

Location-Aware Adaptive Vehicle Dynamics System: Throttle Modulation

Sukhwan Cho, Rebecca Anne Bandy, and John Ferris
Virginia Tech

Joerg Schlinkheider and Marc Wimmershoff
Volkswagen Group of America, Inc.

ABSTRACT

A Location-Aware Adaptive Vehicle Dynamics System (LAAVDS) is developed to assist the driver in maintaining vehicle handling capabilities through various driving maneuvers. An Intervention Strategy uses a novel measure of handling capability, the Performance Margin, to assess the need to intervene. The driver's commands are modulated to affect desired changes to the Performance Margin in a manner that is minimally intrusive to the driver's control authority. Real-time implementation requires the development of computationally efficient predictive vehicle models which is the focus of this work. This work develops one means to alter the future vehicle states: modulating the driver's throttle commands. First, changes to the longitudinal force are translated to changes in engine torque based on the current operating state (torque and speed) of the engine. Next, the required changes to the throttle to affect these desired changes to engine torque are estimated by developing a linearized, inverse engine model based on the steady-state conditions. These predicted changes to the throttle command are used in the correction stage of the algorithm in which a full non-linear vehicle model yields the resulting longitudinal force response to the predicted change in throttle. Finally, the predictor-corrector control loop is closed by comparing the desired longitudinal force to the resulting force. The performance of the throttle modulation method is exhibited through simulation results on two test cases. Results show that the proposed approach yields a significant overall performance improvement.

CITATION: Cho, S., Bandy, R., Ferris, J., Schlinkheider, J. et al., "Location-Aware Adaptive Vehicle Dynamics System: Throttle Modulation," *SAE Int. J. Passeng. Cars - Mech. Syst.* 7(1):2014, doi:10.4271/2014-01-0105.

INTRODUCTION

Autonomous vehicles have been an active area of research for over 30 years; steady progress has resulted in many impressive contributions [1] [2] [3]. As noted by Matthews, 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 [4]. A model of the vehicle 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.

Of course, when a human drives the vehicle, the computer is still of great assistance. Anti-Locking Braking Systems (ABS) and Electronic Stability Control (ESC) systems help maintain stability during braking and agile cornering. However, most of the current Driver Assistance Systems are reactive and only act to control the vehicle based on the current vehicle state with minimal information about the local driving environment. Presently, more Advanced Driver Assistance Systems (ADAS),

such as Collision Avoidance Systems and Lane-Keeping Systems are being developed that are predictive, rather than reactive.

The focus of Location-Aware Adaptive Vehicle Dynamics (LAAVD) research is to develop a system to assist the driver in maintaining vehicle handling capabilities through various driving maneuvers. The proposed method is predictive, estimating the ability of the vehicle to successfully navigate upcoming terrain, and it is assumed that the future vehicle states and local driving environment are known. An Intervention Strategy must be developed such that the vehicle is navigated successfully through a corner via modest changes to the driver's commands, and in a manner that is in harmony with the driver's intentions and not in a distracting or irritating manner. In addition, this Intervention Strategy should use a novel measure of handling capability, the Performance Margin, to assess the need to intervene [4]. Clearly this research relies on the numerous new technologies being developed to capture

and convey information about the local driving environment (e.g., bank angle, elevation changes, curvature, and friction coefficient) to the vehicle and driver.

One critical component of this Intervention Strategy is the development of a predictive powertrain (engine and drivetrain) model. The issue being addressed is that using a full non-linear model to estimate future vehicle states is critical, but not realizable in real time. Therefore, a computationally efficient, but less accurate powertrain model must be developed to make timely predictions of future vehicle states. This prediction is then used in a predictor-corrector algorithm within the Intervention Strategy. The linear model is used to make fast predictions in real time and the full non-linear model is used to make corrections to these predictions. Although the full nonlinear model is not required to run in real time, it still must run quickly enough to make corrections to the linear predictive model several times a second.

The objective of this work is to develop the prediction model which can estimate the required change in throttle input to deliver the desired engine torque and resulting desired longitudinal force. First, the limitations on the performance of the engine are investigated. Second, the linearized inverse engine model is introduced. Third, the relationship between the engine torque and the longitudinal force is developed. Finally, a predictive model for estimating the future states of longitudinal force and throttle input is developed. The integration of these contributions is demonstrated through a case study wherein a desired change in longitudinal force is prescribed and the throttle change required to achieve this change in force is predicted. The accuracy and limitations of the method are discussed followed by concluding remarks.

