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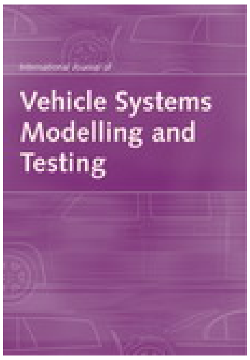

International Journal of Vehicle Systems Modelling and Testing

ISSN online: 1745-6444 - ISSN print: 1745-6436
https://www.inderscience.com/ijvsmt

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DOI: 10.1504/IJVSMT.2023.10058374

Article History:

Received:	05 October 2022
Last revised:	14 November 2022
Accepted:	09 January 2023
Published online:	20 August 2023

Int. J. Vehicle Systems Modelling and Testing, Vol. 17, No. 2, 2023 101

Comparison of methods for winter road friction estimation using systems implemented for floating car data

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Abstract: Winter road maintenance is important for preventing accidents and enabling mobility. If the road friction gets low, there is a higher risk of road accidents. Therefore, it is vital to have information about road friction levels. Traditionally this is done by dedicated vehicles; however, using friction information from floating car data (FCD) would be more beneficial, as the coverage both in time and space increases. In this investigation, road friction data from three FCD suppliers, using only one test vehicle each, has been compared with a continuous method of road friction measurement. The test has been conducted on proving grounds covered with ice and snow, and on public roads covered with water, ice, snow, and slush; thereby both high friction and low friction surfaces have been evaluated. The investigation shows that the FCD provides a continuous method of friction measurement and is closer to the reality of road friction experienced by road users.

Keywords: road friction; friction estimation; winter road maintenance; vehicle data; optical sensor; floating car data; FCD; big data; experimental validation; vehicle testing.

Reference to this paper should be made as follows: Sollén, S. and Casselgren, J. (2023) ‘Comparison of methods for winter road friction estimation using systems implemented for floating car data’, *Int. J. Vehicle Systems Modelling and Testing*, Vol. 17, No. 2, pp.101–111.

Biographical notes: Sofia Sollén received her MSc in Sustainable Energy Engineering at the Luleå University of Technology in 2019 and is currently doing her PhD in Experimental Mechanics at the same university. Her research focuses mainly on the implementation and validation of floating car data for winter road friction follow-up. She is at an early stage of her career, has published multiple papers, and will complete her PhD in a few years.

Johan Casselgren received his MSc in Applied Physics from the Luleå University of Technology in 2005. In 2010, he returned to Luleå University of Technology as a Researcher and received his PhD in Experimental Mechanics in 2011.

His main research area is optical measuring techniques of different phases of water upon asphalt and friction estimation based on different sensors.

1 Introduction

Traditional road friction measurements are often performed using dedicated vehicles and are limited, both in terms of the time during which the measurements are performed and coverage within the traffic system. In recent years, several studies have demonstrated possibilities of implementing floating car data (FCD) to improve the coverage of, for example, friction information from the traffic system. Brockfeld et al. (2007) and Jenelius and Koutsopoulos (2013) have shown how FCD from a fleet of taxi vehicles could improve travel time estimation and route planning. In Autioniemi et al. (2015) and Hu et al. (2019) similar work has been done using FCD to fill the gaps between road weather information system (RWIS) stations for improved road weather forecasts. In a study by Sollén and Casselgren (2021), FCD was implemented for winter road maintenance follow-up by monitoring road friction. According to the results, FCD could be used to improve the coverage provided by current traditional methods, and increase knowledge about the traffic system. For many years, these benefits of knowing more about current road conditions, and especially road friction, have been pointed out as key to improving winter road maintenance; see for instance, Norrman et al. (2000), Pilli-Shvola et al. (2012) and Hinka et al. (2016).

