and moment equations for the platform may be written as

$$\sum F_y = F_{yf} + F_{yr} - m(\dot{v}_y + \dot{\psi} v_x) = 0 \qquad (3)$$

$$\sum M = aF_{yf} - bF_{yr} - I\ddot{\psi} = 0 \qquad (4)$$

Hence, the equations of motion for the yaw and side slip are

$$m\dot{\beta} + \frac{2\beta}{v_x}(C_{\alpha f} + C_{\alpha r}) + \dot{\psi}\left[m + \frac{2}{v_x^2}\left(C_{\alpha f}a - C_{\alpha r}b\right)\right] = \frac{2C_{\alpha f}}{v_x}\delta(t) \qquad (5)$$

$$I\ddot{\psi} + \frac{2\dot{\psi}}{v_x}\left(a^2C_{\alpha f} + b^2C_{\alpha r}\right) + 2\beta\left(aC_{\alpha f} - bC_{\alpha r}\right) = 2aC_{\alpha f}\delta(t) \qquad (6)$$

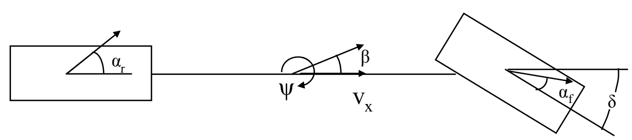

Figure 6: Low order vehicle model with slip angles.

The availability of a steer-by-wire system allows the driver, remote operator, or on-board control system to command the vehicle's trajectory. Steer-by-wire technology replaces the mechanical link with electro-mechanical components between the driver and steering tie rods to decouple the driver and wheels. Consequently, different driver preferences may be achieved as well as enabling semi-autonomous and autonomous vehicle operation. For a front steer-by-wire configuration (refer to Figure 7), the steering wheel servo-motor provides the steering "feel" while the second servo-motor (directional control assembly) offers vehicle maneuverability [20]. The steering system components may be modeled to describe the wheel angle displacement about the kingpin axis for a given driver input torque, T_{driver}, at the steering wheel.

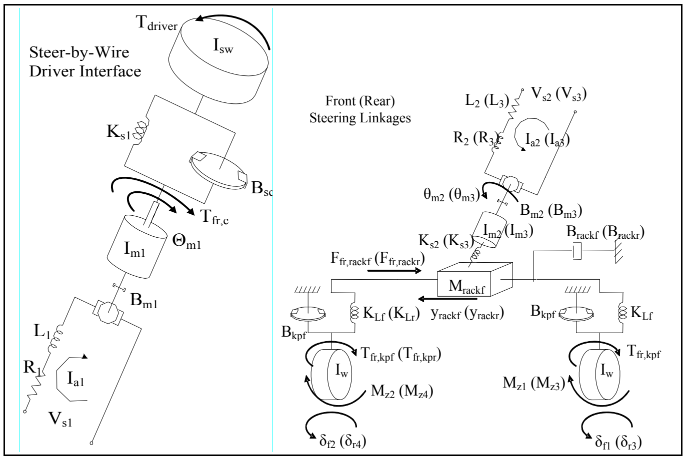

Figure 7: Steer-by-wire system diagram with the driver interface and underhood directional control assembly [21].

The steering wheel and haptic interface motor angular dynamics, θ_{sw} and θ_{M1}, may be stated as

$$\ddot{\theta}_{sw} = \frac{1}{I_{sw}} \begin{pmatrix} T_{driver} - B_{sc}\left(\dot{\theta}_{sw} - \dot{\theta}_{M1}\right) \\ - K_{S1}\left(\theta_{sw} - \theta_{M1}\right) - T_{fr,c} \end{pmatrix} \tag{7}$$