BACKGROUND

The feasibility of the proposed method is dependent on the ability to predict vehicle states and the availability of information about the local driving environment (location, friction, banking, etc.). The information available to the vehicle and the driver continues to grow and 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. [3]. Furthermore, Ahn proposes both longitudinal and lateral dynamics based algorithms to estimate friction using measurements from sensors that are available on typical commercial vehicles [5]. Lee develops a method to estimate the maximum tire-road friction coefficient by designing a tractive force estimator, a brake gain estimator, and a normal force observer [6]. Based on these successful studies, it is assumed in this work that information about the current vehicle state and local driving environment are available.

The linear prediction-nonlinear correction process outlined by Bandy, et al. is fundamental to this work [7]. The system flowchart is reproduced here as Figure 1. A link between the desired change in longitudinal force, calculated from a desired

change in Performance Margin, and the necessary throttle commands is developed here. This is represented in the Linear Predictions box in Figure 1.

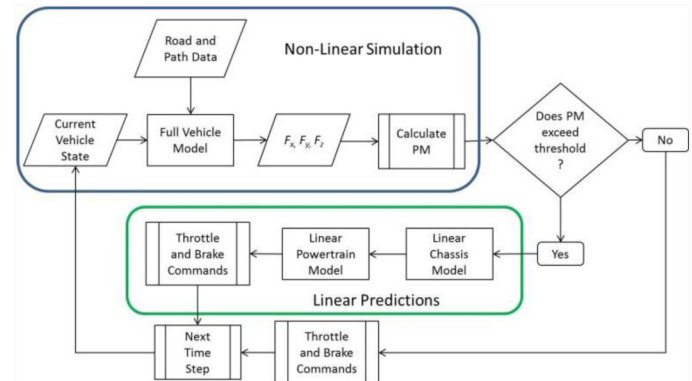


Figure 1. Overview of Intervention Strategy Implementation in Simulation

The success of this throttle manipulation method relies on the accurate and computationally efficient inverse engine model. Since the causality of the system dictates that the changes in throttle must cause a change in torque, the inverse model is defined herein as one in which a desired change in torque produces an estimated change in throttle. A significant amount of recent engine torque control research has been geared towards nonlinear and optimization based control strategies for achieving performance goals for various engine types. Yoon, Kang, Vermillion, Ioannou, and Gerdes use a nonlinear dynamic model of engines to control the engine torque [8] [9] [10] [11] [12]. The successful results of this research can be implemented in the nonlinear correction stage of the predictor-corrector process, highlighted in the upper box in Figure 1. However, the predictive capabilities of these results are limited by the processing capability of a typical Electronic Control Unit (ECU) in the host vehicle. A linearized and computationally efficient predictive model in which the throttle commands can be derived from desired engine torques can solve this efficiency issue.

The Performance Margin (PM) is defined by Matthews as the ratio of the required tractive effort to navigate a driving maneuver under given conditions and the available tractive effort (for the front and rear axles respectively). Specifically, the PM is the ratio of the required resultant tractive force to the maximum available tractive force. This concept is particularly important when deriving the desired change in longitudinal force in the throttle prediction model.

LINEAR PREDICTIVE ENGINE MODEL

When there is a change in throttle angle position, there is a time delay of engine torque response; Figure 2 shows typical simulation results for this time delay. In the two leftmost graphs, the throttle command is a single sinusoid with a period of 200 milliseconds. The torque response is skewed and delayed approximately 50 milliseconds due to the inertia in the

system. On the right side of the figure, the period of the sinusoid is extended to 4 seconds and the 50 millisecond delay is negligible. Therefore the first approach in developing an engine model is to limit the bandwidth of throttle control to elicit steady-state torque responses.

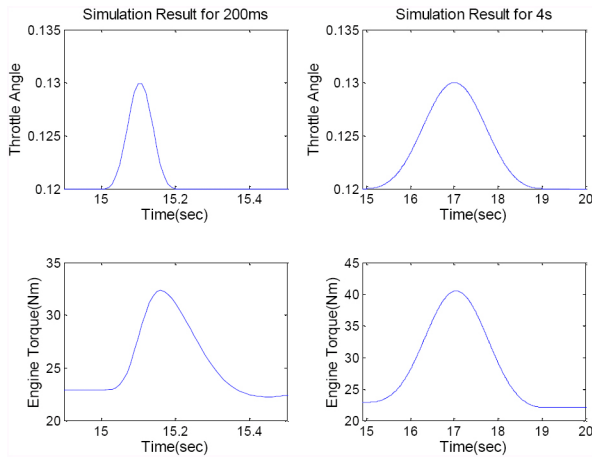


Figure 2. Time delay for resulting change in engine torque response from change in throttle input

Note that throughout this development the changes in the longitudinal forces at the left and right front tire contact patches are identical so that no additional yaw moment is induced. Future work should incorporate yaw control into the overall Intervention Strategy. Also in the current development it is assumed that no gear shifting occurs during the throttle modulation, thus avoiding these impulsive changes to the longitudinal force.