To realise these benefits, much research has been focused on the field of online tyre-to-road friction estimation. The main branches of approaches to the estimation problem can be divided into indirect and direct methods. Direct methods use the planar forces of the tyre (in the longitudinal and/or lateral) and/or the aligning torque acting on the tyre as input to determine the friction directly. Examples of such approaches can be found in Müller et al. (2003) and Ray (1997) for force sensing, and Pasterkamp and Pacejka (1997) for self-aligning torque. Indirect methods categorise all other approaches where some second-order effect or mechanism serves as an indicator of the tyre-to-road friction. Examples of indirect methods can be found in Umeno et al. (2002), where the frequency content of tyre rotational velocity is an indicator of current surface and friction. Other examples can be seen in Breuer et al. (1992), Kongrattanaprasert et al. (2009) and Casselgren (2007), where sound from microphones in the wheelhouse or optical reflections of specific wavelengths are used as indicators. The approach taken by Gustafsson (1997) uses the relative motion of the tyre with regard to the road surface (slip), and relates this to the tyre forces in the longitudinal direction. Even though the method uses the tyre forces, it cannot be classified as a direct method since it uses the force-slip curve as an indicator, rather than using it to directly estimate the friction coefficient.

Direct methods are characterised by the fact that a certain amount of tyre force is needed to be able to estimate the friction. This implies that estimates of the friction will not be always available in an online estimator as the required tyre forces are only present in special driving situations (e.g., braking over a certain level etc.). This is a fundamental property of all direct methods. For indirect methods, the estimate only measures an indicator that correlates to the road conditions, i.e., indirect methods do not estimate the tyre-to-road friction itself. However, the underlying mechanism behind the indicator typically does not need any special conditions, e.g., the sound of the wheelhouse is always present. This implies that the estimate of estimators based on indirect methods is up-to-date at all times in an online in-vehicle situation (Bruzelius et al., 2007). Properties like these make it a complex task to compare and benchmark different approaches.

The Swedish Transport Administration has initiated and is leading a project called Digital Vinter, where three suppliers of road friction data have been procured. The main purpose is to use FCD for winter road maintenance follow-up to ensure the procured services are delivered and that friction levels are correct. This paper will show the results of a measurement campaign for validation of methods for friction estimation performed in January 2020, in Björli, Norway. The three suppliers participated with one vehicle each, and a RoAR Mk6, operated by the Norwegian Public Roads Administration, was used to gather continuous friction measurements during the campaign. The paper starts with a section describing the background of the project and the different friction estimation systems. Then the measurement campaign is described in more detail, including descriptions of the proving grounds and road conditions, followed by results with an included discussion. The paper ends with a summary and conclusions.

2 Background

In spring 2018, the Swedish Transport Administration sent out a tender for friction measurements using vehicle fleets and FCD, the aim was to enable follow-up of the friction requirements that are set in the Standardbeskrivning Vinterväghållning (Swedish Transport Administration, 2017). The tender was aimed at three suppliers, each of whom had to set a confidence value to show the reliability of their measurements. Each supplier was required to set up an interface presenting the FCD to the project managers of the Swedish Transport Administration, as an introduction to this new way of following up with the contractors. The acceptance and incorporation of this new method is a large part of implementing new technology into winter road maintenance. For further validation of the method of using vehicle fleets to monitor the traffic system, a measurement campaign for validation of the suppliers was carried out in Björli, Norway, in January 2020.

Friction requirements for the traffic system in Sweden differ between roads, to establish this a classification system is used depending on for example annual average daily traffic (AADT), if there is transportation on a road which is important for society, etc. For each road class, there are friction levels of 0.25, 0.30 and 0.35, but these also depend on recent precipitation, road surface temperature, and wind speed. As an example, the friction level should be above 0.35 for a highly ranked road a few hours after the precipitation has ended, when the temperature is between –6°C and –12°C. For the same example, the level drops down to 0.25 when the road surface temperature is below –12°C (Swedish Transport Administration, 2017). There are different demands of the friction levels and time of action for road sections, roadsides, and side facilities.

To ensure the friction levels are correct and meet the requirements, independent reference measurements are performed in the traffic system. Reference systems used in Sweden today are for example Coralba and ViaFriction. The Coralba system is installed within a vehicle and uses signals from the anti-lock braking system (ABS) to estimate friction from the retardation, the Coralba should be calibrated against a ViaFriction or similar method. ViaFriction is a separate system that is pulled behind a vehicle. It is a continuous monitoring method, while Coralba gives spot-wise measurements. Available for the measurement campaign in Björli, Norway, in January 2020 was a RoAR Mk6, which is an advanced

ViaFriction system that measures both left and right tyre tracks; more details on the RoAR Mk6 are given in Section 3.

