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Independent Wheel Effects in Real Time Estimation of Tire-Road Friction Coefficient from Steering Torque

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Abstract: Improvement of control technologies and increased public acceptance of active systems on vehicles has led to greater implementation of safety critical assistance systems in production vehicles. However, the estimate of tire friction coefficient utilized within these systems is often obtained using only data from inertial sensors in which the tire friction is weakly represented. In contrast, skilled human drivers utilize steering torque to obtain a sense of the surface friction. In theory, this approach can also be utilized with electric power steering or steer-by-wire technologies, but there are significant challenges in obtaining and interpreting data from the steering system including the signal characteristics of steering torque measurements and the well-known problem of practical measurement of tire slip angles. More importantly, a problem often lost in modeling assumptions is in left/right asymmetry of the steering torques. The work presented in this paper illustrates the weak signal-to-noise ratio for steering torque in carefully controlled experiments and demonstrates that the lumped-axle assumption may lead to poor estimates of the front axle peak force value when attempting to predict it at slip angles less than those required for full saturation of both wheels.

Keywords: Vehicle dynamics, tire modeling, stability, estimation, experimentation.

1. INTRODUCTION

The last decade has seen a significant increase in intelligent driver assistance systems fielded in production vehicles. Public acceptance of driver assistance and autonomous systems is on the rise, and algorithms previously fit only for desktop computer use are being refined and run on embedded hardware suitable for vehicle installation. These types of advancements are enabling much more sophisticated systems to be developed for automotive applications.

However, for applications that involve control of the vehicle motion, there is still at least one significant barrier to achieving the highest fidelity control. The friction coefficient between the vehicle tires and the road surface is a challenge to estimate, and yet is a critical piece of information that dictates the handling capabilities of the vehicle. Algorithms such as the production stability control developed and described by Van Zanten (2000) and others use estimation schemes based on inertial sensing of the vehicle state, which leads to acceptable but purely reactive control action. Other systems seek to estimate the stable handling envelope and control the vehicle to stay within the bounds, such as Inagaki et al. (1994); Beal and Gerdes (2013); Falcone et al. (2007), and Bobier and Gerdes (2013). These systems demonstrated excellent control that can be attained with good vehicle state and friction information, but relied upon *a priori* friction measurements rather than real-time estimates. In addition to yaw and sideslip control systems, adaptive cruise control, forward collision mitigation, and pedestrian safety systems would benefit from more accurate estimation of the surface friction coefficient.

Numerous researchers have attempted to address this problem with various methods. Solving the problem of friction detection *prior* to encountering a low friction condition are vision-based methods that can view the road in front of the vehicle and produce an estimate, such as Holzmann (2006), Sato (2007) and Yamada (2005). However, these methods are strongly dependent on the light conditions and are degraded by blur from vehicle speed and vibrations. Others have studied the longitudinal tire dynamics, utilizing braking and drive torques as excitation to the wheels and ABS wheel speed sensors to determine the wheel dynamics. The technique itself is viable, as shown by Ito (1994); Gustafsson (1998); Canudas-De-Wit et al. (2003), but is quite sensitive to road disturbances and requires higher resolution sensors than the standard ABS equipment. Depending on the driving scenario, the brakes may have to be applied to excite the dynamics for estimation, leading to additional wear, reduced fuel economy, and ride quality degradation. Finally, the lateral and yaw dynamics of the vehicle have been investigated as a mechanism for producing the estimate through normal driving excitation. Pasterkamp and Pacejka (1997) utilized a neural network based on a brush tire dynamics model, while Hsu et al. (2010) examined steering torque as a source of information. A combination of several of the techniques was proposed by Ahn (2011) as a way to provide continuous estimation when sufficient excitation is unavailable to one particular estimation technique.

All of the estimation techniques suffer from a similar problem - lack of data that provides significant discrimination between different friction coefficients. It is clear

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that it should be possible to determine the peak force from the slip and force estimates, but this requires significant excitation of the dynamics. In normal driving situations, this data is rarely available, and typically not prior to the moment when a driver assistance system would need an accurate estimate. It is possible to utilize a pneumatic trail model, as described in the work done by Hsu et al. (2010), to determine the peak force value while at significantly lower lateral excitation. Despite the theoretical validity of the method, it has significant practical challenges due to suspension kinematics, the details of the tire-road interaction, and the large amount of variability in steering torque measurements.

