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Experimental Study on Road Friction Variation and Stopping Distance Uncertainty using ABS Braking Data

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This paper investigates the remaining fluctuation of road friction and stopping distance when the contribution from known sources has been removed. This fluctuation can serve as uncertainty for active safety functions relying on friction estimates. Data from repeated ABS brake maneuvers on several uniform road conditions, including high and low friction surfaces, is analyzed. Road friction estimates are obtained and used to estimate the uncertainty in road friction and stopping distance. Measurements from the same road segment show a friction uncertainty of less than 0.1 with the presented procedure. The stopping distance uncertainty becomes considerable at high speeds and low friction for the intended use in emergency brake functions. Especially for low friction, high estimate accuracy is motivated.

Topics / Testing and Validation, Identification and Estimation

1. INTRODUCTION

Vehicles nowadays are automated for increased safety and driver comfort. Several driver assistance functions, such as autonomous emergency braking (AEB) and slippery road alert, could become safer and give fewer false alerts if road friction is better known. With this intended use, this paper examines how much friction estimates may vary under ideal driving conditions.

Estimating the road friction is challenging. Friction varies with the road conditions, and the estimates are often highly uncertain [1]. The uncertainty, in turn, deteriorates the intended functionality of the driver assistance functions [2], [3]. For emergency braking functions especially, several function improvements have been presented. Some of them require road friction to be known accurately. Road friction under the vehicle is estimated either by lightly applying the brakes to excite the tyres [4] or using vehicle sensors coupled with a vehicle dynamics model [5]. However, when the decision of emergency braking is taken, it is commonly assumed that the friction ahead of the vehicle is the same as the latest estimated one and that friction will not vary along the predicted path. Finally, other research [6] focuses on how the estimates are used for the AEB, assuming that the estimates are accurate enough.

Even at the same road segment, friction varies due to the local road properties, defined here as the true friction variation. When a vehicle is braking, though, the true friction variation is not the only source of variation which affects how a vehicle experiences friction. Other known sources originate from vehicle components, like its tyres and Anti-lock Braking System (ABS) functionality, the current road conditions or the friction estimate algorithm in question and sensor quality. This paper studies friction variation by measuring retardation at hard braking when as many known sources as possible are kept constant. The goal is to compensate for all possible factors, which in some sense correspond to explainable variations so that the least possible variation remains. The remaining variation is considered "non-explainable" and is the uncertainty one must accept when using friction estimates in safety functions.

A test procedure was followed by conducting several brake maneuvers on a test track with a uniform surface to keep known source variation to a minimum. The exact vehicle was used in a short amount of time between each brake maneuver and at a uniform track. For each brake maneuver, a friction estimate is calculated based on the assumption that the vehicle brakes as hard as possible to attain maximum deceleration under the current conditions.

Sets of estimates are formed by grouping them first based on the road surface and tyre type. Second, in literature, there is a known influence of speed to friction from tyre models [7] and the ABS side [8]. In tyre models, the peak friction decreases slightly with speed. Meanwhile, the efficiency of the ABS at low speed (<35 km/h) is inferior to high speed resulting in lower deceleration levels. Those two combined make up for a nonlinear relation of friction and speed [9,10]. Hence, it was decided to group the data in bins of similar initial speed too to examine this connection. Following this test procedure and estimation methodology, the obtained sets of friction estimates contain reduced friction variation. Hence, using the friction estimates to calculate the stopping distance uncertainty results in estimating the lowest achievable stopping distance uncertainty.

2. EXPERIMENTAL SETUP

Data from several brake maneuvers with the ABS active were gathered from two different places with a passenger car. The first is at the Hällered Proving Ground (HPG) which features two different surface areas: a high-friction pavement, and a controlled low-friction basalt area. The second is at Jokkmokk, at the north of Sweden, where snowy and icy road conditions were tested. These are defined as the "HPG" and the "snowy" setups below. A different vehicle was used in each setup, but each vehicle remained the same for all the brake events.

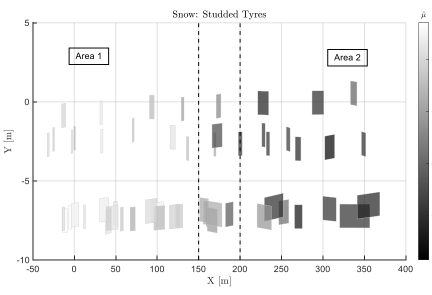
In the snowy experimental setup, the surface was prepared between each set of tests, and road friction is assumed to be uniform within a dataset. Furthermore, the brake events were performed in a straight line one after the other. Only the last brake maneuver came to a full-stop. The car was moved laterally between each run to avoid braking in the same line. This was done to avoid snow/ice property changes after the brake events. Moreover, three types of tyres were tested: studded, Nordic-, and European friction tyres, in five snow/ice road conditions: snow, packed snow, smooth ice, rough ice, and extra rough ice.

