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Using Performance Margin and Dynamic Simulation for Location Aware Adaptation of Vehicle Dynamics

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ABSTRACT

One seminal question that faces a vehicle's driver (either human or computer) is predicting the capability of the vehicle as it encounters upcoming terrain. A Performance Margin (PM) is defined in this work as the ratio of the required tractive effort to the available tractive effort for the front and rear respectively. This simple definition stems from and incorporates many traditional handling metrics and is robust in its scope of applicability. The PM is implemented in an Intervention Strategy demonstrating its use to avoid situations in which the vehicle exceeds its handling capabilities. Results from a design case study are presented to show the potential efficacy of developing a PM-based control system.

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INTRODUCTION

Autonomous vehicles have been an active area of research for over 30 years; steady progress has resulted in many impressive displays of current technology (Yih, Ryu and Gerdes 2005) (Hong and Cipra 2006) (S. A. Beiker, K. H. Gaubatz and C. J. Gerdes, et al. 2006). One seminal question that faces the vehicle's driver (either human or computer) is predicting the capability of the vehicle as it encounters upcoming terrain. A model of the vehicle (either conceptual in the mind of a human based on previous driving experience, or mathematical for the computer in which the complex multi-body dynamics are calculated) and the excitation of this model must both be considered when predicting the resulting vehicle performance. In this way, the driver can make informed decisions about the manner in which the vehicle should be driven. When a human drives the vehicle, the computer is still of great assistance in today's passenger cars. One active area of research hopes to provide even greater assistance to the human driver as another step in the evolution to autonomous driving.

The focus of Location-Aware Adaptation of Vehicle Dynamics (LAAVD) research is to develop a system to avoid situations in which the vehicle exceeds its handling capabilities. The proposed method is not reactive, such as current Electronic Stability Control (ESC) systems, but rather, it is predictive, estimating the ability of the vehicle to successfully navigate upcoming terrain. An Intervention Strategy is then developed based on this prediction of the vehicle's performance. This Intervention Strategy is intended to be minimally intrusive to the human driver's control authority, yet through modest changes to the throttle and brake commands allow the vehicle to be navigated through a corner.

This approach is unique in that the driver drives the vehicle (as opposed to autonomous driving), yet the system is predictive rather than reactive. The goal of this research is to enhance (not replace) existing reactive safety systems such as ESC systems and Anti-lock Braking Systems (ABS). For example, the proposed system would predict that the vehicle is approaching a curve at a high rate of speed for the given conditions, alert the driver to the issue, then make modest corrections to the driver's brake and throttle commands. The intent is to avoid the situation in which the ESC system would become active. The ESC system is envisioned to have higher control authority than the proposed system and would take over control of the vehicle if the situation cannot be avoided.

Current methods used to objectively quantify vehicle handling include phase plane analysis, and the Milliken Moment Method (S. Inagaki, I. Kshiro and M. Yamamoto

1994) (Milliken, Wright and Milliken, Moment Method - A comprehensive tool for race car development, SAE Technical Paper 942538 1994). These techniques use vehicle states to measure the controllability and stability of a vehicle for a given set of initial conditions. Typically, boundary values from these methods represent a vehicle's handling limits. This type of analysis is helpful for the design of a vehicle. However, these methods are not ideal for in situ calculations of an operating vehicle's current (or future) handling characteristics. To capture this, the Performance Margin (PM) - a metric quantifying the relative ability of the vehicle to successfully navigate the upcoming road conditions - is defined and described in this paper.

BACKGROUND

The feasibility of the proposed method is dependent on the availability of path predicting and friction coefficient (μ) predicting systems. While there are no such systems included on any present commercial vehicle design, there is a great amount of research currently being done in both fields. An overview of the practicality of implementing a Global Positioning System (GPS)-based control system into ground vehicles is discussed by Beiker et al. (S. A. Beiker, K. H. Gaubatz and J. C. Gerdes, et al. 2006). Furthermore, Ahn proposes both longitudinal and lateral dynamics based algorithms to estimate μ using measurements from sensors that are available on typical commercial vehicles (Ahn 2011). Therefore, for this work, it is assumed that path and μ can be accurately estimated.

