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Abstract. Data-driven development of friction estimators for passenger vehicles is becoming popular. They rely mainly on training data to obtain an accurate estimate of the current road conditions. However, reference or training data for natural conditions containing available friction is sparse. This limits the development of data-driven approaches for friction estimation. The current paper presents progress in a project devoted to developing a method to use standard equipment for road monitoring to acquire reference data for friction estimation, relevant to specific tyres and operating conditions. Results show how a mapping between existing test equipment readings and the real experienced coefficient of friction of a car tyre can be made.

Keywords: Tyre-to-road friction · friction measurement · friction reference value

1 Introduction

The available tyre-to-road friction limits the motion envelope of any road vehicle and is a hard constraint on all vehicle motion control functionality such as ABS, ESC, etc. For autonomous vehicles, this is even more pronounced and a correct prediction of friction ahead of the vehicle is a necessity to ensure safe operation. The current state-of-the-art friction estimation approaches use physical models. These approaches give correct estimates point-wise, and require special conditions to operate, leading to low data availability (see e.g. [1] and references therein). A current trend to solve the availability problem is to make use of data-driven approaches and machine learning. These types of approaches rely on available training data for all conditions the car is intended to operate. The availability of such data is currently very limited, which constrains the development of such algorithms and ultimately also the development of autonomous vehicles. A common problem is that there exists no good method to continuously measure a reference value of the tyre-road friction for a car. On test tracks, with large surfaces of uniform

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friction, a full ABS brake test can be used for determining the friction. On real roads, however, where the surface conditions may be rapidly changing, such a measurement is in most cases impossible due to road curvature, and even more importantly, traffic safety.

Measuring the road surface is an ongoing activity for most road administrators. The main objective of such measurements is to monitor the conditions of road segments and to use this information for decision-making of road maintenance. Recently, the use of vehicles in a fleet as probes to a centralized cloud for this purpose has been investigated. However, the established method for these types of measurements is through dedicated devices attached to a vehicle. An example of such devices can be an extra tyre with a fixed slip ratio and a force sensor. A common aim with all these measurement techniques, including the cloud-based ones, is to monitor the road conditions. Hence, standard methods with special tyres are typically used.

In the current paper, the aim is to develop a measuring method for the vehicle industry that can provide them with the required reference friction data using the devices used typically by road administrators. The use of standardized methods with measurement devices cannot be applied directly to the problem that the vehicle industry is facing. The friction measurements need to reflect the friction level and conditions a car would experience to be relevant. Hence, translations between the readings from the device and the car friction level need to be developed through measurement campaigns. The purpose of this project has been to develop a method to derive this translation with a focus on minimizing the required measurements and additional sensors required.

2 Methodology

A commercial road friction measurement device that VCC has acquired (see Fig. 1a) was used via test track measurements to establish the correlation between friction values from this device and a few Volvo passenger cars on different road friction conditions. By driving in a caravan with a car, denoted the target vehicle, the continuously measured road friction values can then via the known correlation be transformed into reference friction values representative of the target vehicle. Wireless communication between the road friction device (RFD) and a target vehicle (TV) has been set up so that the reference friction can be logged synchronously together with other sensor data in the car.

The RFD is a trailer from the Norwegian producer ViaFriction, and this particular model is commonly used for routine friction assessment of winter roads in Sweden, carried out by the Swedish Transport Agency. It is equipped with two measurement wheels, one in each wheel track. Test tyres of type Trelleborg Unitester 520 were used, which is the standard test tyre to be used for winter road friction measurements according to the method description prescribed by the Swedish Transport Agency. The wheel load is set to 1000 N, and the measurement is supposed to be carried out at a fixed brake slip value of 20%. Commonly, road friction equipment of this type, measuring the longitudinal friction for a braked wheel, uses a mechanical gear system to provide a very stable wheel slip value regardless of the road friction. This particular RFD however, instead uses an electrical motor for each test wheel that continuously regulates the wheel slip. It was found that the wheel slip in many cases was unstable and care had to be taken to assure that obtained measurement data fulfilled the wheel slip requirement.

The available friction for a target vehicle equipped with specific tyres would most easily be determined from straight brake tests on a test track with a homogeneous surface. In this project there was an opportunity to also measure the available friction for a specific tyre by using VTI's tyre test equipment BV12. The BV12 (see Fig. 1b) is a mobile equipment for tyre friction characterization, which can measure both longitudinal and lateral friction slip curves of the tyres to determine the peak friction at various operating conditions. In theory, friction models based on slip curves measured at different wheel loads could be applied to different target vehicles which use the same tyre, thus expanding the use cases for a specific tyre mapping.

To limit the number of measurements it was decided to focus only on longitudinal brake friction. The BV12 brake slip curves are measured at constant speed, just as the RFD friction, while a brake test with a car will comprise a speed interval. Two week-long measurement campaigns were carried out on snow and ice tracks in Northern Sweden. The three equipment were driven consecutively, laterally displaced on the test tracks to avoid each other's wheel paths. Measurements carried out within a time frame of 5 min were considered to be pairwise comparable.