This last issue is a particularly challenging one, as steering torque is affected by road irregularities, tread interactions, and other real excitations causing variability separate from true noise. In fact, these measurements are mostly "real" changes in the tire grip. However, this level of variation is too much to feed into a real time controller and is averaged by the much slower physical dynamics of the vehicle itself. Therefore, the friction detection problem is coupled to a problem of discerning significant sudden changes in the friction coefficient from natural variation about a steady mean value. Several of the studies of friction detection propose techniques intended to improve the ability of the algorithm to separate real changes in friction coefficient from the associated signal variation. However, these filters are typically based on some sort of averaging or observer structure and introduce significant delay to the estimate that could be hazardous in a case of a sudden surface friction change. Furthermore, careless use of filtering can alter input signals in such a way that correlated variations in the multiple input signals become offset and further damage the output estimates. Therefore, it is desirable to develop a technique that works point-wise in time and requires only a few data points to calculate an acceptable estimate of the surface friction.

The work presented in this paper attempts to address the issues in discerning the friction coefficient by looking in detail at the signals available for estimation using steering torque. In particular, data was collected in a series of experiments with a steer-by-wire vehicle testbed equipped with independent left and right steering systems. Examining these highly controlled experiments leads to insight regarding the portions of the natural variation that are truly random and some that are accurate signals of wheel friction, even though the variation causes challenges in using resultant estimates for control. In the next section, the basic models used to analyze the data are presented, followed by descriptions of the estimation approach, vehicle and experiments. Finally, the results are presented and analyzed, showing where there are matches and mismatches between the data and the models typically utilized for friction estimation, as well as examining the noise and variation characteristics of the input signals and the resulting outputs.

2. VEHICLE AND TIRE MODELS

2.1 Chassis Model

The experiments presented in this work were conducted with a steer-by-wire test vehicle with separate left and right steering actuators and are intended to demonstrate the different behaviors between the inside and outside wheels when cornering. Thus, this work employs a three-wheel model of the dynamics, as seen in Figure (1). In this model, the front wheels are allowed to have different steering angles, slip angles, and lateral forces. However, because the forces on the left and right wheels of the rear axle cannot be isolated, the rear axle is considered as a single lumped wheel with a common slip angle and combined lateral force.

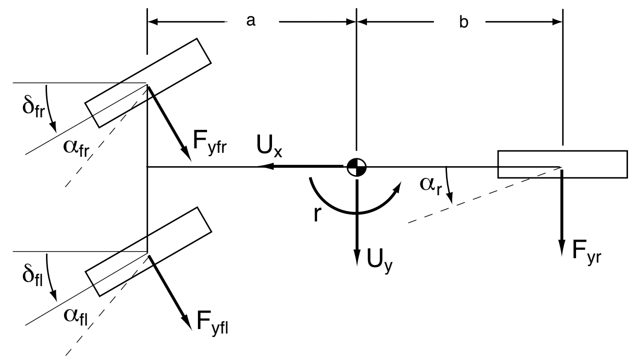

Fig. 1. Three Wheel Vehicle Dynamics Model

It is straightforward to write expressions for the slip angles of each of the wheels based on the chassis kinematics. Assuming small angles, the lateral velocities of the wheel centers can be written in terms of U_y, the lateral velocity of the vehicle CG, r, the yaw rate of the vehicle, and a or b, the distances along the longitudinal axis from the vehicle CG to the front and rear axles, respectively. Similarly, the longitudinal velocities of the wheel centers can be written in terms of U_x, the longitudinal velocity of the vehicle CG, r, and c, the half track width of the vehicle. Taking the ratio of these velocities yields the slip angles, as given in (1).

$$\alpha_{FL} = \frac{U_y + ar}{U_x - cr} - \delta_{FL} \tag{1a}$$

$$\alpha_{FR} = \frac{U_y + ar}{U_x + cr} - \delta_{FR} \tag{1b}$$

$$\alpha_{R} = \frac{U_y - br}{U_x} \tag{1c}$$

Note that in these equations, $\frac{U_y+ar}{U_x \pm cr}$ is an approximation of $\arctan\left(\frac{U_y+ar}{U_x \pm cr}\right)$ since the argument of the arctangent function is small for all data utilized in this work.

The dynamic equations describing the vehicle lateral and rotational motion are given by (2), where F_{yFL}, F_{yFR}, and F_{yR} are the front left, front right, and lumped rear lateral forces, m is the vehicle mass, and I_{zz} is the vehicle yaw moment of inertia. U_x is assumed to be constant for the purposes of the dynamic model. This assumption preserves the linearity of the dynamic equations and is reasonable considering that the tire friction estimates are developed for very short time intervals during which changes in longitudinal vehicle velocity are small. Small angle approximations are also utilized to derive the slip angle expressions.