

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 Inagaki'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, Tamaddon 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 \(1\)](#).

$$\sigma_{res} = \sqrt{(\sigma_x^2 + \sigma_y^2)} \quad (1)$$

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 \(2\)](#).

$$\sigma_{max} A_{contact} = \mu |F_z| \quad (2)$$

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