Several methods for analyzing vehicle performance during maneuvers have been developed. This section reviews a selection of those methods and introduces the PM.

Phase Plane Method

The phase plane method to analyze vehicle dynamics during critical cornering scenarios is discussed by Inagaki et al. This method utilizes the vehicle side slip angle, and angular velocity for state variables. From his experiments, Inagaki's proposed control system minimizes side slip motion by applying braking force to the cornering outer wheels when the vehicle is on the verge of exceeding the stable limits determined using the phase plane method. This concept is similar to the proposed control system utilizing PM in that system parameters are used to trigger corrective actions to prevent losing control of the vehicle. However, the systems are different in that Inagaka's system determines future states based on current states where the PM system calculates future parameters using path prediction and known road-profile data. Also, utilizing longitudinal, lateral, and vertical forces vice side slip and angular velocity inputs provide a more accurate account of weight transfer due to pitch from acceleration or road profile changes.

Fuzzy Logic and Total Safety Margin

There are multiple publications which use fuzzy logic to predict future vehicle states. Davoudi et al. introduce a method of calculating the center of gravity (CG) position and velocity based on measured dynamic vehicle changes such as pitch and yaw (Davoudi, Menhaj and Davoudi 2006). These CG values are inputs to a controller which uses fuzzy logic to determine whether or not the vehicle is at risk of overturning. Davoudi also proposes interventions such as altering damper heights, actuating brakes, and limiting allowed steering angles to prevent rollover situations. These alterations fundamentally change the vehicle dynamics and can be incorporated into an Intervention Strategy as part of the Location-Aware Adaptation of Vehicle Dynamics research. Duprey et al. incorporate a GPS signal to predict future lateral velocity, yaw rate, roll angle, and roll angle rate (Duprey, Tamaddoni and Taheri 2008). These values are used to determine future vehicle stability based on output from a fuzzy based predictive controller. Calculated maximum allowable values for lateral acceleration, lateral velocity, yaw rate, and roll angle are combined to produce a Total Safety Margin (TSM) which is a quantitative measure of a vehicle's stability. Duprey's and Davoudi's research primarily focuses on preventing rollover scenarios, which can be considered an important component of LAAVD research. Some of their concepts are reflected in the PM based Intervention Strategy method outlined here. Although not discussed in this paper, expansion of the use of PM based interventions to prevent encountering a rollover condition is a possible area of future research.

Tire Stresses

The development of the PM preserves the basic principles developed in the Dugoff Tire Model (Dugoff, Francher and Segal 1970). The resultant tire-road stress, σ_{res}, developed at a point in the tire contact patch on an X-Y plane caused by an alteration of speed (causing longitudinal stress, σ_x) or steering angle (causing lateral stress, σ_y) can be represented by Equation (1).

$$\sigma_{\mathrm{res}} = \sqrt{\left(\sigma_{\mathrm{x}}{}^2 + \sigma_{\mathrm{y}}{}^2\right)} \tag{1}$$

The stress limit at which the point in the tire contact patch begins to slip, σ_{max}, is a product of the normal force, F_z, and the coefficient of friction, μ, over the area of the contact patch as shown in Equation (2).

$$\sigma_{\max} A_{\mathrm{contact}} = \mu |F_z| \tag{2}$$

where A_{contact} is the contact patch area. It should be clear that the interface at the tire contact patch is a unilateral geometric constraint, so that if the positive sense of the vertical force, F_z is defined as compression of the tire by the ground, then there can be no negative force exerted by the ground on the tire. In this way, the absolute value function for the vertical force can be eliminated from Equation (2). In calculating the vertical tire force, care should always be taken to enforce this unilateral constraint.