In the HPG setup, the vehicle had summer tyres and was tested on two road conditions: wet asphalt and basalt. All brake events here were conducted to a full-stop.

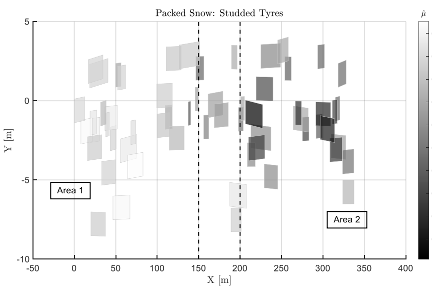
The test vehicles were equipped with a data-acquisition system which notably includes high-precision GPS, velocity, and accelerometer sensors. Furthermore, characteristics of the ABS operation was also gathered.

3. ROAD FRICTION VARIATION EFFECTS

For each brake maneuver, a road friction coefficient estimate is calculated when the vehicle brakes as hard as possible and the ABS is activated. To calculate the friction estimates, measurements of position, velocity, and acceleration are used. In vehicles, these are commonly available from the GPS, wheel speed sensors, and accelerometers, respectively.



(a) Snow



(b) Packed Snow

Fig. 1 Varying friction map of snow region

For $i = 1, \ldots, N$ brake maneuvers conducted in the same location and with uniform friction throughout the braking path, the road friction estimate $\hat{\mu}_i$ is defined as

$$\hat{\mu}_i = \frac{1}{2}\frac{v_{0,i}^2 - v_{end,i}^2}{s_i g} \quad (1)$$

where $v_{0,i}$ is the initial and $v_{end,i}$ the final speed of the brake maneuver, s_i is the stopping distance, and g is the gravity constant. This is the peak friction value that can be achieved in real world conditions for this specific vehicle under the assumption of hard braking such that

$$a_{x,i}(t) = a_{x,i,min} \ \forall t \in [t_{0,i}, t_{end,i}] \quad (2)$$

where $a_{x,i}$ is the longitudinal acceleration over the hard braking time t and $a_{x,i,min}$ is the highest feasible deceleration.

Applying (1) for the N brake maneuvers, a set of estimates $\hat{\boldsymbol{\mu}} = [\hat{\mu}_1, \ldots, \hat{\mu}_N]^\top$ is obtained. The friction uncertainty of $\hat{\boldsymbol{\mu}}$ is defined as

$$\hat{\delta}_\mu = \max(\hat{\boldsymbol{\mu}}) - \min(\hat{\boldsymbol{\mu}}) \quad (3)$$

An estimate of the stopping distance uncertainty $\hat{\delta}_s$ is calculated from (1) putting $v_{end,i} = 0$ and taking the difference between the largest and the smallest distance

$$\hat{\delta}_s = \max(\boldsymbol{s}) - \min(\boldsymbol{s}) = \frac{v_0^2}{2g}\left(\frac{1}{\min(\hat{\boldsymbol{\mu}})} - \frac{1}{\max(\hat{\boldsymbol{\mu}})}\right) \quad (4)$$

A necessary step for the calculation is to assume that the initial velocity used for the whole set is the same, such that $v_{0,\max(s)} = v_{0,\min(s)} = v_0$. To make the speed assumption valid, the estimates $\hat{\boldsymbol{\mu}}$ are grouped into bins of similar initial speed. The initial speed medians of the bins are used instead for the estimation of $\hat{\delta}_s$, along with the obtained boundaries of $\hat{\boldsymbol{\mu}}$.

3.1 Data Analysis

For each dataset, two bins of initial speeds are chosen, one at "low-speed" and one at "medium-speed". In the snowy dataset, there is significant variation in the initial speed of the maneuvers. Apart from that, there is time variation when the ABS is triggered after the brake pedal is pressed. That is, the driver may press the brake pedal differently each time. The low-speed bin is chosen in the range of [25 45) km/h and the medium-speed bin at [45 65] km/h. In this way, the medians of the bins lie at 35 and 55 km/h, respectively. In the HPG datasets, the initial speed was controlled tighter in the tests, with slight variation within the bins. The medians lie at 30 and 60 km/h for the low- and medium-speed setting, respectively. The calculation of (3)-(4) is performed on the grouped initial speed medians.

