HEAVY VEHICLE BRAKING USING FRICTION ESTIMATION FOR CONTROLLER OPTIMZATION



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Abstract

A novel electronic brake system (EBS) has demonstrated a 17 percent reduction in stopping distance on a tractor semi-trailer combination during vehicle tests in low friction conditions relative to a modern EBS. Even though these results were promising, it was observed that the novel EBS required more information about the road surface to achieve optimal braking performance. In this paper, the development of an on-line friction estimation method for heavy vehicles, as well as an optimization method that can be used to adjust the slip controller settings, according to the road friction, is described. Results from both simulation and real testing of a Volvo 8x4 FMX truck showed that real-time friction estimation is feasible and increased braking performance can be achieved. Simulation results have shown a reduction in braking distance of up to 20 percent on most road surfaces, as well as a reduction in air usage in most cases.

Keywords: Heavy Vehicles, Emergency Braking, Friction Estimation, Controller Optimization, Slip Control Braking, Vehicle Testing

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1. Introduction

Heavy vehicles are overrepresented in fatal crashes, possibly as their larger size puts passenger vehicle occupants at a greater risk [7]. Although it is difficult to prove a direct causality, the improvement of braking performance could reduce the contribution of heavy vehicles in fatal accidents [8].

In previous HVTT papers, a novel electronic brake system (EBS) developed by the Cambridge Vehicle Dynamics Consortium (CVDC) and Haldex Brake Products Ltd. has been implemented on a tractor semi-trailer combination [1,2]. Vehicle tests carried out in [2] with the CVDC system demonstrated a 17% reduction in stopping distance in low friction conditions relative to a modern EBS. These results were promising; however, it was observed that the CVDC system required information about the road surface in order to achieve optimal braking performance. This paper presents an on-line friction estimation method that can be used to obtain the road surface information required by the CVDC system, as well as an optimization method that can be used to adjust the slip controller settings in response to detected changes in road friction.

2. Methods

The methods that have been used are described in different steps. Initially, model-based development of a wheel slip controller was carried out in MATLAB and Simulink. Then, validation was performed on the developed models using test data from winter testing. Afterwards further function development in order to improve the performance of the existing system in different friction situations was done. The newly developed functions were tested on a truck in real life to evaluate their performance.

2.1 Slip control braking

The CVDC brake system incorporates a slip control algorithm which utilizes the high control bandwidth of its novel valve design to accurately track longitudinal wheel slip demands during extreme braking maneuvers [2]. The slip controller is located in the wheel-based brake ECUs. Each local brake controller receives individual brake torque demands from a global vehicle motion controller, allowing optimal control during extreme braking and turning maneuvers.

Figure [1] illustrates how the slip control braking system can be incorporated with a global motion management system. Each wheel of the vehicle has an individual local brake controller, which includes several software components, as shown in Figure [2].



Figure 1: Modular brake system layout for future HGV



Figure 2: Schematic overview of the local brake controller components (lines and boxes with the dashed lines indicate those added during this work)

More specifically, a first order sliding mode controller creates the demand pressure for the pressure controller (P_{SMC}) using the longitudinal braking force (\hat{F}_x , from a force observer), the measured wheel slip (λ), the slip error (λ_{error} , calculated relative to a wheel slip reference, λ_{ref}), the longitudinal velocity (v_x) and the longitudinal acceleration (a_x) of the vehicle. As is shown in Figure [2] wheel speed (ω) is required by the force observer and slip calculation blocks, this signal is obtained from a wheel speed sensor. The pressure controller produces a pulse-width-modulation (PWM) mark-space ratio demand R_{ms} for the inlet and outlet valves connected to the brake chamber. The PWM signal drives the inlet and outlet valve states (v_{states}), and in turn controlling the brake chamber pressure (P_C). Brake torque at the wheel (T_B) is generated via the brake actuator, which in this case is a disc brake. A pressure transducer is used to measure the internal valve pressure signal, which is used by the pressure observer to calculate the pressure at the brake chamber.

