

Vehicle Road Runoff and Return - Effect of Limited Steering Intervention

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ABSTRACT

Vehicle safety remains a significant concern for consumers, government agencies, and automotive manufacturers. One critical type of vehicle accident results from the right or left side tires leaving the road surface and then returning abruptly due to large steering wheel inputs (road runoff and return). A subset of runoff road crashes that involve a steep hard shoulder has been labeled shoulder induced accidents. In this paper, a limited authority real time steering controller has been developed to mitigate shoulder induced accidents. A Kalman Filter based tire cornering stiffness estimation technique has been coupled with a feedback controller and driver intention module to create a safer driving solution without excessive intervention. In numerical studies, lateral vehicle motion improvements of 30% were realized for steering intervention. Specifically, the vehicle crossed the centerline after 1.0 second in the baseline case versus 1.3 seconds with steering assistance at 60 kph. For the case of an attentive driver, the final heading angle of the vehicle was reduced by 46% from 0.48 radians to 0.26 radians. However, a persistent challenge remains regarding the interpretation of driver commands and application of corrective steering actions available with on-board control systems.

1. INTRODUCTION

Driving is a complex task that requires both physical and cognitive operator skills which cannot yet be completely emulated by an autonomous controller for all scenarios which may be encountered when operating a ground vehicle. However, the driver's reaction time may not be sufficiently fast to adjust to quickly changing road conditions. In these somewhat rare situations, an on-board control system might intervene to prevent, or mitigate the severity of, an accident. Specifically, an active steering system will be investigated as

a possible solution to the problem of “shoulder induced accidents.” In this scenario, automotive accidents occur due to the vehicle leaving the road shoulder and then returning abruptly, as commanded by the driver through large steering wheel angles, which typically results in striking oncoming traffic or losing control of the chassis and striking stationary obstacles on either side of the road. Unfortunately, the operator may not be adequately trained for this driving scenario and unable to properly maintain lateral control when returning to the road surface. The underlying difficulty arises from the wheels returning to the road surface with a large steering angle which may introduce a large vehicle yaw angle which destabilizes the platform motion. As noted by Epstein [1], the recovery strategy typically includes staying calm, firmly gripping the steering wheel, and easing off the accelerator pedal to gradually slow down (brake carefully if required) when wheels drift off the roadway. When vehicle speed has reduced sufficiently, then the driver should safely steer back onto the pavement [2]. The severity of return to roadway steering maneuvers, following an off-road excursion, may precipitate vehicle rollover accidents; Larson et al. [3] has investigated single vehicle rollovers due to off-road excursion and recovery events.

One key to possible computer intervention in a shoulder induced incident is the concept of “Driver Intention”. If the driver intended to swerve abruptly to avoid an obstacle, then it is imperative that the intervention system does not override the operator's command. However, swerving when returning to the road should be overridden until the driver has sufficient time to react. Simply put, a vehicle may leave the road surface for many reasons. For example, excessive vehicle speed, roadway obstacles, driver inattention, and/or outside influences such as alcohol/drugs may trigger a run-off-road (ROR) event [4]. Past ROR research has largely focused on roadway design issues. Passive measures have been

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undertaken to warn drivers of impending road runoff such as roadway rumble strips [5,6,7]. Roads have also been designed with extended hard shoulders which offer drivers more room for errors which may be corrected before a road runoff event occurs [8]. A first step towards actively solving the shoulder induced accident problem through smart vehicle intervention was presented by Black et al. [9] in which the authors introduced the ROR concept and opportunities for driver intention. The availability of an advanced steer-by-wire system, with accompanying real time computer intervention, can help to mitigate the dangerous effects of run-off-road scenarios for the average driver.

The remainder of the paper has been organized as follows. Shoulder induced accidents and subsequent vehicle behavior will be described in Section 2. Next, the Kalman filter based cornering stiffness estimator will be presented in Section 3 with numerical validation using the CarSim software package. The concept and development of the driver intention module will be introduced in Section 4. Representative numerical results for the control algorithm for different operating scenarios will be presented and discussed in Section 5. The Conclusion is contained in Section 6. The [Appendix](#) contains a complete Nomenclature List.