Three different winter tyres for the target vehicle, a Volvo XC60, were used: a European winter tyre, a Nordic winter tyre, and a studded winter tyre. The test tracks were prepared so that friction levels with the RFD were within 0.05–0.45. Measurements were carried out to allow for mappings at different vehicle speeds, wheel loads and inflation pressures. An optical sensor from Teconer [2] was also used for distinguishing between ice and snow surface in case this information would be necessary for the mapping.

The test tracks were rectangular, typically 20 m wide with a length of 600–1000 m. The Snow tracks were made available by the tyre manufacturer Pirelli, and were prepared according to their expertise to allow for repeatable tests. Tracks with different hardness of snow were used in the purpose of covering a range of available friction. Still, snow on these kind of tracks is generally much harder than conditions often found on the roads, and consequently exhibit quite high friction levels. The snow hardness was in the range of 82–90 CTI units (see ref [3] for a definition of snow hardness), and the ambient temperature ranged from +2 to −6 °C, with the snow temperature a few degrees colder. The RFD measured friction values varied between 0.28–0.44.

(a) (b)

Fig. 1. The Volvo road friction device (a) and VTI BV12 tyre test equipment (b)

The ice tracks were divided into parallel corridors, 3 m wide and 300 m long, which could be prepared differently to allow for different preparation. A special ice-rugging trailer with 10 studded tyres rolling with large slip angles was constructed in order to transform a smooth ice with low friction, to rugged ice with different friction levels. In combination with large weather variations ice surfaces with RFD friction levels in the range of 0.05–0.45 were obtained.

3 Results

To obtain a functional translation of a brake slip curve on snow to the average friction obtained from full ABS braking with a passenger car, unprocessed data from a previous project [4] was analyzed. Brake tests on snow carried out with both BV12 and a passenger car for more than 40 different tyres indicate a close correlation between the slip curve peak friction and the average ABS retardation as shown in Fig. 2a. A linear fit suggests that the obtainable ABS friction is 85% of the peak friction of the brake slip curve on this type of hard packed snow surface. This relation was used in the analysis of the current study, and a generally good agreement between BV12 and XC60 results indicate that it works well, despite a different car and different snow tracks. Since slip curves on snow are quite flat, as shown in Fig. 2b, it is not surprising that the peak value is a good indicator of the attainable ABS brake friction. Slip curves on ice generally show a quite marked peak at low brake slip values, where the friction decreases significantly at higher slip. To estimate the ABS brake friction on ice, the integral of the slip curve within a fixed slip interval was used. As a starting point, the interval 5–55% was used, with the possibility to tune the interval according to comparisons with the XC60 results.

Data from the two campaigns is presented in Fig. 3, where the average RFD friction value of both wheel tracks is compared to the BV12 and the XC60 results.

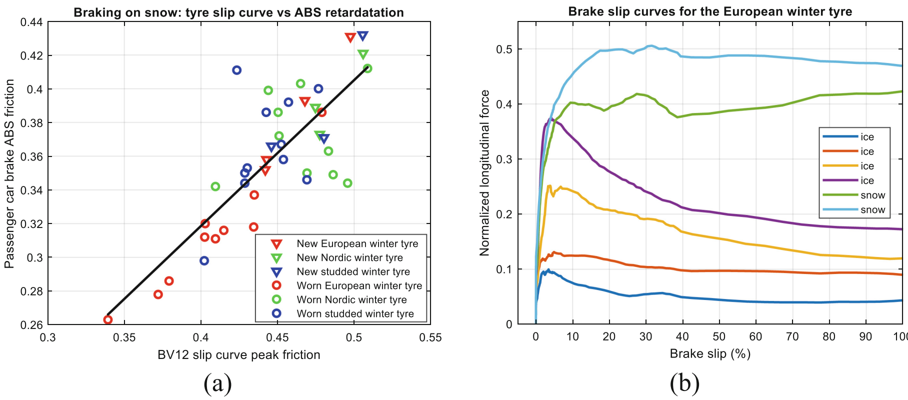

Fig. 2. Correlation between slip curve peak friction and ABS brake friction on snow (a) Typical brake slip curves on ice and snow for the European winter tyre (b)

Initial measurements were carried out at both 30 and 50 km/h, but since no clear difference was observed at these speeds, the majority of the measurements were then done at 50 km/h. Most data was collected for the Nordic winter tyre, for which both BV12 and XC60 show a similar picture. The RFD underestimates the available friction at very slippery ice as well as for packed snow, while it provides a good estimate at intermediate ice friction levels. The data for the European winter tyre shows a similar behavior, but the European winter tyre has lower performance on slippery ice compared to the Nordic tyre, leading to a good correspondence with the RFD also at low friction.

