Large-scale implementation of floating car data monitoring road friction

S. Sollén | J. Casselgren

Abstract

In Sweden today, friction measurements are performed manually, often using methods generating spot-wise measurements. Because the low numbers of measurements provided by these methods are insufficient to follow up on the friction requirements set by the Swedish Transport Administration, the Administration has initiated the Digital Winter project. In Digital Winter, floating car data (FCD) are utilised for road friction estimation. The focus in this investigation is on coverage, and on whether the FCD detects harsh weather conditions with decreasing road friction. Two different methods—one continuous and one slip-based—are implemented in this investigation. Furthermore, different approaches on how to build the vehicle fleet to collect the FCD have been applied using different combinations of commercial and private vehicles. The results showed that both methods detect low-friction events, and for roads with high annual average daily traffic (AADT), the data collection using slip-based methods and larger fleets gives more data points than for smaller fleets using continuous methods, and the reverse is true for lower AADT. The results showed differences between the two fleets in terms of coverage for the weekly and daily distributions, but overall, the method of using FCD for road friction estimation seems promising for the follow-up of winter road maintenance.

1 INTRODUCTION

Today’s vehicles contain many sensors, which gather information and generate big data as part of the automotive industry’s shift towards fully autonomous vehicles [1]. The increasing amount of floating car data (FCD) over the coming decades will generate new possibilities for the development of intelligent transport systems. Real-time Traffic Information can also be used to improve road weather forecasts, road conditions, traffic safety etc. [2–4]. As previously stated by various authors, winter road maintenance could be improved by implementing FCD in order to enhance targeted winter road maintenance through monitoring the road conditions [5–9].

Several studies have been performed using FCD and vehicle fleet monitoring of road conditions with the aim of bridging the gaps in monitoring data between road weather information system (RWIS) stations [10]. An experimental investigation was conducted to evaluate the possibilities of using FCD and RWIS stations to improve road weather forecasts [11]. The investigation focused on a method to estimate the road surface temperature by surveying a larger proportion of the traffic system in order to fill in the gaps between the RWIS stations. Another study used sensors in smartphones fitted on vehicle dashboards together with data from RWIS stations to assess and predict the road conditions. This was achieved by analysing the roughness of the road surface in combination with the weather information [12].

Vehicle fleets and FCD have also been implemented in different experimental set-ups for travel time estimation and route planning. Brockfeld et al. conducted a measurement campaign in 2005 using a vehicle fleet of taxis in the city of Nürnberg, Germany, and implemented FCD for travel time estimation [13]. The results were promising, and traffic patterns during rush hours and on different weekdays could be visualised as variations in travel times. A similar case study was conducted using taxis on a section of road in Stockholm, Sweden, from 2010...
through to the end of 2011 [14]. The travel pattern observed in the later study indicated that the travel times for the taxis are, in general, lowest on Mondays and Fridays in comparison with the rest of the working week. It was also noted that travel time would increase by 1% for every 4 h of snowfall.

Winter road maintenance in cold regions is essential for the accessibility of the traffic system, but at the same time, the maintenance emissions account for one-third of the total environmental impact [15]. Studies conducted to optimise route planning for maintenance vehicles and to minimise the use of chemicals have proven effective in terms of both safety and reduced environmental impact [7, 16].

Besides positive effects, such as optimised travel time and fewer emissions, an effective winter road maintenance programme based on FCD could reduce casualty numbers [2, 3, 9]. Annually, there are around 5000 fatalities and 418,000 injuries due to accidents in severe weather conditions, which together account for 21% of all vehicle accidents worldwide [17]. In Sweden, there are around 200–300 fatalities due to traffic-related accidents every year, and from 2009 through to the end of 2019, 12.9% of all serious or fatal accidents occurred in winter conditions [18–28]. Even though Sweden has one of the world’s safest traffic systems, and is aiming for Vision Zero [29], Belin et al. stated that work remains to be done before the goal of a casualty-free traffic system is achieved [30]. Real-time information on the weather and the state of the road ahead of the vehicle in order to avoid accidents has been pointed out as an important way of achieving this goal [31, 32]. This real-time information could be generated using FCD and vehicle fleets continuously monitoring the road friction.