$$\ddot{\theta}_{M1} = \frac{1}{I_{M1}} \begin{pmatrix} - B_{M1}\dot{\theta}_{M1} - B_{sc}\left(\dot{\theta}_{M1} - \dot{\theta}_{sw}\right) \\ - K_{S1}\left(\theta_{M1} - \theta_{sw}\right) + T_{M1} \end{pmatrix} \tag{8}$$

where T_{M1} denotes the motor torque. The servo-motor rotational dynamics for the direction control assembly are

$$\ddot{\theta}_{M2} = \frac{1}{I_{M2}} \begin{pmatrix} - B_{M2}\dot{\theta}_{M2} + T_{M2} \\ - K_{S2}\left(\theta_{M2} - y_{rack_f}/r_p\right) \end{pmatrix} \tag{9}$$

The two servo-motor currents, i_{a1} and i_{a2}, become

$$\frac{di_{a1}}{dt} = \frac{1}{L_1}\left(- R_1 i_{a1} - k_{b1}\dot{\theta}_{M1} + V_{S1}\right) \tag{10}$$

$$\frac{di_{a2}}{dt} = \frac{1}{L_2}\left(- R_2 i_{a2} - k_{b2}\dot{\theta}_{M2} + V_{s2}\right) \tag{11}$$

Finally, the rack and wheel displacements may be written as

$$\ddot{y}_{rack_f} = \frac{1}{m_{rack_f}} \begin{pmatrix} -\dfrac{2K_{Lf}}{r_L}\left(\dfrac{y_{rack_f}}{r_L} - \delta_F\right) - F_{fr,rack_f} \\ - B_{rack_f}\dot{y}_{rack_f} + \dfrac{K_{S2}}{r_p}\left(\theta_{M2} - \dfrac{y_{rack_f}}{r_p}\right) \end{pmatrix} \tag{12}$$

$$\ddot{\delta}_F = \frac{1}{I_f} \begin{pmatrix} - K_{Lf}\left(\delta_F - y_{rack_f}/r_L\right) \\ - T_{fr,kpf} - B_{kpf}\dot{\delta}_F - M_z \end{pmatrix} \tag{13}$$

To investigate a sudden return to the road surface in a shoulder induced accident, these dynamics were used to simulate a standard J-turn step steering input maneuver. The model parameters corresponded to a generic 4-door sedan. The event was simulated at V=72 kph with a step steering input of θ_{sw} =90° at the hand wheel. The trajectory shown in Figure 8 demonstrates the severity of the incident without driver correction. The vehicle quickly develops a high yaw angle as it darts for the centerline. To emphasize the small window that the driver has to react in a potential SIA, the lateral position of the vehicle is plotted against time in Figure 9. The correction window is less than a second, especially considering how quickly the vehicle attains a high yaw angle.

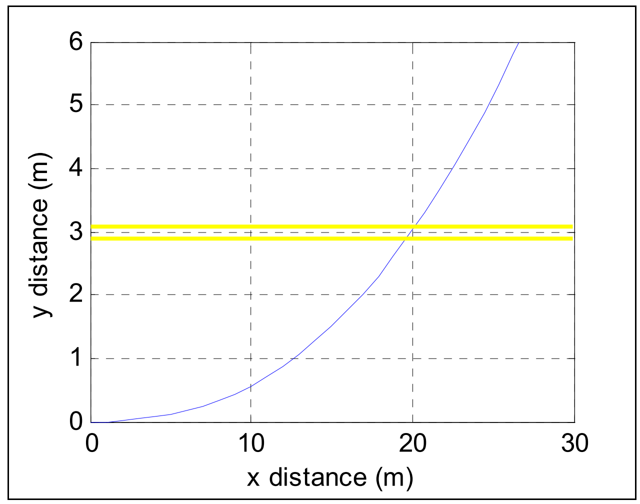

Figure 8: Vehicle trajectory during an emulated shoulder induced accident (simulated J-turn); roadway double solid line at 3 meters crossed by vehicle.