The friction estimation block needs accurate input signals to be able to give reasonable estimates of the friction coefficient. More specifically, as can be seen in Figure [2], it requires the longitudinal braking force (in this case coming from a discrete time Luenberger force observer), the estimated normal force (\hat{F}_z), coming from a normal load estimator, the longitudinal wheel slip, which has been additionally filtered, the longitudinal acceleration and the demand pressure coming from the global vehicle motion management controller (P_D). The specific details of existing controllers and observers is outside the scope of this paper. For more information regarding the Luenberger force observer, readers are directed to [3], which describes an extended version of the observer used in this paper. For more information relating to the slip controller and pressure controller readers are directed to [4].

2.2 Validation

Before function development of the friction estimation and controller optimization algorithms could begin, the existing systems' performance in simulation had to be validated against data obtained during recent vehicle tests (where the systems were run in winter conditions). These validation tests can be divided in two categories: unit testing of the brake controller and testing the brake controller in a full vehicle simulation environment. For unit testing of the brake controller, all specific inputs such as estimated normal load and wheel slip were taken directly from logged data. As expected, the outputs from the local brake controller corresponded exactly to those logged during testing, meaning that the local brake controller was correctly implemented in Simulink.

The next step was to validate the local brake controller with respect to the complete vehicle. By changing the friction coefficient in the simulation environment, braking on low friction conditions could be simulated. Important metrics that were compared were wheel slip and brake pressure, but in the brake-in-turn maneuvers, also yaw rate and sideslip angle were compared. Again, good correspondence was observed, enabling the use of the full vehicle model for the function development of an adaptive local brake controller.

2.3 Function Development

Having validated the slip control braking model along with the vehicle dynamics model, the next step was to develop a friction estimation algorithm, as well as an adaptive reference slip algorithm based on the estimated tire-road friction coefficient (μ_{ff}). An optimization algorithm for the slip controller was also developed which modified the switching gain (k_s) used by the

slip control based on the information from both the friction estimation and the adaptive reference slip algorithms.

2.3.1 Friction Estimation

The friction estimation method that has been used is a slip-slope friction estimation method that utilizes longitudinal vehicle dynamics using parameter identification techniques in real time (recursive least-square algorithm – forgetting factor), according to [5]. This method assumes that at low-slip levels, the normalized longitudinal force (ρ) of each tire is proportional to its slip. This linear relationship is illustrated by the following formula:

$$\rho = \frac{F_x}{F_z} = K\lambda \tag{1}$$

where *K* is the slip-slope, F_x is the longitudinal braking force, F_z is the normal force and λ is the longitudinal wheel slip. Equation (1) can be rewritten in parameter identification format as:

$$y(t) = \varphi^{T}(t)\theta(t)$$
(2)

where:

$$y(t) = \frac{F_x}{F_z} =$$
 (system output) (3)

$$\theta(t) = K \quad (unknown parameter) \quad (4)$$
 $\varphi(t) = \lambda \quad (system input) \quad (5)$

The unknown parameter K (4) can be estimated using parameter identification techniques in real time (recursive least-squares algorithm - forgetting factor), and afterwards it can be used for the real-time estimation of the friction coefficient.

The linear relationship between the friction coefficient and the slip slope at low-slip regions can be expressed by the following formula, according to [5]:

$$\mu = AK + C \tag{6}$$

where K is the slip-slope, A is the proportionality constant and C is a bias constant. The proportionality constant A of equation (6) is the same for all different kinds of surfaces, but it is different with respect to the chosen tire model, according to [5].

The slip-slope based friction estimation method has a different implementation on high levels of slip. More specifically, for high values of slip, the normalized longitudinal force becomes constant and is independent on the slip. In that case, the normalized longitudinal braking force (ρ) can be used directly to provide information about the friction coefficient using the standard parameter identification format, as illustrated by equation (2), but with different variables to the system as it can be seen by the following formulas:

y(t)	=	F_x			(system output)	(7)
$\theta(t)$	=	μ			(unknown parameter)	(8)
$\varphi^{T}(t)$	=	F_z^T	=	F_z	(system input)	(9)

2.3.2 Adaptive Reference Slip

Figure [3] shows that the optimal longitudinal slip (λ) is different for each friction coefficient. Using this information (and the estimated tire-road friction coefficient), an improved reference slip demand signal (λ_{ref}) can be obtained for the sliding mode slip controller using the information about the estimated friction coefficient from the friction estimation block.