The Swedish Transport Administration has initiated and is leading a project called Digital Winter in Sweden, for which suppliers of friction data have been obtained. The main purpose is to use the data to follow up on winter road maintenance in order to ensure that the procured services have been delivered and that the friction levels are correct. This paper presents the results of friction estimation measurements performed using FCD between October and April. The focus of the investigation is the coverage of FCD and to determine whether the data are able to detect weather situations that lead to low friction on the road. The paper starts with a section describing winter road maintenance in Sweden and the different road sections and road conditions used as examples. The two measuring and estimation systems, RoadCloud OY and NIRA Dynamics AB, are then introduced, followed by a section describing the results together with some important examples and a discussion. The paper concludes with a summary of findings.

2 | BACKGROUND

Friction measurements in Sweden are currently conducted manually using a Coralba or similar instrument. A Coralba generates spot-wise measurements using signals from a vehicle’s anti-brake system (ABS) to estimate friction from deceleration. As the system is dependent on how and where the driver is breaking the outcome can change from driver to driver, the measurements become biased. This method provides around 50–100 measurements per month and the vehicles involved are only driven for the purpose of performing friction measurements. These low numbers of measurements are insufficient for following up on the friction requirements set by the Swedish Transport Administration in their standards for winter road maintenance, Standardbeskrivning Vinterväghållning [33].

During spring 2018, the Swedish Transport Administration issued a call for tenders for friction measurements using vehicle fleets to collect FCD instead of spot-wise measurements. The call for tenders sought more than one supplier, and the suppliers were allowed to choose operating areas provided there were three different winter road contractors maintaining the roads in the chosen areas. The call for tenders placed different demands on suppliers for measurement coverage and time resolution. These demands differed depending on the class of the road (in Sweden, roads are classed mainly according to the amount of traffic). The suppliers were also instructed to set a confidence value for the measurements in order to show measurement reliability, and were required to use existing vehicle fleets, in other words, no specific road friction measurements with dedicated vehicles were allowed. The friction had to be reported for road sections no longer than 500 m, and the reports, with all friction data, had to have a frequency of one per hour.

Each supplier also undertook to set up an interface to present the data to the project managers at the Swedish Transport Administration, among others, in order introduce them to this new way of using FCD to monitor contractors. The acceptance and incorporation of this new method is a major step in the implementation of new technology in winter road maintenance. This paper presents FCD measured and collected by the suppliers according to the contract between them and the Swedish Transport Administration. The FCD have been analysed based on monthly observations, and statistics are presented on a weekly and a daily basis.

3 | ROAD SECTIONS

Three different road sections in Sweden have been used as examples in the results, and both suppliers are active in the three road sections. Table 1 presents facts about each road section, such as operating area, annual average daily traffic (AADT) etc. The roads have the same standard class for winter, which is

| Operating area     | Length, one-way | AADT ($\times 10^3$) | Functional road class | Standard class winter |
|--------------------|-----------------|----------------------|-----------------------|----------------------|
| Västerås, Enköping | 32 km           | 13–17                | 0                     | 1                    |
| Göteborg           | 25 km           | 20–55                | 0                     | 1                    |
| Göteborg           | 9 km            | 5–15                 | 3                     | 1                    |

TABLE 1 Facts and statistics for the given road sections. Information gathered from the official website of the Swedish Transport Administration [34]
based on a scale from 1 to 5, where a lower number demands a more efficient clearance of the road. But the roads differ in functional road class, a number indicating how important the road section is for the region, on a scale from 0 to 9, where 0 represents the most important road sections. Since the road sections differ in functional road class, the results could give an indication of the potential coverage with a small variation in road sizes.

3.1 | E18, Västerås to Enköping

The road section of the E18 between Västerås and Enköping is a dual carriageway with two lanes in each direction and a total length of 32 km. The road section is located in central Sweden and is one of the larger roads in and out of Stockholm, the capital city of Sweden. Located midway between these cities is a test site called Sagån, which is owned by the Swedish Transport Administration. The AADT for the road section is around 15,000, with a higher traffic intensity close to the city centre of Västerås. The functional road class is 0, which implies that the road is important for the region, and the standard winter maintenance class is 1.

3.2 | E6/E20, Göteborg

The road section on the E6/E20, located in the operating area of Göteborg in the south of Sweden, is a dual carriageway with two to three lanes in each direction. The road section is close to central Sweden and has one of the highest traffic densities in the country, with an AADT of 55,000 for some parts of the 25-km road. The functional road class is 0, which implies that the road is important for the region, and the standard winter maintenance class is 1.