Although the surface was prepared between each test in the snowy setup, two distinct areas are noted when visualizing the brake events in a friction map, see Fig. 1. A friction map is defined here as a GPS map containing relevant friction information. In this case, the friction coefficient estimates of (1) are projected onto the map. The figure shows that the local road properties are an important aspect of the experienced friction. The two identified areas, area 1 and area 2, are examined separately for their friction distributions.

Applying (1) for the packed snow road condition to get $\hat{\boldsymbol{\mu}}$ for the 3 types of tyres and plotting the estimates against initial speed gives varying dependencies as visualized from the linear regression fits, see Fig. 2. As the number of data are not enough, the realization of noise affects the slope of the fit. This adds to the motivation of grouping the estimates in bins of initial speed as the grouping reduces the uncertainty, provided that the mean is not compromised.

3.2 Road Friction Estimate Results

In the packed snow road condition dataset, the results for $\hat{\boldsymbol{\mu}}$ and its uncertainty $\hat{\delta}_\mu$ from (3) are presented in Table 1 and visualized in Fig. 3. A comparison of the different types of tyres is first made. The studded tyres exhibit the best grip, followed closely by the Nordic and the European friction tyres in order of appearance. Regarding the speed dependence, as speed increases, the studded and the European tyres exhibit small increases in grip, while the Nordic show no difference (area 1) or even a decrease (area 2). Between the different areas, there is a decrease in the road friction coefficient from area 1 to area 2 for all tyres showing that variation can exist between different segments on the same road. Finally, the friction uncertainty is chaotic as it changes between different tyre types, initial speeds, and areas.

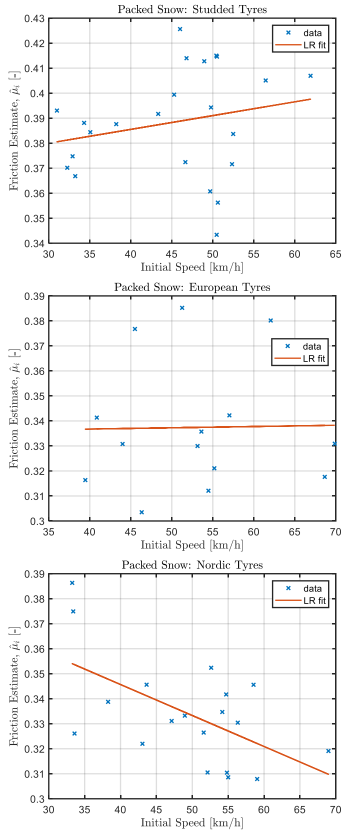
The results of the HPG dataset are presented in Table 2 and visualized in Fig. 4. For both cases, friction means drop while friction uncertainty increases with initial speed. As in the previous results, the difference in the friction means between the 2-speed bins is about 0.01-0.02. The uncertainties are universally smaller than 0.1, though larger than the difference in the means. Due to that, no clear answer can be given for the speed dependency of friction, see also the discussion in Fig. 2. The magnitude of the uncertainty and difference between friction means with speed is on the same scale as other studies [9,10]. Here, more tyre types and surfaces are presented for low-to-medium speeds.

Table 1 Road Friction Estimate Results: Packed Snow

		Friction Mean $\bar{\mu}$		Friction Uncertainty $\hat{\delta}_\mu$	
Initial Speed (km/h)		35	55	35	55
Tyre type	Area				
Studded	1	0.42	0.44	0.06	0.04
Studded	2	0.38	0.39	0.03	0.08
European	1	0.40	0.41	0.09	0.08
European	2	0.33	0.34	0.03	0.08
Nordic	1	0.42	0.42	0.03	0.07
Nordic	2	0.35	0.33	0.06	0.04

Table 2 Road Friction Estimate Results: Wet Asphalt and Basalt

	Friction Mean $\bar{\mu}$		Friction Uncertainty $\hat{\delta}_\mu$	
Initial Speed (km/h)	30	60	30	60
Wet Asphalt	1.03	1.02	0.02	0.07
Basalt	0.21	0.19	0.01	0.02



(a) Studded

(b) European

(c) Nordic

Fig. 2 Road friction estimates vs. initial speed for the packed snow condition for 3 types of tyres (Area 2)

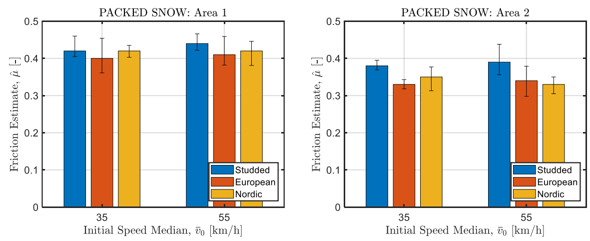


Fig. 3 Road friction estimate means and uncertainty for several types of tyres and areas of braking