3 Friction estimation systems

The three suppliers of friction data in the Digital Vinter project all use their own methods to estimate the tyre-to-road friction; because the information regarding their methods is company-related and as such, a trade secret, the companies do not want to share it. One stipulation for all three companies is to use existing vehicle fleets so that no more vehicles are added to the traffic flow. In this paper, the different suppliers are NIRA Dynamics, RoadCloud and AFRY/Volvo Cars. Notable is that both NIRA Dynamics and AFRY/Volvo Cars use built-in sensors and base their friction estimation on tyre slip. RoadCloud's method is also based on tyre slip to get a friction estimate, but uses ABS braking as a reference for the optical sensor.

For the measurement campaign in Björli, a RoAR Mk6 was used to get continuous measurements of road friction. RoAR Mk6 uses a Trelleborg T520 tyre, shown in Figure 1(A). The three suppliers had different types of studless winter tyres; NIRA Dynamics and RoadCloud had two different models from Continental, while AFRY/Volvo Cars had a model from Pirelli. An example of a studless winter tyre used by one of the suppliers is shown in Figure 1(B). Since there are no patterns in the Trelleborg T520 tyre, its performance will differ compared to the tyres of the three suppliers, as the tyres of the three suppliers are developed for winter conditions, with softer rubber and patterns to ensure a good grip on roads covered with ice and snow.

Figure 1 Trelleborg T520 tyre (A) and a standard studless winter tyre (B) (see online version for colours)

3.1 RoAR Mk6

The RoAR Mk6 used during the campaign is owned by the Norwegian Public Roads Administration and has a wagon with dual ViaFriction tyres, measuring both the right and left tyre tracks. The ViaFriction uses continuous longitudinal slip for friction estimation and the slip can be chosen to be fixed, surveillance or variable, depending on needs. The measuring tyres are the Trelleborg T520 model, see Figure 1(A), and as well as friction measurements, the temperature is recorded, and pictures of the road conditions are continuously gathered.

As well as multiple friction, slip and temperature values, the data contain longitude, latitude, timestamp, distance, road number and speed measurements.

3.2 NIRA dynamics

NIRA Dynamics has developed its own software called tyre grip indicator (TGI), which is pre-installed within vehicles. The friction estimation is based on signals from the CAN bus using standard vehicle sensors, and the method is slip-based. Data are presented with latitude and longitude together with a friction estimation, confidence number and timestamp. The algorithm used during the measurement campaign was JD9-R1908A.2.0.

3.3 RoadCloud

RoadCloud installs optical road sensors in commercial vehicles such as taxis, buses, and home care service vehicles. This method gives continuous estimation together with slip-based measurements for the estimation of friction and road surface conditions. The optical sensor is placed just inside the left tyre track and the surface conditions are defined as wet, pooling, slush, icy, dry, etc. For RoadCloud's slip-based measurements, signals are gathered from inertial measurements and the CAN bus. The data are presented for each road segment with latitude and longitude, together with a friction estimation, confidence number and timestamp.

3.4 AFRY/Volvo Cars

AFRY/Volvo Cars collects data already existing in the vehicle, and the friction estimation is calculated based on systems such as the ABS, i.e., slip-based. The owner of the vehicle must activate the function to send the data. The information that leaves the vehicle is anonymous and presented for a road segment with latitude and longitude, together with a friction estimation, confidence number and timestamp. The confidence from AFRY/Volvo Cars is based on the number of active systems.