3.3 | Road 158, Göteborg

The smallest and shortest road of the three is the section of road 158 located in the operating area of Göteborg, in the south of Sweden. The road, called Säröleden, is 9 km long and the majority of the road is a 2+1, three-lane road. The AADT is close to 15,000 in the northern parts near the city centre, while the AADT is around 5,000 further south. The functional road class is 3, which is a lower class than the other two road sections described here, but the standard winter maintenance class is 1, just as for the other two. This implies that the efficiency of the road clearance is supposed to be the same for road 158 as for the other two road sections, even though it has a lower volume of traffic.

4 | FRICTION ESTIMATION SYSTEMS

RoadCloud OY (RoadCloud) and NIRA Dynamics AB (NIRA) use existing techniques for friction estimation and are two suppliers of friction data in the Digital Winter project. Both of them use vehicle fleets already travelling in the traffic flow, ensuring no extra travel dedicated solely to road friction measurements, and both are present on the three road sections presented in Section 3. This paper defines the fleet size in one operating area as small with the number of vehicles below 100, medium when the number of vehicle lies between 100 and 1,000, and large for fleets with more than 1,000 vehicles.

4.1 | RoadCloud OY

RoadCloud installs optical road condition sensors in commercial vehicles used as taxis, buses and home care service vehicles for geographic coverage in the chosen reference areas. This method provides continuous estimates together with slip-based measurements for estimating friction and surface conditions. The optical sensors are often positioned close to the left-hand wheel track and the surface conditions are defined as wet, moist, pooling, slushy, snowy, icy and dry. For the slip-based measurements, signals are gathered from inertial measurements and the controller area network (CAN) bus. The data are presented for each road section with latitude and longitude together with a friction estimation, confidence number and timestamp.

The fleet included 108 vehicles in the reference areas during the spring of 2020. In Göteborg, the RoadCloud fleet included 45 vehicles, consisting of a mixture of delivery vehicles, taxis and buses. On the E18 between Västerås and Enköping, the size of the fleet was 63 vehicles, broken down into taxis, buses, home care service vehicles and delivery vehicles. Both fleets are considered as small.

4.2 | NIRA dynamics AB

NIRA has developed its own software, called Tire Grip Indicator (TGI), which is installed in vehicles using either an external dongle plugged into the on-board diagnostics (OBD) connector of a vehicle, or is pre-installed in the electronic control unit (ECU). For this project, a dongle was used and the algorithm versions were JD9R1809B.1.6 or JD9-R1908A.2.0 for the data presented. NIRA uses taxis, rental vehicles etc. in its fleet. The friction estimation is based on signals from the CAN bus using standard vehicle sensors and the method is slip-based. The data are presented with latitude and longitude together with a friction estimation, confidence number and timestamp. The confidence from NIRA is based on the total number of vehicles from the NIRA fleet passing over the same road section.

In the spring of 2020, the fleet consisted of 430 vehicles in the reference areas. In Göteborg, the NIRA fleet consisted of 118 vehicles, mostly taxis but some privately owned vehicles as well. For the E18 between Västerås and Enköping, the number of vehicles was 47 and included a mix of private vehicles, rental cars, home care service vehicles and delivery vehicles. The fleet in Göteborg is defined as a medium fleet, while the fleet for the E18 is considered as a small fleet.
4.3 Strengths and weakness of the two friction estimation systems

The strength of using an optical system such as RoadCloud’s system is that it delivers a continuous friction estimation, meaning a measurement with a resolution up to at least every second metre. The optical road condition sensors explore the properties of reflected light of specific wavelengths to classify the state of the water on the road [35]. That is if the water is in liquid form, snow, ice or slush. In addition to the fast response, another beneficial system parameter is that an optical system delivers a general friction estimation based on current road conditions. One of the drawbacks is that extra equipment needs to be installed after the vehicle has been produced, and at this stage the equipment is more expensive than the slip-based method that is only based on software. This means that there will be a lot of data from each vehicle but implementing a larger fleet is challenging.