Figure 3: Friction curves generated by simulation of the front axle of a Volvo FMX 8x4 for the Pacejka tire model for a specific set of truck tire properties [9].

2.3.3 Slip Controller Optimization

The sliding mode slip controller has been further improved by optimizing the controller's switching gain (k_s), as preliminary testing has shown that a well-chosen (k_s) can find an optimum for braking performance and air-usage for different friction surfaces, see Figure [4]. A novel Monte-Carlo like optimization method is used for on-line controller gain optimization. Friction surfaces are categorized in bins. For each bin, braking performance is measured with respect to the switching gain. If a large enough data set is available, the algorithm can converge to a braking gain for which the average braking performance is best.



Figure 4: Pareto plot on the influence of k_s on the air usage and stopping distance on dry road for a Volvo FMX 8x4.

The friction estimation wheel-based function and the optimization block which have been developed in this research can be seen in Figure [2], along with the optimization block and the optimized slip demands (lines and boxes with the dashed lines indicate those added during this work).

3. Results

In this section, results from both simulation and real testing of a Volvo 8x4 FMX truck are presented. Figure [5] shows the performance of the local brake controller during a braking event including a sudden transition from high to low friction. The left-hand figure shows simulation results, and more specifically, it shows the longitudinal velocity of the vehicle, the wheel speed, the friction coefficient estimation and the longitudinal wheel slip of the front left-hand wheel of the vehicle, when μ changes from packed snow to polished ice during a hard-braking event. The right-hand figure shows results from real vehicle testing, and more specifically, it shows the longitudinal velocity of the vehicle, it shows the longitudinal velocity of the vehicle speed, the friction coefficient estimation and the longitudinal wheel speed, the friction coefficient estimation and the longitudinal velocity of the vehicle, the wheel speed, the friction coefficient estimation and the longitudinal velocity of the vehicle, the wheel speed, the friction coefficient estimation and the longitudinal velocity of the vehicle, the wheel speed, the friction coefficient estimation and the longitudinal velocity of the vehicle, the wheel speed, the friction coefficient estimation and the longitudinal velocity of the vehicle, the wheel speed of the vehicle, when μ changes from dry asphalt to wet basalt during a hard-braking event. In both systems, the same forgetting factor for the recursive least-squares (RLS) algorithm has been selected.

As can be seen in Figure [6], the friction estimation algorithm is able to capture the reference friction coefficient on packed snow quite accurately. Furthermore, when the reference friction coefficient changes from high to low μ , the friction estimation algorithm is able to capture this change and predict the new friction coefficient within one second, in simulation. The discrepancy between the reference and new (i.e. after the friction step change) friction coefficient occurs due to the different wheel slip demands and controller gains before and after this friction step change.

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When it comes to the real test results presented in figure [6], it can be seen that, due to the very short time spent on the high- μ surface, the friction estimation algorithm has not yet converged to the actual friction coefficient when the friction step change occurs. However, the algorithm is able to capture the actual friction coefficient of the low-friction surface, since the vehicle is braking on this surface for a longer period of time. The main difference in behavior of the friction estimation algorithm in Figure [6] compared to Figure [5] can be seen just after the friction step change occurs. The main reason for this delay between simulation and experiment is that the wheel lock that occurs during real vehicle testing does not allow the RLS to work properly (i.e. violation of its initialization conditions), and hence the algorithm is not able to predict the new friction coefficient. Furthermore, it should be noted that the tuning of the braking force observer has a significant influence on the performance of RLS filter. During the experiment, more conservative values for pole placement and frequency were used compared to those used in simulation (Figure [5]). Ongoing and future vehicle testing will focus on assessing the RLS algorithm's performance when more aggressive force observer tuning gains are used.



Figure 5: Friction estimation performance from simulation results.



Figure 6: Friction estimation performance from real test data

4. Conclusions

Simulations have shown that the friction could be estimated online and that a set of optimized parameters for the slip controller could be generated on-line during braking maneuvers. Friction estimation and controller optimization have shown to have positive effects on the braking performance and air consumption. Preliminary vehicle tests have demonstrated that the friction estimation gives reasonable results on the test track. More extensive research has to be conducted however, to show that the on-line parameter estimation converges in a reasonable amount of time so that the full benefits of slip control braking can be achieved.

5. References

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