Milliken Moment Method

MRA Moment Method, is a technique for analyzing and graphically portraying the stability and control of an automobile (Milliken and Milliken, Race Car Vehicle Dynamics 1995). It was initially developed for analysis of race car vehicle dynamics, but has been used for all types of vehicles. By analyzing the balanced and unbalanced forces and moments acting on a vehicle, the MMM provides quantitative values for categories such as front tire saturation, vehicle maneuvering area, stability, and control. A normalized lateral and longitudinal force is developed with respect to the product of the coefficient of friction and the normal load.

$$\overline{F}_{\mathrm{x}} = \frac{F_{\mathrm{x}}}{\mu F_z} \tag{3}$$

$$\overline{F}_{\mathrm{y}} = \frac{F_{\mathrm{y}}}{\mu F_z} \tag{4}$$

This combination of normalized lateral and longitudinal forces is equivalent to a normalized resultant force. This normalized resultant force is then discussed in terms of a normalized slip variable.

In the early 1990's, Milliken et al. showed that this method can be used to analyze peak performance through a corner as well as vehicle characteristic sensitivity identification. Approximately 15 years later, Hoffman et al., took the MMM one step further by explicitly quantifying controllability and stability using closed loop dynamic simulation (Hoffman, et al. 2008). Utilizing CarSim, Hoffman uses a closed-loop four-wheel bicycle model with the Pacejka Magic Tire Formula Model with a given steering input and a constant initial speed. Combining the MMM with dynamic simulation provides useful and measurable vehicle handling information. Hoffman proposes a safety margin that is a combination of controllability and stability margins. Unlike the PM based control system, which calculates future states, Hoffman's safety margin is derived on current vehicle states.

Definition of Stability using Lateral Force

The effect that lateral force on stability is explained by Pacejka (Pacejka 2006). In discussing stability of the motion at large lateral accelerations using a bicycle model, a relationship is defined

$$\phi_i = \frac{1}{F_{zi}} \frac{\partial F_{yi}}{\partial \alpha_i} \tag{5}$$

where i = 1, 2 to represent front and rear tires respectively. A condition for stability is

$$\phi_1 \phi_2 \left(\frac{\partial \delta}{\partial 1/R} \right)_V > 0 \tag{6}$$

At the saturation point for a given set of tires, the $\frac{\partial F_{yi}}{\partial \alpha_i}$ term in Equation (5) will equal zero and the condition for stability defined in Equation (6) will not be met. Presently, it is shown that the Performance Margin reaches unity at the saturation point of the front (or rear) tires; the PM for the front (rear) tires reaching unity is equivalent to φ_1 (φ_2) reaching zero. In this way, the stability criteria developed by Pacejka is preserved in the Performance Margin

DEFINITION OF THE PERFORMANCE MARGIN (PM)

Presently, the Dugoff stress relationships are reformulated as equivalent tractive forces acting over the area of the contact patch and the normalization developed by Milliken are integrated into the formulation. The PM is defined as the ratio of the required tractive effort to navigate a turn under given conditions and the available tractive effort (for the front and rear respectively). The fraction of the available traction that is required for the vehicle to navigate a turn (given its speed and states) can be calculated. Specifically, the PM is the ratio of the required resultant tractive force to the maximum available tractive force and is written

$$\mathrm{PM} = \frac{\sqrt{\left({F_{\mathrm{x}}}^2 + {F_{\mathrm{y}}}^2 \right)}}{\mu F_z} \tag{7}$$

Note that the resultant stress proposed by Dugoff is reformulated as a resultant tractive force in the numerator and the resultant tractive force is normalized by the product of the friction coefficient and the normal force, as developed by Milliken.