The strength of the slip-based method as used by NIRA is that it uses existing sensors in the vehicles. So no extra sensors are needed to make the friction estimation. But in this project, the system was so new, a dongle had to be used to handle the connection from the vehicles to the cloud. The slip-based system uses the wheel speed and the slip to estimate the friction between the vehicle tyre and the road surface. But for to obtain sufficient slip to be able to estimate the friction with high accuracy, a certain level of force is needed, which makes the slip-based method discontinuous compared with the optical system [36]. To obtain an estimation, there needs to be some excitation, meaning braking, steering or acceleration. The major advantage of the slip-based method is that it is based on software that can be implemented in vehicles from production, so the fleet can be a sizeable one with over 10,000 vehicles when it is deployed. Summarising the information, for the optical system, each system delivers more data per sensor but it is more difficult to install as well as more costly, so the fleets are smaller. For the slip-based method, the system delivers less data per vehicle but since it can be installed during production, the fleets can be much larger.

5 RESULTS

This section presents results based on the monthly data gathered by RoadCloud using the continuous method, and NIRA using the slip-based method. Data were collected in Sweden for the winter seasons, 1 January 2019 to 30 April 2019, and 1 October 2019 to 30 April 2020. Examples are presented separately for the road sections of E18, E6/E20 and 158.

Table 2 shows the total number of reported measurements for each road section and supplier, respectively. Notable in Table 2 is that for the E18 and 158, RoadCloud shows a higher number of measurements than NIRA, but for E6/E20 there is almost double the number of measurements for NIRA. This demonstrates how the two different techniques work. In one, the optical sensor collects continuous data which increases the amount of data, although the fleet is smaller and the AADT is around 15,000. But for a road section with as large of an AADT as the E6/E20 (55,000), the data set from NIRA becomes large as well since they have a medium-sized fleet in Göteborg that attracts the busier roads.

5.1 E18, Västerås to Enköping

The distribution of measurements for an average week on the E18 road section is shown in Table 3. Both suppliers show a decrease in data during weekends. RoadCloud, the continuous method, is more effective because it does not include private vehicles, consisting mostly of taxis and buses on the E18. For NIRA, the slip-based method, the delivered data are stable in general, even though there is an evident effect from weekends and Mondays, similar to what Jenelius and Koutsopoulos also concluded [14]. The pattern seen for NIRA is probably due to the number of private and rental vehicles in the fleet, which are used regularly throughout the week. The distribution of measurements from Tuesday through to the end of Friday is stable at around 16% for NIRA.

The hourly variation of data delivery for the E18 during one average day is presented in Table 4. A drastic decrease in data can be seen during the night, and around 80% of all friction events occur between 6 AM and 6 PM for both suppliers. The suppliers also show a small decrease between morning traffic and lunchtime traffic, and both have their daily peak around midday. The pattern for RoadCloud is more typical in terms of working hour intensity than the pattern for NIRA, and shows a significant decrease in data delivery starting after 4 PM NIRA includes privately owned vehicles on the E18, which is probably the reason for the greater evening traffic intensity in comparison with RoadCloud.

### Table 2
| RoadCloud | NIRA |
|-----------|------|
| E18 32 km | 786,006 | 107,633 |
| E18 25 km | 466,312 | 87,188 |
| E18 9 km | 563,349 | 80,481 |

### Table 3
| Day    | RoadCloud | NIRA |
|--------|-----------|------|
| Sunday | 4.4%      | 12.4%|
| Monday | 17.5%     | 12.5%|
| Tuesday| 18.7%     | 15.9%|
| Wednesday| 19.0%   | 16.1%|
| Thursday| 17.7%    | 15.7%|
| Friday | 18.0%     | 16.2%|
| Saturday| 4.7%     | 11.1%|
TABLE 4  Average distribution during one day for E18, 1 January 2019 to 30 April 2020

| Time       | RoadCloud | NIRA |
|------------|-----------|------|
| 12 AM      | 1.0%      | 1.6% |
| 2 AM       | 1.6%      | 1.7% |
| 4 AM       | 5.7%      | 4.8% |
| 6 AM       | 16.6%     | 12.3%|
| 8 AM       | 15.0%     | 10.7%|
| 10 AM      | 15.5%     | 16.3%|
| 12 PM      | 18.8%     | 12.2%|
| 2 PM       | 13.1%     | 13.7%|
| 4 PM       | 6.4%      | 11.3%|
| 6 PM       | 3.4%      | 6.1% |
| 8 PM       | 1.6%      | 7.6% |
| 10 PM      | 1.4%      | 1.7% |

FIGURE 1  Number of weekly measurements for E18, 1 October 2019 - 30 April 2020

The overall trend in weekly data delivery for the E18 from 1 October 2019 to 30 April 2020 is shown in Figure 1; note the logarithmic scale on the y-axis. For both suppliers, a decrease in data can be seen for the second half of December during the Christmas holidays, when schools and companies close down. RoadCloud restarts immediately in January, while NIRA does not reach the same level as before the holidays. In February, a rise in data can be seen for both suppliers. There is a winter school holiday at this time of year in Sweden that is likely to account for the increase, as people travel between the two cities for social activities.