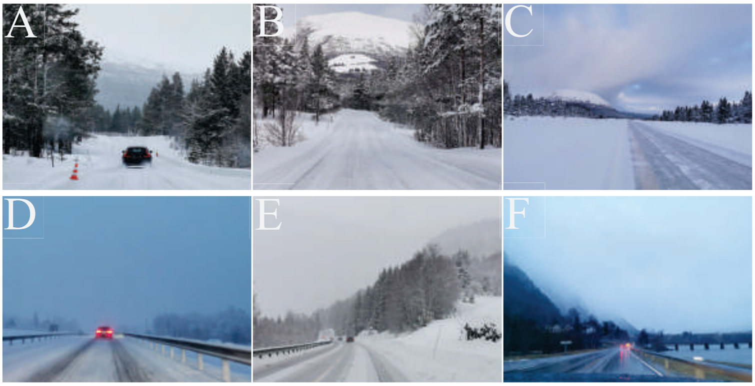
4 Proving grounds and road conditions

The measurement campaign was conducted at proving grounds in Björli, Norway, operated by the Norwegian Public Roads Administration, and on surrounding public roads. Conditions of the proving grounds consisted of snow- and ice-covered roads, and for high friction, public roads close by the facilities were also used since wet roads were available during the time of the campaign. The campaign was carried out over two days between 21 and 22 January 2020. The temperature varied around –4°C to +1°C for the campaign, mostly depending on the altitude. As Björli is situated 574 meters above sea level, and some parts of the public roads go all the way down to sea level, the temperature could change rapidly, within minutes, thereby changing the road condition. The following driving sequences were performed during the campaign, also seen in Figure 2:

- **The airport road** (Figure 2(A) and (B)) consisted of homogeneous snow. To some extent the road was worn down after the first day (Figure 2(A)) and also ploughed in the morning of the second day, so the road showed more icy sections for the second day of the measurement campaign (Figure 2(B)). This, in combination with a higher temperature, made the friction decrease between the two days. The airport road had some inclination and curves, the start-stop locations and sections for acceleration were marked with cones, and the road section was driven in both directions.

- **The airstrip** (Figure 2(C)) was a prepared, almost homogeneous, ice track. The tests were performed in the same way as the tests on the airport road, but for a shorter distance; the track was driven in both directions.
- **Public roads** (Figure 2(D)–(F)) had alternating road conditions from ice and snow with medium/low friction, to wet asphalt with high friction, and vice versa. On the public road, no repetition was performed as the road condition changed so rapidly. At higher altitudes, the conditions were mostly snowy, often with clearly visible tyre tracks (Figure 2(D) and (E) but also wet asphalt generating higher friction levels (Figure 2(F)). As mentioned earlier the shift from snow to visible asphalt was rapid due to the differences in elevation, driving towards the coast.

Figure 2 Road conditions for the proving grounds and public roads. The snow-covered airport road for both days (A and B), prepared ice at the airstrip (C), and a variation of road conditions on the public roads (D-F) (see online version for colours)



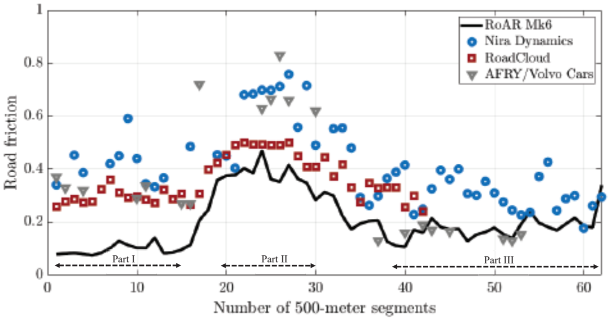
5 Results and discussion

This section firstly presents an overview of the two long drives on public roads, followed by an analysis of the driving sequences performed during the measuring campaign. The section ends with a discussion comparing the suppliers.

5.1 Analysis of the long drives at public roads

In Figure 3, the average road friction is shown for the drive from Björli towards Trollveggen. The road stretch is divided into 500 m segments, over which the average value of the friction measured by each supplier is calculated. In general, all methods recognise the same greater changes in road conditions, and the drive is divided into three parts representing these changes; see Figure 3. The measurements by RoadCloud were lost when driving through a tunnel after 42 road segments (21 km) due to connection problems.