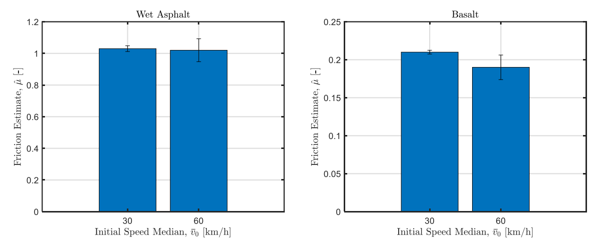


Fig. 4 Road friction estimate means and uncertainty for the wet asphalt and basalt road conditions

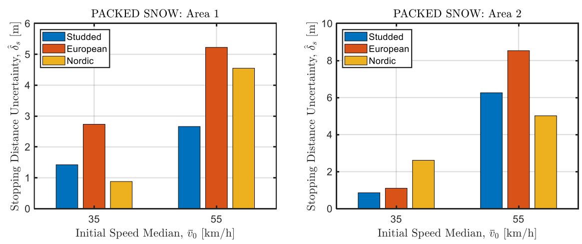


Fig. 5 Stopping distance uncertainty for several types of tyres and areas of braking

4. REALIZATIONS OF UNCERTAINTY

4.1 Stopping Distance Uncertainty

Using the packed snow dataset results from Table 1 to estimate the stopping distance uncertainty from (4) gives Fig. 5. The main message here is that even though the friction uncertainty might be small (<0.1), the stopping distance uncertainty becomes considerable with small increases in speed in this low-friction case. That is expected as the stopping distance uncertainty grows quadratically with speed in (4). For an emergency brake function, this growing uncertainty complicates matters. Especially if all collisions were to be avoided, the smart function risks becoming overly conservative. Note that for a high-friction surface, the stopping distance uncertainty is smaller. For the example of the wet asphalt, from Table 2, the uncertainty is calculated to be about 0.1 m for 30 km/h and 1 m for 60 km/h.

4.2 Impact Velocity

An alternative way of interpreting how the friction uncertainty affects an emergency braking function is to calculate an estimate of the velocity of impact for a forward collision. The worst-case scenario would be that the friction takes the lowest value in the uncertainty interval, while the function assumes the average friction when estimating the stopping distance towards a stopped target ahead of the vehicle. From (1), the speed at the end of the braking event is

$$v_{end} = \sqrt{v_0^2 - 2gs\hat{\mu}} \qquad (5)$$

The worst-case is obtained for the lowest limit of friction

$$\hat{\mu} = \bar{\mu} - \hat{\delta}_\mu/2 \qquad (6)$$

The stopping distance assuming the nominal value of the friction, $\bar{\mu}$, and the speed $\bar{v}_0$ is obtained by inserting $v_{end} = 0$ into (1) which gives

$$s_p = \frac{\bar{v}_0^2}{2g\bar{\mu}} \qquad (7)$$

Inserting (6) and (7) into (5) gives the impact velocity

$$v_p = \bar{v}_0 \sqrt{\frac{\hat{\delta}_\mu}{2\bar{\mu}}} \qquad (8)$$

An emergency braking function could be calibrated based on an acceptable impact velocity so that accidents are only mitigated. An example of how the impact velocity can be useful is presented in Table 3, using the results of Table 2. It is observed that the impact of uncertainty is more significant under low-friction road conditions. At high speed, a 0.02 uncertainty in Basalt corresponds to a 14 km/h equivalent impact velocity, while a 0.07 uncertainty to an 11 km/h impact velocity for the high-friction case. This difference is traced back to the ratio of $\hat{\delta}_\mu/\bar{\mu}$. The result motivates the need for increased accuracy under low-friction road conditions.

Table 3 Impact velocity calculations

Road Condition	v_p at 30 km/h	v_p at 60 km/h
Wet Asphalt	3.0	11.1
Basalt	4.6	13.8

5. CONCLUSION

This paper examines the variation in friction for minimal change in the experimental conditions by repeating brake maneuvers with the exact vehicle at a uniform surface. In this way, one obtains an indication of the lowest uncertainty limit in experienced friction useful for driver assistance functions. Results show that friction uncertainty less than 0.1 is achievable when considering local road properties, road classification, tyre type, and initial speed factors. Grouping friction estimates with initial speed reduces uncertainty, despite the connection of speed with friction mean being negligible. Still, a friction uncertainty less than 0.1 induces considerable uncertainty in stopping distance estimations at low friction and high speed. This relation is verified with the proposed velocity impact measure. The takeaway is the need for higher precision of the friction estimates at low friction, and this need increases with speed.

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