For vehicle handling considerations, the front pair of tires can be combined to analyze open loop controllability and the rear set of tires can be coupled to analyze open loop stability. Grouping the front set and rear set of tires, this relationship can be expressed as

$$\mathrm{PM}_{Front} = \frac{\sum_{i=1}^{2} \sqrt{\left({F_{\mathrm{xi}}}^2 + {F_{\mathrm{yi}}}^2 \right)}}{\sum_{i=1}^{2} \mu F_{zi}} \tag{8}$$

$$\mathrm{PM}_{Rear} = \frac{\sum_{i=3}^{4} \sqrt{\left({F_{\mathrm{xi}}}^2 + {F_{\mathrm{yi}}}^2 \right)}}{\sum_{i=3}^{4} \mu F_{zi}} \tag{9}$$

A PM value of unity for a pair of tires means the resultant forces are equal to the maximum tractive force. When this occurs, the tires will lose traction and spin (if the rear tires saturate before the front) or plow (if the front tires saturate before the rear). Again, this saturation condition corresponds to a change in the stability relationship defined by Pacejka in which the stability criterion in Equation (6) becomes positive. A suitable threshold for the PM can then be set; a threshold of 0.3 is used in this research for demonstrative purposes.

The formulation of the PM is simple and based on solid traditional metrics for vehicle stability. Yet the simplicity of the PM should not mask the complexity of interrelationships that are required in its calculation. Since the PM is all-encompassing, and most vehicle dynamic relationships are interlinked by design, the PM is constantly changing in every transient condition. Mathematically modeling and predicting how perturbations to the vehicle state will affect the PM is challenging.

Although the simplicity of the PM may create a challenging prediction problem, it is also the greatest advantage in analyzing vehicle dynamics. There are a myriad of possible changes from steady state a vehicle can encounter while operating. A change in road bank alters roll, which shifts weight and effects lateral forces and vertical loading. Applying the brakes induces a pitch, causing a weight transfer of a different nature. Turing the steering wheel creates a slip angle which has various effects on vehicle dynamics. The effects of all of these maneuvers or events are captured by the robust PM. Current research focuses on overall vehicle handling, and insomuch, needs a parameter that captures the overall performance capability of the vehicle.

DEMONSTRATION OF USE: COMPUTER SIMULATION

The goal of this research is to develop an Intervention Strategy based on PM values for a passenger vehicle under any typical driving condition. Again, this highlights the robustness of an Intervention Strategy based on the Performance Margin; it is applicable to the complete spectrum of driving situations. Implementation of the PM in one candidate Intervention Strategy is demonstrated in a simple example to show that the PM can be used as a viable tool to keep the vehicle from exceeding performance thresholds. Consider the times and actions necessary to keep a sedan traveling at 75 kph on a surface with a constant μ of 0.85 navigating a 90 degree turn with a radius of 50 meters as shown in Figure 1. Without intervention, a loss of traction will occur.

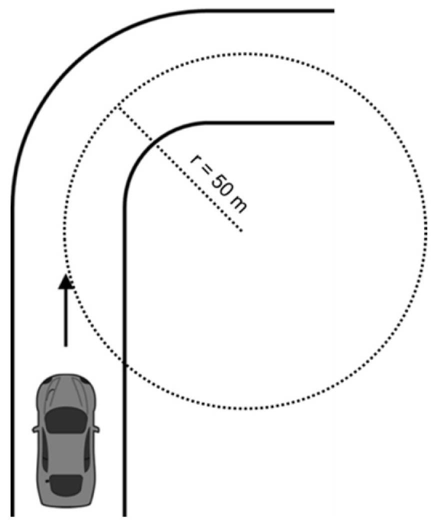

Figure 1. The designed path to test the PM based intervention strategy.

The experiment is conducted in 12-second segments. After simulation results are obtained for the first segment (0-12 sec), the data are analyzed to determine if at any time in that 12 seconds the PM exceeded the cutoff threshold and what intervention, if any, would be necessary. The next 12-second segment (from 1 to 13 sec) one second after the previous segment is simulated and analyzed. If intervention is necessary at any step (whether it be an alarm, throttle input adjustment, or brake application), it is implemented as necessary in the subsequent steps. This sequence mimics a driver's intuitive reaction when approaching a sharp turn-decrease speed via reduction in throttle and/or brake application. This general framework for a simple Intervention Strategy is shown in Figure 2.