The increase at the end of the season for both suppliers is probably caused by a change in driving patterns due to the Covid-19 pandemic. The recommendations for Sweden in spring 2020 were to avoid public transportation and to travel by car, which could have led to a larger amount of data being generated for the E18.

A close-up of the amount of daily measurements for the E18 is shown in Figure 2, for the period 19 November 2019 through to the end of 19 December 2019. RoadCloud shows a clear difference between working days and weekends, with a decrease in data on Saturdays and Sundays. This is also shown in Table 3.

This is due to differences between the fleets, where the RoadCloud fleet partly consists of buses and taxis on the E18, which are used more frequently during working days. For NIRA, the data delivery is more irregular.

Figure 3 presents the average friction for the E18 for the same period of time. It can be seen that both suppliers indicated some severe road conditions from 29 November 2019 through to the end of 3 December 2019, as the friction drops drastically. On 10 December 2019, both suppliers indicated low friction, but as with the first longer period of severe road conditions in this example, the drop in average friction is more significant for RoadCloud. In general, the average daily friction reported by RoadCloud is lower than that reported by NIRA for the E18 during this period of time.

Table 5 shows an example of the distribution of low-friction events on the E18 from 9 December 2019 through to the end of 11 December 2019. It can be clearly seen that for 10 December 2019, this section of the E18 indicated slippery road conditions, since both suppliers report a rise in low-friction events in comparison with surrounding days. For RoadCloud, 61.8% of all friction events throughout the day were below the limit of 0.35 and the same number for NIRA was 9.1%. The difference between the suppliers shown in Table 5 can also be seen in Figure 3, where the daily mean for NIRA is well above the average for RoadCloud.
The geographical coverage for the E18 for each supplier separately, for 10 December 2019, is shown in Figure 4, with friction events below 0.35 marked as black circles. The low-friction events for RoadCloud measurements indicated slippery conditions for the entire road, while for NIRA, slippery conditions seem to be located around ramps and exits; see Figure 4. The difference in estimated friction between RoadCloud and NIRA could be explained by the position on the road, as RoadCloud mostly measures between the wheel tracks, while NIRA often measures within the wheel tracks.

Figure 5 shows a photograph from an RWIS station at the Sagån test site, located between the two cities on the E18. The photograph was taken during morning traffic, around 8 AM, and a string of snow is clearly seen in the middle of each lane. The snow string is partly located where RoadCloud estimates the friction with its sensor, thereby generating the differences along the road section that are given by the suppliers in Figure 4 and Table 5. The snow had fallen during the previous evening but stopped around midnight. On 10 December 2019, temperatures were stable at around $-4^\circ$ C.

### 5.2 E6/E20, Göteborg

Table 6 shows the average weekly distribution of measurements on the E6/E20. Even though there is a decrease for the suppliers at weekends, RoadCloud is affected the most, with an optical fleet mostly based on delivery vehicles in Göteborg. RoadCloud is stable for working days, when compared with NIRA, the slip-based method, which has less data on Mondays and Fridays than for Tuesday through to the end of Thursday in an average week. One theory for the decrease on these days for NIRA could be lower demand for taxis, since this road is partly used by traffic to the airport.

The distribution during an average day for the E6/E20 is shown in Table 7. For RoadCloud, the distribution is not as even as for NIRA, and the decrease during the night is slightly larger for RoadCloud. RoadCloud’s measurements indicate a clear difference during lunchtime with less traffic, but between 4 AM
TABLE 7  Average distribution during one day for E6/E20, 1 January 2019 to 30 April 2020

| Time          | RoadCloud | NIRA |
|---------------|-----------|------|
| 12 AM - 2 AM  | 3.9%      | 5.1% |
| 2 AM - 4 AM   | 6.4%      | 5.1% |
| 4 AM - 6 AM   | 12.2%     | 8.0% |
| 6 AM - 8 AM   | 12.9%     | 9.8% |
| 8 AM - 10 AM  | 11.6%     | 9.1% |
| 10 AM - 12 PM | 7.5%      | 9.2% |
| 12 PM - 2 PM  | 12.5%     | 10.2%|
| 2 PM - 4 PM   | 12.9%     | 11.7%|
| 4 PM - 6 PM   | 9.0%      | 10.3%|
| 6 PM - 8 PM   | 3.9%      | 7.5% |
| 8 PM - 10 PM  | 4.0%      | 6.5% |
| 10 PM - 12 AM | 3.0%      | 7.3% |