5. Training and Active Control for SIA Mitigation

The crucial moments to intervene in a likely shoulder induced accident are before the vehicle first leaves the road surface, while the vehicle's tires are off the road surface, and the small window immediately after the vehicle returns to the road surface. Although important, the first is not the focus of this research project. Instead, the goal is to synergize with current and future ROR prevention by completing the circle of safety.

In the second intervention window (one or more tires off the road surface), there are opportunities to slow the vehicle down either through an active system or driver education. Active steering intrusion is not recommended in this window because the driver's intention cannot be identified yet. The third intervention window has greatest potential for active steering to mitigate SIAs. This window requires an immediate reaction from the driver to straighten the steering wheel and avoid losing control of the vehicle. With proper training and experience, a driver can do this unassisted. However the current education infrastructure does not support this level of training. Instead of requiring a sharp response from the driver, an active steering system could intervene and make the necessary corrections before the driver realizes that danger is imminent.

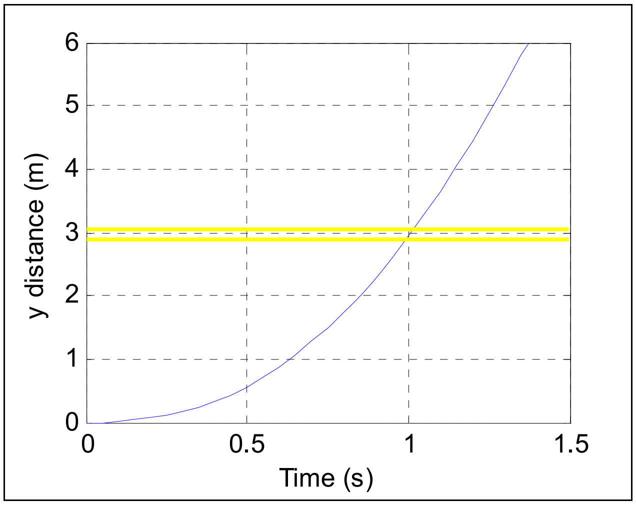

Figure 9: Lateral vehicle position versus time for shoulder induced accident; roadway double solid line crossed within one second for vehicle traveling at 72 kph with high yaw.

5.1 Run-Off-Road Driver Training

Driver training can be implemented with hands on simulator and vehicle exercises. Classroom driver education already exists to provide a medium for increasing awareness of the dangers involved in ROR incidents. Although this may be covered lightly in the current system, the severity is not being realized by drivers. The major problems in ROR crashes from the standpoint of human factors are overconfidence combined with inexperience. Effective classroom education can not provide drivers with experience, but it would make drivers more cautious in a ROR event. Classroom education offers drivers a greater respect for the potential dangers along with a procedure for responding in the safest manner possible. Although driver education is not specifically an engineering problem, it must be taken into account and properly researched. The most effective training approach requires simulator and/or in-vehicle experience in a safe controlled environment. Special equipment would be used to duplicate the primary factors involved in returning to the road. Drivers would experience the excessive steering angles required to return to the road followed by the sudden yaw of the vehicle as it clears the obstruction. This would offer drivers more respect for potential dangers and provide them valuable experience. ROR training could be combined with other car control training programs to increase the overall skill and experience of all drivers.

5.2 Active Braking Control

There are two primary forms of active assistance that can be employed by integrated vehicle hardware/software in an ROR recovery scenario. These are speed reduction prior to return and active steering correction immediately after the vehicle returns to the road surface. The speed reduction system would apply a controlled deceleration through the antilock brake system and illuminate a dashboard warning light to notify the driver of danger. However, this system cannot account for all of the deceleration required to completely avoid an accident because of unknown driver intention. None-the-less, it can serve as a good reminder to the driver and provide partial accident mitigation. Within the realm of existing electronic stability control systems, ROR events may be accommodated to a certain extent.