Figure 3 Average road friction along the public road from Björli to Trollveggen. For further evaluation, the road is divided into three parts, representing different road conditions (see online version for colours)

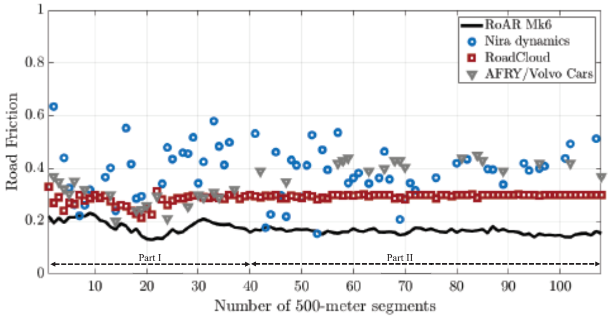


The RoAR Mk6 indicated exceptionally low friction in the beginning (see Part I in Figure 3), compared to the other suppliers. This is not realistic since the drivers did not reduce their speed due to the road conditions, and if the friction is as low as 0.1 it is difficult to steer the vehicle. An explanation could be that in the first part of the road, there was slush, and as the RoAR Mk6 has less weight than an ordinary car, the measuring tyre did not penetrate the slush in the way that the cars did, resulting in lower fiction values.

There is a clear peak in average road friction represented by Part II in Figure 3. All the methods recognise this change and show the highest friction during this drive towards Trollveggen. Interesting here is that RoadCloud, the optical method, does not reach above 0.5 as do the other FCD suppliers, probably due to the calibration regarding wet asphalt. For Part III in Figure 3, AFRY/Volvo Cars and RoAR Mk6 follow each other, while NIRA Dynamics, in comparison, mostly indicates higher friction.

Figure 4 illustrates the changes in average road friction along the drive from Dombås towards Björli. The road stretch is divided into 500 m segments and the average value of the friction measured by each supplier is calculated over these segments. The drive is divided into two parts, see Figure 4, where Part I was icy, especially in the tyre tracks, and Part II was mostly snow-covered.

Figure 4 Average road friction along the public road from Dombås to Björli. For further evaluation, the road is divided into two parts representing different road conditions (see online version for colours)



All suppliers indicate a drop in road friction for Part I (Figure 4). NIRA Dynamics indicated a fluctuating friction level during the entire drive compared to other methods, and showed the highest friction values. For Part II (Figure 4), both RoadCloud and RoAR Mk6 gave stable friction measurements of around 0.30 and 0.17, respectively. AFRY/Volvo Cars and NIRA Dynamics are closer to each other for Part II, even if the measurements of NIRA Dynamics are more scattered. This is probably due to large transversal changes in road conditions, which make it impossible for the drivers to keep an equal position in the tyre tracks.

5.2 Analysis of all driving sequences

In Table 1, the average road friction for all the drives is included, together with the standard deviation. The same pattern is shown for the different methods at the proving grounds, the snow-covered airport road, and the ice-covered airstrip. RoAR Mk6 indicates the lowest road friction while NIRA Dynamics and AFRY/Volvo Cars, the two slip-based methods, show almost the same numbers for both examples. RoadCloud is somewhere between, or above, the other methods; see Table 1. For the airstrip, the road friction indicated by RoadCloud was the highest and increased for each lap. This was probably due to the ice being worn down slightly every lap, generating a roughness and causing the light from the optical sensor to spread more for each lap, which was not noticed by the slip-based methods.

Table 1 Average road friction presented with standard deviation, within parentheses, for each road and method, separately. For the two long drives on public roads, the results are divided into road sections representing a significant change in road conditions, see Figures 3 and 4

	RoAR Mk6	*NIRA Dynamics*	*RoadCloud*	*AFRY/ Volvo Cars*
Airport road				
Snow	0.27 (0.03)	0.36 (0.04)	0.31 (0.03)	0.37 (0.06)
Airstrip				
Ice	0.16 (0.05)	0.21 (0.06)	0.28 (0.06)	0.21 (0.03)
High friction road				
Wet asphalt	0.83 (0.02)	0.98 (0.01)	0.50 (0.00)	0.77 (0.00)
Public road				
Björli to Trollveggen				
Part I	0.10 (0.02)	0.41 (0.08)	0.29 (0.03)	0.33 (0.03)
Part II	0.37 (0.04)	0.61 (0.13)	0.47 (0.04)	0.68 (0.09)
Part III	0.22 (0.12)	0.31 (0.07)	0.30 (0.04)	0.15 (0.02)
Public road				
Dombås to Björli				
Part I	0.18 (0.03)	0.40 (0.11)	0.28 (0.03)	0.29 (0.05)
Part II	0.16 (0.01)	0.37 (0.10)	0.30 (0.01)	0.41 (0.03)

The average road friction on the high friction road see (Table 1) was, as expected, high, with a low or non-existing standard deviation. RoadCloud indicated the lowest road friction at a value of 0.50, which may be unreasonably low compared to the other methods, and is probably caused by the calibration of the optical sensor.