FIGURE 6  Number of weekly measurements for E6/E20, 1 October 2019 - 30 April 2020

and 10 AM, and noon and 4 PM, the distribution is evenly spread. One reason that NIRA’s measurements indicate a more even distribution is probably due to a larger share of taxis, as mentioned above. For RoadCloud, around 66% of the friction events occur between 6 AM and 6 PM, and the corresponding number for NIRA is around 60%.

Looking at the number of weekly measurements for the E6/E20 in Figure 6, note the logarithmic scale on the y-axis, where a decrease in data delivery is evident in the second half of December, during the Christmas holidays. There is also a peak in February during the winter school holidays for both suppliers. The increase for RoadCloud in March is probably due to the Covid-19 pandemic, when the recommendations were to avoid public transportation. This could be explained by an increase in online shopping, and thereby the delivery vehicles in the fleet would be used to a greater extent. NIRA does not report the same benefits of the change in driving patterns due to the pandemic, since people were advised to work from home when possible.

Figure 7 shows the variations in daily data delivery from 10 January 2020 to 10 February 2020 for the E6/E20. As seen in Table 6, the pattern over a week for RoadCloud is very symmetrical and the decrease on Saturdays and Sundays is clearly seen in Figure 7. The figure also shows an increase in daily data delivery in February when compared to January for both suppliers due to the winter holidays.

According to Figure 8, there were no severe road conditions for the E6/E20 in Göteborg over a longer period between 10 January 2020 and 10 February 2020. RoadCloud’s measurements indicate a more fluctuating friction curve for this period, but both suppliers are well above the critical friction levels, which is to be expected since the weather was stable.

Table 8 shows a close-up of the distribution of low-friction events from 2 February 2020 to 4 February 2020. The number of events below 0.35 is low. The average temperature for this period was around +2.0°C. During the night of 2-3 February 2020, the temperature fell to -3.0°C and may have caused slippery conditions. Some precipitation did occur during the same evening, mostly rain, but there was some light snow in some parts of the city, which may have led to slippery roads or aquaplaning.

Figure 9 gives the location of all friction events on 3 February 2020, with events below 0.35 marked with black circles. Looking at the locations for the low-friction events, most critical spots seem to be located close to a ramp or exit.

The photograph in Figure 10 shows the road at Willinsbron Söderut, during evening traffic on 3 February 2020. The location is close to multiple exits and ramps, and wheel tracks are...
TABLE 8  Distribution of friction events for the lower levels of the E6/E20, 2 February 2020 to 4 February 2020

| Date       | Limit | RoadCloud | NIRA |
|------------|-------|-----------|------|
| 2 February | < 0.25 | 0 %       | 0 %  |
| 2020       | < 0.30 | 0 %       | 0.1 %|
|            | < 0.35 | 0 %       | 0.7 %|
| 3 February | < 0.25 | 0 %       | 0.1 %|
| 2020       | < 0.30 | 0.5 %     | 0.1 %|
|            | < 0.35 | 2.3 %     | 0.6 %|
| 4 February | < 0.25 | 0 %       | 0.1 %|
| 2020       | < 0.30 | 0.5 %     | 0.5 %|
|            | < 0.35 | 0.5 %     | 0.7 %|

FIGURE 9  Location of friction events on the E6/E20, 3 February 2020. Black circles represent events below 0.35 in estimated road friction.

FIGURE 10  Photograph of the road at Willmsbron Söderut, E6/E20, during evening traffic on 3 February 2020.