5.3 Active Steering Control

An active steering control system may be designed to quickly reduce the steering angle as soon as the vehicle returns to the road surface following a ROR event. Instead of providing a pre-programmed response, the system would predict the driver intentions and compensate to match this intention as tire/road properties change. An elegantly designed steering controller for ROR safety would also increase stability and safety in patched ice, split mu, and tire blowout scenarios. As shown in Figure 10, the control system would estimate the tire/road interface parameters under the assumption that the driver reacts to the current conditions with a certain amount of learning delay. If the tire/road interface changes suddenly, the estimator will sense the change before the driver and adjust the steering input to match the previous conditions. This acts as a reaction time buffer, allowing the driver to smoothly transition between road surfaces without losing control of the vehicle. By focusing on driver intention, the control remains non-invasive during ideal conditions while becoming robust enough to assist in other hazardous driving situations (e.g., patched ice, tire blowout, and split mu).

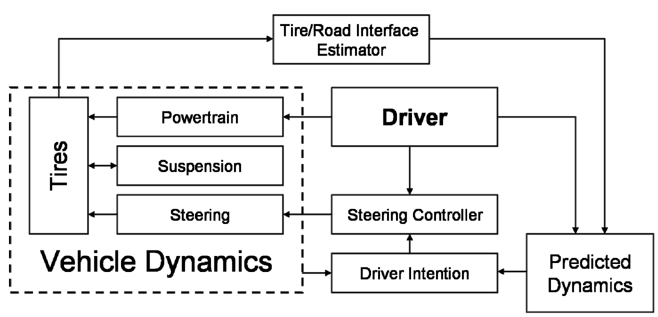

Figure 10: Schematic diagram of active steering controller.

The key to the problem of determining driver intention is understanding the perceived road conditions. All drivers will have a delay in sensing changing road conditions. Although an active steering controller could adjust to changing road conditions quickly, the supplied input may not reflect the output desired by the driver. Consequently, two sets of parameters must be estimated: the true vehicle parameters and the driver's perceived vehicle parameters. The simplest estimation of the perceived parameters comes from a simple time delay of the true vehicle parameters. The current steering input combined with the perceived vehicle parameters can be used to determine the driver's intention. This becomes the controller's target to track to make the vehicle stable and predictable in unpredictable conditions.

As an exploratory approach to the problem, a classical control strategy was applied. The control modules estimated the tire cornering stiffness and provided steering corrections based on the driver's intention. The road wheel angle has been displayed in Figure 11 for the baseline and controlled cases with a gradual steering wheel input from 0° to 90°. The cornering stiffnesses are initially 0 N/rad to simulate the tires catching on the lip of the road shoulder. At t=10 sec, the cornering stiffnesses are returned to their normal values, essentially creating a J-turn with 90° steering input. Figures 12 and 13 display the improvements offered by the active control algorithm which regulated the steering angle. The driver was provided 75% more time to react with an approach towards the centerline at a 30% milder yaw angle. After one second, the vehicle only deviates 0.57m from the edge of the road, making this maneuver much more subtle and manageable for the driver.

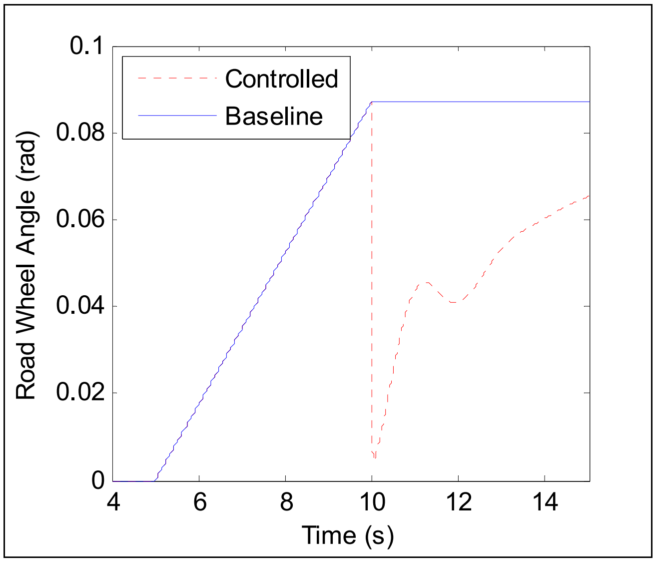

Figure 11: Road wheel angle (90° steering wheel angle) for road runoff maneuver with/without controller; note gradual road wheel angle with control system.