2. VEHICLE BEHAVIOR DURING A SHOULDER INDUCED ACCIDENT

Any time a vehicle's tire(s) leaves the primary road surface, a shoulder induced accident (SIA) has the opportunity to occur. During a standard SIA event, the driver corrects by commanding a steering wheel angle to move the vehicle back towards the center of the road. When a roadway shoulder is involved, the sidewall of the tire may impede the return when it snags on the road's edge. To compensate, the driver may need to supply a larger steering angle. Once sufficient steering input has been provided, the tires climb the shoulder and the vehicle returns to the road surface with an excessive steering angle as shown in [Fig. 1](#). In this case, a passenger sedan's right wheels traveled off the pavement onto a gravel shoulder and the resulting return to road produced a high yaw scenario on a closed test track.

The progression of events beyond this point largely depends on the driver. An unaware driver may not realize that such a large steering angle exists, such that they will be slow to react to the vehicle's darting motion. If the driver's reaction is too slow, then the vehicle may cross the centerline and strike an oncoming vehicle or stationary object on the left side of the roadway (assuming traffic drives on the right-hand side of road). In a slow or fast reaction scenario, the driver may over correct, creating a vehicle skid or travel off the road surface on the right side. With a high center of gravity vehicle, these over corrections may trigger a rollover event during the skid or from turning into a ditch.



Fig. 1. Vehicle position shortly after road return during a shoulder induced event on a closed test track course

There are three factors that contribute most to the danger of an SIA. The first factor is a high steering angle which may be unavoidable with a high shoulder. Lower steering angles can be used if the driver builds lateral velocity before contacting the shoulder. The second factor is excessive speed during the event. At lower speeds, the high steering angle is not a problem because the vehicle will not dart or put the vehicle into an unstable mode. Finally, slow and improper driver responses create the most danger. Average drivers do not understand the potential danger in a road return maneuver, so they are not ready to take evasive actions. The active steering controller presented in this paper aims to offer the driver more time to react by reducing the high steering angle during the moments following a road return event.

3. LIMITED AUTHORITY STEERING CONTROL

A number of opportunities may be identified to intervene in a likely shoulder induced accident. In descending order of attractiveness they include: (a) before the vehicle first leaves the road surface, (b) while the vehicle's tires are off the road surface, and (c) the short window immediately after the vehicle returns to the road surface. Although important, the first opportunity is not the focus of this study since it is in the realm of human factors and modern electronic stability control systems. 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 braking system and/or driver education training. Active steering intrusion is not recommended in this window since the driver's intention cannot be fully identified. The third intervention window has the 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 after returning to the roadway. With proper training and experience, a driver can do this maneuver unassisted. Note that a reduction in vehicle speed can also improve the hazardous situation which

offers more time for evasive action. However, current driver education infrastructure does not typically support this level of training through driving simulator and/or real world driving time on a closed track due to economic concerns. Instead of requiring an experienced response from the driver, an active braking and/or steering system could intervene and make the necessary corrections before the driver realizes that life threatening danger is imminent.

An active steering control strategy (refer to Fig. 2) will be developed to mitigate the danger of a shoulder induced accident after it has been initiated by the driver. The determination of driver intent requires an understanding of the perceived road conditions. All drivers will have an inherent delay in sensing changing road conditions. Although an active steering controller could quickly adjust to changing road conditions, the supplied input may not reflect the output desired by the driver. Consequently, two parameter sets must be calculated for the tire/road interface's lateral handling

characteristics: (a) the estimated vehicle parameters, $\hat{C}_{af}$ and $\hat{C}_{ar}$, and (b) the driver's perceived vehicle parameters, $\tilde{C}_{af}$ and $\tilde{C}_{ar}$. The variables C_{af} and C_{ar} represents the front and rear tire cornering stiffnesses, respectively. The symbol $\hat{\cdot}$ denotes the estimate of the cornering stiffness, while the symbol $\sim$ represents the driver's perceived cornering stiffness.

To predict the driver's perceived parameters, a time delay, τ , will be placed on the vehicle parameters, $\tilde{C}_{af} = \hat{C}_{af}(t - \tau)$ and $\tilde{C}_{ar} = \hat{C}_{ar}(t - \tau)$. The steering wheel input, δ_{sw} , may be combined with the perceived vehicle parameters, $\tilde{C}_{af}$ and $\tilde{C}_{ar}$, to determine the driver's intention. This computation becomes the steering controller's target to track through the commanded front wheel angle, δ , to realize a stable vehicle.

3.1. CORNERING STIFFNESS ESTIMATION

An active steering controller requires the estimation of the lateral tire, F_y . The longitudinal tire force, F_x , was not estimated since the recovery event was assumed to occur at a constant velocity, $\dot{v}_x = 0$. To be compatible with a two degree-of-freedom chassis model, the cornering stiffnesses, C_{af} and C_{ar} , were estimated. The selected estimation technique was based on Sierra et al. [10] who compared multiple cornering stiffness estimation techniques to demonstrate their strengths and weaknesses, including the accuracy, operating range, and required sensors.