In this example, this sequence continues until the vehicle safely maneuvered around the turn without exceeding the threshold.

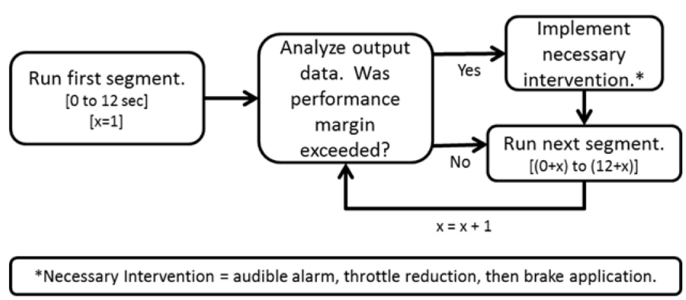

Figure 2. Flowchart of the intervention process.

Analysis of Experiment

In this scenario, if the driver takes no corrective action and there is no control system present, the PM would exceed the cutoff at 13 seconds and would momentarily lose control at 22 seconds as the PM of the rear tires briefly exceeds unity.

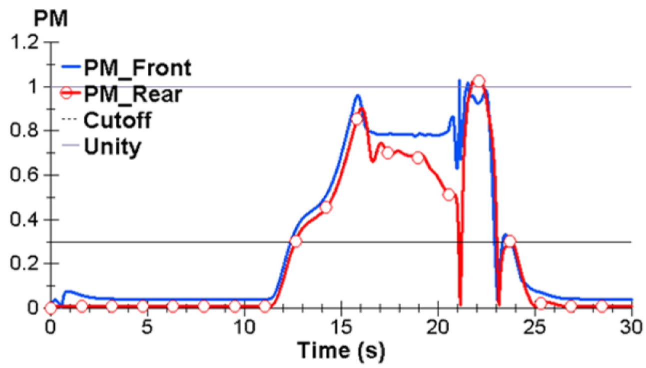

Figure 3. PM plots with no corrective actions or interventions.

In this situation, an alarm would alert the driver he or she was about to exceed the cutoff. If no actions are taken by the driver, the control system would lower lateral acceleration by reducing the throttle and applying the brakes. These events could occur in a number of ways - immediate or gradual reduction of throttle, brake pulses, steady brake pressure, etc. For this example, the system brake pressure rapidly increases then reduces back to zero while the throttle is reduced to zero at approximately 3% per second. The effect this has on PM is shown in Figure 4.

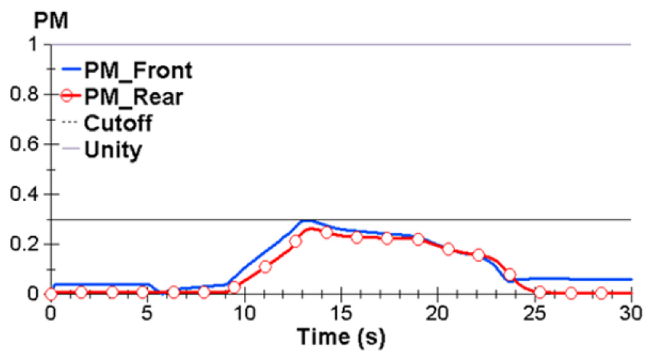

Figure 4. Predicted PM after throttle reduction and brake application.

This example demonstrates how a PM based control could maintain a vehicle within desired safety parameters, even with no action from the driver. Once a thorough understanding of the PM is obtained, it can be used to calculate the most efficient means of throttle and brake manipulations necessary to maintain safety while still maximizing performance.

The interventions performed in this example mimic what a driver's intuition would lead him or her to do for this simplified situation. However, if the driver failed to recognize a pothole or bump in the road these actions may not be enough to keep the car within safe limits. For example, Figure 5 shows the resultant PM graph for the same scenario discuss previously with a sinusoidal shaped bump (from 0 to π) perpendicular to the driver's path immediately before the turn.