TABLE 9  Average distribution on road 158 for weekdays, 1 January 2019 to 30 April 2020

| Day       | RoadCloud | NIRA |
|-----------|-----------|------|
| Sunday    | 10.3 %    | 10.4 %|
| Monday    | 15.8 %    | 13.5 %|
| Tuesday   | 15.1 %    | 15.8 %|
| Wednesday | 15.2 %    | 14.4 %|
| Thursday  | 15.7 %    | 15.5 %|
| Friday    | 15.9 %    | 15.9 %|
| Saturday  | 11.8 %    | 14.0 %|

TABLE 10  Average distribution during one day for road 158, 1 January 2019 to 30 April 2020

| Time      | RoadCloud | NIRA |
|-----------|-----------|------|
| 12 AM     | 2 AM      | 3.8 %| 7.1 %|
| 2 AM      | 4 AM      | 2.8 %| 9.9 %|
| 4 AM      | 6 AM      | 10.4 %| 10.8 %|
| 6 AM      | 8 AM      | 12.3 %| 8.6 %|
| 8 AM      | 10 AM     | 9.7 %| 5.6 %|
| 10 AM     | 12 PM     | 9.0 %| 6.1 %|
| 12 PM     | 2 PM      | 9.1 %| 8.0 %|
| 2 PM      | 4 PM      | 11.9 %| 12.7 %|
| 4 PM      | 6 PM      | 11.0 %| 8.3 %|
| 6 PM      | 8 PM      | 8.1 %| 7.3 %|
| 8 PM      | 10 PM     | 5.9 %| 6.5 %|
| 10 PM     | 12 AM     | 5.8 %| 9.0 %|

seen for each lane. As demonstrated and stated earlier, this was a rainy evening, which could have caused low-friction events generated by aquaplaning.

5.3  Road 158, Göteborg

Table 9 shows the weekly distribution for an average week on road 158 in Göteborg. Distribution is even for both suppliers. Common to both suppliers is that Sundays have the least amount of data. For NIRA, the slip-based method, it is interesting that the patterns on a Monday stand out from the working day and weekend patterns, with less data on average in comparison with Saturdays.

Looking at the average daily distribution in Table 10, it can be noted that RoadCloud, the continuous method, delivers less data during the night and shows an increase in data for the morning rush hour, 4 AM to 8 AM, and afternoon rush hour, 2 PM to 6 PM NIRA is very stable, with two peaks at 5 AM and 3 PM, respectively. For RoadCloud, around 63% of the friction events occur between 6 AM and 6 PM, while the corresponding number for NIRA is closer to 50%.

Figure 11 shows the weekly data delivery. Note the logarithmic scale on the y-axis, which shows an increase in data for
RoadCloud in February during the winter holidays, and also from the middle of March to the end of the season when the Covid-19 pandemic reached Sweden. The trend is almost constant until February for both suppliers, even though the Christmas holidays are shown to have some effect in the NIRA data. During the last two months of winter 2020, for the section of road 158, NIRA indicates a negative trend that stabilises at a lower level during April. This is probably due to a lower demand for taxis during the pandemic and to people working from home.

The number of measurements on a daily basis for road 158 is shown in Figure 12. In general, both suppliers indicate the same pattern and are stable until February, when the data delivery shifts due to the winter school holidays. RoadCloud measurements show the difference between weekends and working days.

The average friction for the same period is shown in Figure 13, during which time no dramatic change is visible. Both suppliers are stable around an estimated road friction of 0.7. For most of the days, NIRA indicates a slightly higher friction on average in comparison with RoadCloud.

Table 11 shows how the measurements were distributed for the lower levels for the period 2 February 2020 to 4 February 2020. As can be seen for all 3 days, there were no events below 0.25, and only a few under 0.30. The average temperature for this period was around $+2.0^\circ$C, and during the night of 2–3 February 2020, the temperature fell to $-3.0^\circ$C and may have caused slippery conditions. Some precipitation did occur during the same evening, mostly rain, but there was some light snow in some parts of the city, which may have led to slippery roads or aquaplaning. There were some events with low friction on 3 February 2020, when both suppliers showed a small but notable percentage of low friction.

For 2 February 2020, NIRA indicated low friction for 5.4% of the measurements, while RoadCloud gave no evidence of low friction. 2 February 2020 was a Sunday, and as shown in Table 9, both suppliers deliver less data during weekends for road 158, which may have impacted the coverage. During the night between 1 February 2020 and 2 February 2020, there was some light rainfall and the temperature fell to below zero later the same evening. Since NIRA has a better nightly coverage for road 158 (see Table 10), the low friction events are most likely to have occurred during the night.