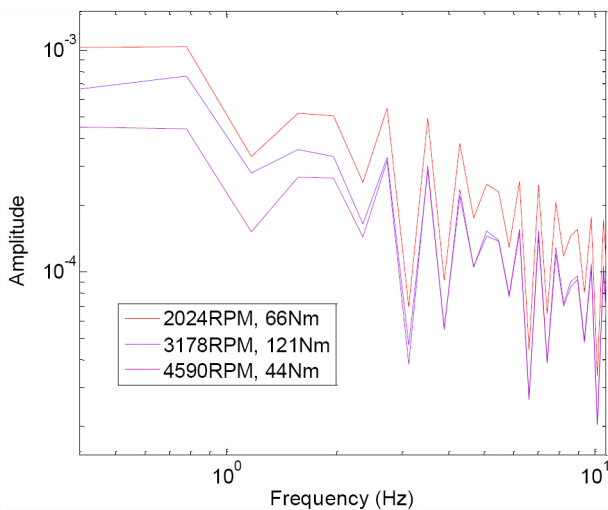


Figure 3. Result with respect to the magnitude of FRF for change in throttle input and resulting engine torque output

The Frequency Response Function (FRF) of the engine torque due to throttle commands for a specific example is shown in Figure 3. In this case, the system exhibits a proportional gain response up to approximately 0.7 Hz. The torque response is not controllable at frequencies higher than 1.5 Hz. That is, any request to change the engine torque beyond this frequency

cannot be achieved by manipulating the throttle. Intermediate frequencies will be dominated by the dynamics of the powertrain system which are avoided in this work.

It is assumed that the engine state, when operating under steady-state conditions, can be adequately described by its speed and torque (η_{ss}, τ_{ss}). The FRF for a wide range of engine states all demonstrate similar tendencies in their response. Specifically, if there is a small change to the throttle, ΔTh , there is a proportional response in the resulting change in torque, $\Delta \tau$, assuming that the change in throttle occurs at a frequency less than 0.7 Hz. At these frequencies, only the gain changes as the state changes. Although the causality is such that the change in throttle causes the change in torque, the inverse relationship is desirable in developing the Intervention Strategy. From this observation, the inverse FRF is defined as a function of frequency, f , and parameterized by the engine speed and torque (η_{ss}, τ_{ss}), as shown in Equation (1).

$$H_{inv-eng}(f; \eta_{ss}, \tau_{ss}) = \frac{\Delta Th(f; \eta_{ss}, \tau_{ss})}{\Delta \tau(f; \eta_{ss}, \tau_{ss})} \quad (1)$$

For example, consider the case in which there is negligible change in the phase as the state changes and the magnitude of the response is only a function of the engine state, not the frequency. In this case, it may appropriate to approximate the FRF by the transfer function in Equation (2).

$$G_{inv-eng}(s) = K_p(\eta_{ss}, \tau_{ss}) \cdot \frac{(1+T_z s)}{s(1+T_p s)} \quad (2)$$

A system identification process proceeds by simulating the system at steady-state conditions over a wide range of engine states. In this particular example, the engine states are distributed from 870 to 6000 rpm and from -10 to 400 Nm, thus forming a calibration map. At each of these calibration points, the frequency response for the change in throttle and change in torque are calculated and the time constants, T_z and T_p , are determined by the cutoff frequencies in the bode plot. The proportional gain, K_p , is defined as a function of the engine state and can be approximated by a bivariate polynomial of the form represented in Equation (3).

$$\begin{aligned} \hat{K}_p(\eta_{ss}, \tau_{ss}) = & \beta_0 + \beta_1 \eta_{ss} + \beta_2 \tau_{ss} + \beta_3 \eta_{ss}^2 + \\ & \beta_4 \tau_{ss}^2 + \beta_5 \eta_{ss}^3 + \beta_6 \tau_{ss}^3 + \beta_7 \eta_{ss}^{-1} + \\ & \beta_8 \tau_{ss}^{-1} + \beta_9 \eta_{ss}^{-2} + \beta_{10} \tau_{ss}^{-2} \end{aligned} \quad (3)$$

The polynomial coefficients, β_i , are found using a generalized inverse approach such that the squared error in the estimate of the gains is minimized. The linear, predictive, inverse engine model, which provides the estimated change in throttle from the desired change in torque, is of the form represented in Equation (4). Note that this equation is written in the Laplace transform domain to simplify notation.