6. Summary

Run-off-road incidents are a significant problem in the realm of vehicle crashes. A variety of measures are being taken to decrease the opportunity of a vehicle leaving the road surface. However, the circle of safety must be closed to mitigate accidents that occur once the vehicle leaves the road. This can be done through improvements in driver training and active steering technology. The potential severity of shoulder induced accidents was demonstrated with a simulated J-turn. The advantages of an active steering controller were presented with a 75% increase in reaction window and 30% decrease in centerline yaw angle. Future activities will enhance the active steering controller and conduct human subject testing in a driving simulator.

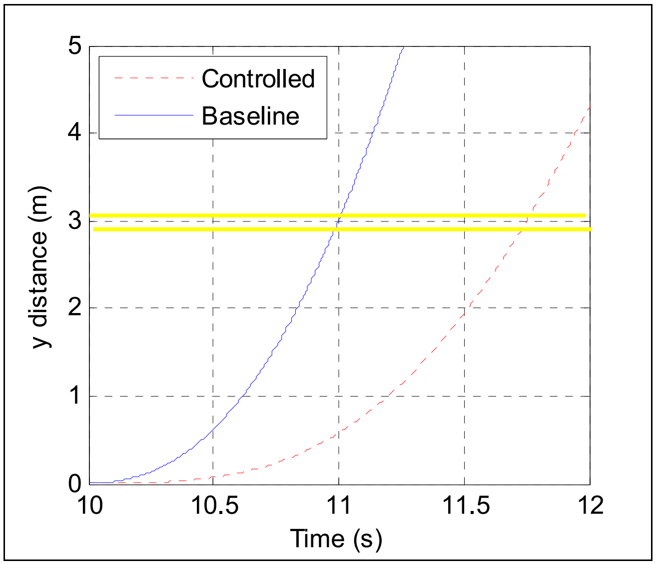

Figure 12: Elapsed time for vehicle to cross double solid line with/without control; 75% gain in reaction time period.

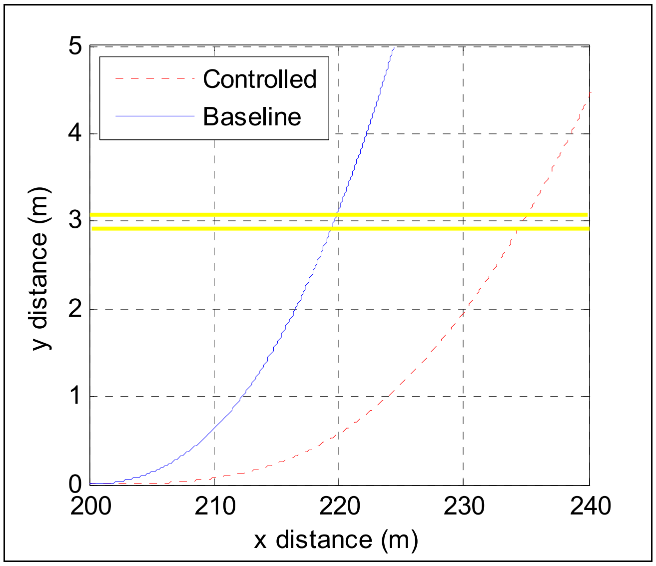

Figure 13: Vehicle roadway position for emulated road runoff with/without control; 30% improvement in yaw.

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