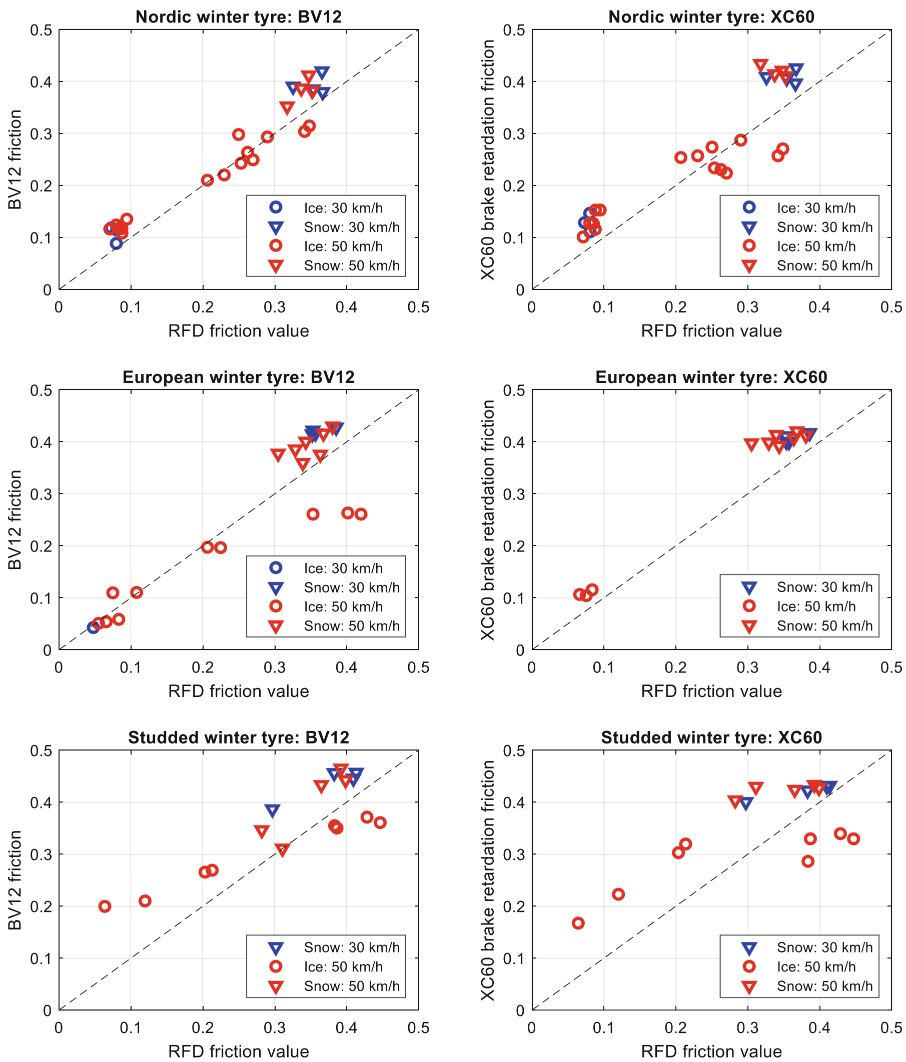

Fig. 3. RFD friction values compared to estimated brake friction from BV12 measurements and brake tests with the XC60.

An interesting anomaly for ice with very high friction is observed for the BV12 data This particular ice track was covered with a layer of frost resulting in extremely high

RFD values, which clearly overestimated the brake friction for the European tyre. Unfortunately, the XC60 was not available for measurements with this tyre at this condition, but results for the studded tyres shows a similar behavior for both BV12 and XC60 on this high friction ice. As expected, the studded tyre generally provides increased ice grip level compared to the other tyres (as well as the RFD) on all other ice surfaces, while performing on par with the studless tyres on snow.

Two different mappings seem to be needed at RFD friction levels above 0.3 - one for snow and one for ice. Thus, information about the road conditions would be necessary. A technology using an optical sensor to discriminate between ice and snow has been tested in this project, and while the results on homogenous test tracks are promising, further testing is needed to conclude its effectiveness on real winter roads.

Measurements at different wheel loads (±50%) with the BV12 showed a very small effect on the brake friction. As did changes of the inflation pressure.

Comparison with the RFD driven straight and along a slalom pattern resulting in a lateral acceleration of 0.1 g indicated that the RFD friction value is decreased by 10% when measuring in a curve.

4 Conclusions

The results of elaborate field tests on ice and snow demonstrate that a dedicated road friction device can be a useful tool for continuously measuring available brake friction on winter roads for a specific vehicle and tyre, however the measured friction level by RFD should be adjusted for different tyre types. The data indicates that a model with piecewise linear mappings could be used, but additional information regarding the road surface conditions at RFD friction levels above 0.3 would be needed.

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