In Table 1, for the long drives on public roads, the drives are divided into two or three parts, depending on the change in road conditions. The same parts are marked in Figures 3 and 4. Interesting here is that AFRY/Volvo Cars and NIRA Dynamics are not as close as they were on the proving grounds. This is especially seen in the measurements for Part III during the drive from Björli towards Trollveggen, where AFRY/Volvo Cars shows an average friction coefficient half the size of NIRA Dynamics. This is also visualised in Figure 3. Additionally, Part III to Trollveggen is the only drive where a supplier shows an average friction measurement below that of RoAR Mk6.

5.3 Comparison of suppliers

Overall, the three suppliers follow the reference measurement of RoAR Mk6 well; the friction levels are often higher but that is expected as there are different types of tyres on the RoAR Mk6 system compared with the test vehicles, as shown in Figure 1. The increased friction is shown both for the tests on the proving grounds and the public roads; there are some outliers in the measurements but when these systems are implemented in vehicle fleets such outliers can be filtered away. If this were to be implemented as it is, would it affect the results? Well, if the supplier shows low values, then it is slippery, and is like a ‘safety margin’ between the friction level of the suppliers compared to the RoAR Mk6.

Overall, the three suppliers show similar values; the largest difference is on the wet asphalt but here all three still show high friction, as they should. Some adjustments could be made here but it appears to be more of a calibration issue. Regarding coverage for the long drives, for these tests NIRA Dynamics showed the best spatial coverage, but RoadCloud should have had the best coverage as their system is continuous. The reason for this could be some human errors, such as taking a wrong turn, or some connection issues. What is interesting is that all three suppliers report the differences in the proving grounds, and they also find the differences in friction for the long drives. This is promising as all three systems are developed to be incorporated in vehicle fleets as floating car data. Then if one vehicle loses connection, there will be others that make up for this.

This investigation shows that by getting data from only one vehicle per supplier, the friction data are acceptable compared to the RoAR Mk6 method used today in winter road maintenance, both in Norway and Sweden. From that, it is possible to conclude that using these three technologies to monitor road friction for winter road maintenance follow-up would be more effective than using today’s systems. This is mainly due to having more sources, which makes it possible to filter out erroneous data, and having a larger spatial coverage; additionally, the need for any unnecessary driving is eliminated, which is good for the environment.

6 Summary and conclusions

In this investigation, road friction data from three suppliers of FCD, using only one test vehicle each, have been compared with a continuous method for road friction measurement. The test has been carried out on proving grounds covered with ice and snow, and on public roads covered with water, ice, snow and slush, so both high friction and low friction has been evaluated. Notable is that the proving grounds were more or less homogeneous, while the public roads were non-homogeneous, with different road conditions in the tyre tracks than on the sides.

The investigation showed that the road friction data from the FCD suppliers follows the continuous measurements of detecting low and high situations on the roads. However, the data from the FCD suppliers have higher values than the continuous measurement, mainly because the friction measurements gathered by the FCD suppliers are based on winter friction tyres, compared with the smaller and smoother tyres on the continuous measurement vehicle. This is an interesting observation as the continuous measurement systems are used for road winter maintenance follow-up in both Norway and Sweden, but as it shows lower friction values than those experienced by road users, it can be concluded that there is a safety margin for winter road maintenance. What can also be further discussed is the cost and environmental impact of having this safety margin within the winter road maintenance program, which might be reduced when using FCD instead.

Acknowledgement

The findings presented in this paper are based on the results of the project, Digital Vinter, initiated and funded by the Swedish Transport Administration.

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