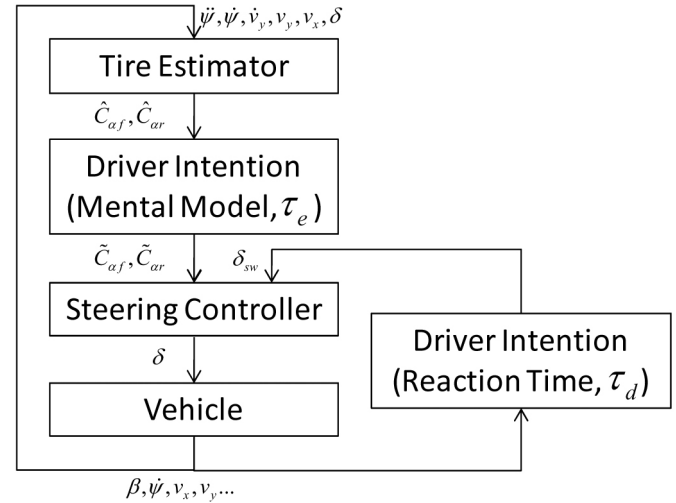


Fig. 2. Steering controller with driver commanded angle, δ_{sw} , and supplement to yield front wheel steer angle, δ

The lateral and yaw vehicle dynamics may be written in terms of the front and rear cornering stiffnesses, C_{af} and C_{ar} , as

$$m(\dot{v}_y + \dot{\psi}v_x) = 2C_{af}\alpha_f + 2C_{ar}\alpha_r \quad (1a)$$

$$I\ddot{\psi} = 2aC_{af}\alpha_f - 2bC_{ar}\alpha_r \quad (1b)$$

where v_x and v_y denote the longitudinal and lateral velocities.

The variable $\dot{\psi}$ represents the vehicle yaw rate. The parameters a and b correspond to the distances from the front and rear axles to the center of gravity (CG). The term δ denotes the steered front road wheel angle.

The front and rear tire slip expressions, $\alpha_f = \delta - \frac{v_y + a\dot{\psi}}{v_x}$ and $\alpha_r = \frac{b\dot{\psi} - v_y}{v_x}$, may be substituted into [equation \(1\)](#) to obtain

$$m(\dot{v}_y + \dot{\psi}v_x) = 2C_{af}\left(\delta - \frac{v_y + a\dot{\psi}}{v_x}\right) + 2C_{ar}\left(\frac{b\dot{\psi} - v_y}{v_x}\right) \quad (2a)$$

$$I\ddot{\psi} = 2aC_{af}\left(\delta - \frac{v_y + a\dot{\psi}}{v_x}\right) - 2bC_{ar}\left(\frac{b\dot{\psi} - v_y}{v_x}\right) \quad (2b)$$

The cornering stiffnesses may be isolated by solving for these two unknowns such that

$$C_{af} = \frac{1}{2} \frac{(b\dot{v}_y m + b\dot{\psi} m v_x + I\ddot{\psi})v_x}{(-v_y - \dot{\psi}a + \delta v_x)(a+b)} \quad (3a)$$

$$C_{ar} = \frac{1}{2} \frac{(a\dot{\psi} m v_x + a\dot{v}_y m - I\ddot{\psi})v_x}{(\dot{\psi}b - v_y)(a+b)} \quad (3b)$$

Note that these two expressions require knowledge of the vehicle model states ($\dot{\psi}$, $\ddot{\psi}$) and (v_y , $\dot{v}_y$). Sierra et al. [10] observed that this technique was unreliable when the front and rear slip angles approached zero, $\alpha_f = \alpha_r \cong 0$. Thus, estimation was not performed when the steering was on-center, $\delta_{sw} \cong 0$, which corresponds to “no commanded” lateral motion. For a shoulder induced accident scenario, the driver typically commands a large steering wheel angle, $\delta_{sw} \neq 0$, and maintains this posture even after the vehicle returns to the road surface. Consequently, the constraint does not present a limitation to the application.