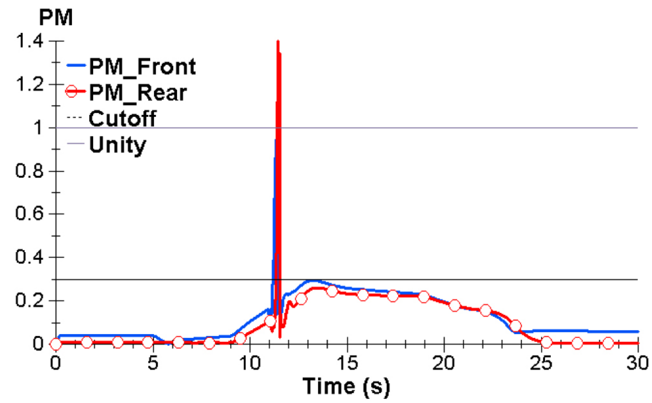

Figure 5. The PM of the previous example with an added speed bump prior to the turn.

This condition results in the PM spiking above not only the cutoff but also unity, causing a momentary loss of traction while in the turn. If terrain data was available, this potential loss of control would be anticipated, necessary interventions would occur to reduce the PM, and the undesired situation would be avoided by a PM based control system. Figure 6 shows the resulting PM based on interventions tailored around the discussed scenario.

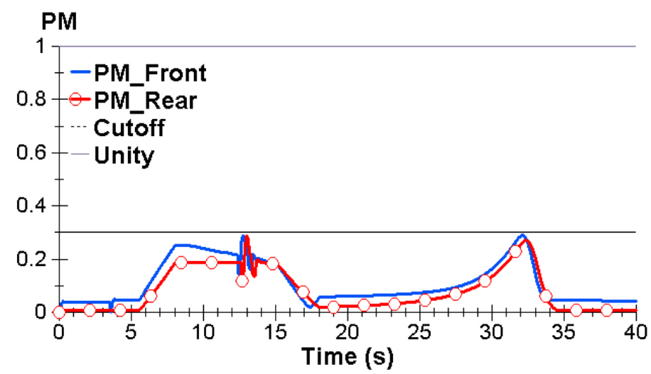

Figure 6. Predicted PM with added speed bump and active control system.

DISCUSSION

The PM as the measure of vehicle handling capability proved effective in the development of an Intervention Strategy for this scenario. A system that could strategically implement throttle and brake interventions in a vehicle about to enter a dangerous situation could prevent loss of control. While some parameters needed for an on-the-fly PM calculation are already available from existing stability control systems, the process for measuring others is still in development. A throttle and brake intervention system based on PM is a foreseeable addition to the active stability control repertoire that would react to anticipated situations as opposed to events that are currently happening. Such a system could greatly reduce vehicle control-related incidents.

The proposed method of changing PM involves reducing longitudinal forces on the tire patches by altering throttle and brake. It was observed through simulations that varying the methods of throttle reduction or brake application have complex and unique effects on the resultant PM. Since the PM cutoff is a known value, once an understanding of the behavior of PM with varying conditions exists, optimized throttle and brake commands can be obtained.

Since the PM is calculated using future longitudinal, lateral, and vertical forces, a PM based control system could be utilized for not only maneuvers on curved roads, but also for banked roads, split mu conditions, bumps, dips, load shifts, and combinations of all these situations.

CONCLUSIONS

A set of specific intervention strategies has been shown to work for one particular set of initial conditions. As the factors affecting the PM value are studied and different intervention strategies are tested, implementation criteria can be established to match the most effective action with the relevant circumstance. Experimenting with a variety of initial conditions, such as road bank, μ, desired speed, intended course, and cutoff limits will all affect the PM.

Future research will include development of a linearized model to predict changes in longitudinal forces to brake and throttle changes (Δ(brake, throttle) $\rightarrow \Delta F_X$). After this is completed, then a computationally efficient model that captures how changes to the longitudinal forces will affect changes to the PM will be developed ($\Delta F_X \rightarrow \Delta$ PM). These models will then be validated versus the full non-linear response for several case studies. Once a deeper understanding of this method is achieved, a minimally intrusive Intervention Strategy will be developed to find the optimal changes in brake and throttle to affect the desired change in longitudinal force, and resulting change in PM. This Intervention Strategy will then be implemented and validated.

REFERENCES

1. Ahn, C. S. *Robust Estimation of Road Friction Coefficient for Vehicle Active Safety Systems*. Ph D. Dissertation, Mechanical Engineering, University of Michigan, University of Michigan, 2011.

2. Beiker, S., Gaubatz, K., Gerdes, J., and Rock, K., "GPS Augmented Vehicle Dynamics Control," SAE Technical Paper 2006-01-1275, 2006, doi: 10.4271/2006-01-1275.

3. Beiker, S., Gaubatz, K., Gerdes, J., and Rock, K., "GPS Augmented Vehicle Dynamics Control," SAE Technical Paper 2006-01-1275, 2006, doi: 10.4271/2006-01-1275.

4. Davoudi, M., Menhaj, M., and Davoudi, M., "A Fuzzy Based Vehicle Dynamic Stability Control (FDSC)," SAE Technical Paper 2006-01-3483, 2006, doi: 10.4271/2006-01-3483.

5. Dugoff, H., Fancher, P., and Segel, L., "An Analysis of Tire Traction Properties and Their Influence on Vehicle Dynamic Performance," SAE Technical Paper 700377, 1970, doi: 10.4271/700377.

6. Duprey, B., Tamaddoni, S., and Taheri, S., "A New Fuzzy Based Stability Index Using Predictive Vehicle Modeling and GPS Data," SAE Technical Paper 2008-01-2597, 2008, doi: 10.4271/2008-01-2597.

7. Hoffman, R. C., Stein J. L., Louca L. S., and Huh K.. "Using the Milliken Moment Method and dynamic simulation to evaluate vehicle stability and controllability." *International Journal of Vehicle Design* 48, no. 1/2 (2008): 132-148.

8. Hong, D. W., and Cipra R. J.. Visualization of the Contact Force Solution Space for Multi-limbed Robots. ASME Journal of Mechanical Design, 2006.

9. Milliken, W. F., and Milliken D. L.., "Race Car Vehicle Dynamics," Society of Automotive Engineers, Warrendale, PA, ISBN 978-1-56091-526-3, 1995, doi: 10.4271/R-146.

10. Milliken, W., Wright, P., and Milliken, D., "Moment Method - A Comprehensive Tool for Race Car Development," SAE Technical Paper 942538, 1994, doi: 10.4271/942538.

11. Pacejka, H. B., "Tire and Vehicle Dynamics," Society of Automotive Engineers, Warrendale, PA. ISBN 978-0-08097-016-5, 2006, doi: 10.4271/R-418.

12. Inagaki S., Kshiro I., and Yamamoto M.. "Analysis on vehicle stability in critical cornering using phase-plane method." *Proceedings of AVEC, Toyota Motor Corporation*, 1994.

13. Yih, Paul, Ryu Jihan, and Gerdes Christian J.. *Modification of Vehicle Handling Characteristics via Steer-by-Wire*. IEEE Transactions of Control Systems Technology, 2005.

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DEFINITIONS/ABBREVIATIONS

PM - Performance Margin

σ_{res} - Resultant Tire-Road Stress

σ_x - Longitudinal Stress

σ_y - Lateral Stress

σ_{max} - Stress Limit

F_z - Normal Force

F_y - Lateral Force

α - Slip angle

μ - Coefficient of Friction

$A_{contact}$ - Contact Patch Area

$1/R$ - Path curvature