The tire cornering stiffnesses, C_{af} and C_{ar} , may be predicted using a Kalman [11] filter. To ensure accurate and stable estimation, two specific thresholds were implemented. The estimation was only activated with front road and steering wheel angles and angular velocities of $|\delta| \geq 0.833^\circ$ (0.015 rad), $|\delta_{sw}| \geq 15^\circ$ (0.26 rad), $|\dot{\delta}| \leq 2.222 \text{ deg/s}$ (0.078 rad/s), $|\dot{\delta}_{sw}| \leq 40 \text{ deg/s}$ (1.40 rad/s), respectively. Specifically, the front road wheel angle threshold was set to ensure that the vehicle was not traveling in a straight line during estimation. The road wheel angular velocity threshold was set to temporarily ignore transient steering maneuvers with large magnitudes since the model loses accuracy during rapid steering inputs.

The state space description for the continuous Kalman filter [12] becomes

$$\dot{\hat{x}} = F\hat{x} + Gu, \quad z = H\hat{x} + v \quad (4a)$$

$$\dot{\hat{x}} = F\hat{x} + K(z - H\hat{x}), \quad K \equiv PH^T R^{-1} \quad (4b)$$

with

$$\hat{x} = \begin{bmatrix} \hat{C}_{af} \\ \hat{C}_{ar} \end{bmatrix}, \quad Q = \begin{bmatrix} Q_f & 0 \\ 0 & Q_r \end{bmatrix}, \quad R = \begin{bmatrix} R_f & 0 \\ 0 & R_r \end{bmatrix}, \quad P_0 = \begin{bmatrix} P_{01} & 0 \\ 0 & P_{02} \end{bmatrix},$$

and $F = G = H = I$. An assumption of white state and measurement noise has been imposed. These matrix definitions may be substituted into [equation \(4\)](#) so that

$$\begin{bmatrix} \dot{\hat{C}}_{af} \\ \dot{\hat{C}}_{ar} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{C}_{af} \\ \hat{C}_{ar} \end{bmatrix} + \begin{bmatrix} K_f & 0 \\ 0 & K_r \end{bmatrix} \begin{bmatrix} C_{af} - \hat{C}_{af} \\ C_{ar} - \hat{C}_{ar} \end{bmatrix} \quad (5a)$$

$$\begin{bmatrix} K_f & 0 \\ 0 & K_r \end{bmatrix} = \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} \begin{bmatrix} R_f & 0 \\ 0 & R_r \end{bmatrix}^{-1} = \begin{bmatrix} \frac{P_1}{R_f} & 0 \\ 0 & \frac{P_2}{R_r} \end{bmatrix} \quad (5b)$$

$$\begin{bmatrix} \dot{P}_1 & 0 \\ 0 & \dot{P}_2 \end{bmatrix} = \begin{bmatrix} 2P_1 & 0 \\ 0 & 2P_2 \end{bmatrix} - \begin{bmatrix} \frac{P_1^2}{R_f} & 0 \\ 0 & \frac{P_2^2}{R_r} \end{bmatrix} + \begin{bmatrix} Q_f & 0 \\ 0 & Q_r \end{bmatrix} \quad (5c)$$

The solutions to the Riccati [equations \(5\)](#) were calculated numerically in MATLAB during the vehicle simulation. The estimated front and rear tire cornering equations may be expressed as

$$\dot{\hat{C}}_{af} = \hat{C}_{af} + K_f(C_{af} - \hat{C}_{af}) \quad (6a)$$

$$\dot{\hat{C}}_{ar} = \hat{C}_{ar} + K_r(C_{ar} - \hat{C}_{ar}) \quad (6b)$$

The variables C_{af} and C_{ar} may be constructed from [equation \(3\)](#) using measured vehicle operating variables including $\dot{\psi}$, $\ddot{\psi}$, $\dot{v}_y$, v_y , v_x , δ . The K values may be simplified from

$$\text{equation (5b) to } K_f = \frac{P_1}{R_f} \text{ and } K_r = \frac{P_2}{R_r}.$$

3.2. NUMERICAL IMPLEMENTATION

The cornering stiffness estimator was evaluated using the CarSim Version 6 software package which generated the vehicle dynamic behavior ($\dot{\psi}$, v_y , v_x , β). A small passenger sedan was selected for the study and the corresponding vehicle database. During real-time applications, the estimated cornering stiffnesses, $\hat{C}_{af}$ and $\hat{C}_{ar}$, based on the measured variables, stiffness expressions and Kalman filter, were supplied to the chassis model described by [equation \(2\)](#). The system outputs, $\dot{\psi}$ and β , were compared to the CarSim results to verify the accuracy of the estimation in terms of tire cornering stiffnesses and yaw rate.

The vehicle was driven with a $f = 0.25 \text{ Hz}$ sinusoidal steering input with an amplitude of $\delta_{sw} = 90^\circ$. The velocity was