By studying the locations of the friction events on 3 February 2020, in Figure 14, it can be noted that RoadCloud’s measurements indicate low friction for each road section at least once during the day. On the other hand, NIRA only shows low friction close to one of the ramps and exits along the road, even though the measurements were taken along the entire road.

Figure 15 shows a photograph of the road at Hovåsmotet during evening traffic on 3 February 2020. It can be clearly seen...
5.4 | Comparison of suppliers and roads

The total data delivery for each supplier, as shown in Table 2, provides evidence of an important difference between the continuous and slip-based methods. In most of the cases, there will be a larger amount of data for the continuous method, RoadCloud, in comparison with the slip-based method, NIRA. This is due to the size of the fleet, since one vehicle from the RoadCloud fleet will deliver more data than one vehicle from the NIRA fleet. On the E6/E20, NIRA generates more data than RoadCloud, even though RoadCloud uses a continuous method and NIRA is slip-based, but for Göteborg, the NIRA fleet is more than twice the size of the RoadCloud fleet; see Table 1. For RoadCloud, the amount of data is almost the same for road 158 and the E6/E20, even though the section of the E6/E20 is almost three times as long and has more lanes and a higher AADT. The differences between the roads within a single region are probably due to commercial vehicles using fixed routes, generating areas with higher concentrations of data.

Measurements from both suppliers follow each supplier's own distribution patterns over an average week, independent of road section; see Tables 3, 6, and 9. In general, RoadCloud's measurements are more affected during weekends than NIRA's measurements. But this effect is greater for RoadCloud on the E18, which runs between two cities, than for the two road sections in Göteborg, the E6/E20 and road 158, which remain within the region. Worth noting is the effect seen on Mondays, and sometimes Fridays, with less data delivered in comparison with other working days, especially by NIRA; see Tables 3, 6, and 9. This pattern is also seen for RoadCloud for the E18 and E6/E20, albeit not as distinctly. One explanation could be the lower demand for taxis on the first day of the week, since both fleets contain taxis, as for this example. This pattern for taxis was also evident in the study by E. Jenelius & H.N. Koutsopoulos [14].

An examination of the distribution for an average day in Tables 4, 7, and 10 reveals fluctuations in data delivery. A certain behaviour and movement is clearly evident in the fleets, and assumptions can be made concerning the nature of the driving patterns for private vehicles in comparison with commercial vehicles. It is easy to distinguish the morning and afternoon rush hours from the night hours within both suppliers and road sections. A difference in driver behaviour is evident when comparing the larger roads, the E18 and E6/E20, since the E6/E20 runs within a city, while the E18 runs between two cities. The traffic flow is also higher for the E6/E20, at least for RoadCloud. Adding road 158 to the comparison leads to an even more uniform distribution during an average day, especially for NIRA.

The lack of data between midnight and 4 AM (see Tables 4, 7, and 10) may not be a problem, since the planning is often done before midnight. The road conditions in the morning, when the data delivery increases once again, will give both the maintenance suppliers and the Swedish Transport Administration feedback on the work carried out during the night. The maintenance vehicles normally try to avoid high-traffic roads in rush hour when possible, so the morning traffic will give guidelines for work that has to be performed before the afternoon rush hour. And finally, the afternoon traffic gives guidelines for the plans drawn up before midnight for the maintenance work scheduled for between midnight and 4 AM, for which there is a lack of data. Since there are fluctuations in traffic flow, and thereby the data delivery, the maintenance suppliers and
Swedish Transport Administration get feedback on road conditions for when the roads are most often in use.

There is a similar pattern to the weekly variations in delivered data shown in Figures 1, 6, and 11 over the season. For both suppliers, and all three roads, the winter school holidays in the beginning of February have a positive impact on the amount of delivered data. By contrast, the Christmas holidays have a negative effect for all given examples, except for RoadCloud on road 158, the road with lower volumes of traffic. This is probably due to the location of the road, as it is closer to where people live and go to visit during the Christmas holidays. NIRA showed a slower recovery after the Christmas holidays in comparison with RoadCloud for all roads, especially the E18, as shown in Figure 1. This could be due to the number of private vehicles in the fleet since that is where the biggest difference between them lies, apart from the measuring technique.

Figures 1, 6, and 11 also show the effect of a changed travel pattern due to the Covid-19 pandemic. For the RoadCloud fleet, the effect was only a positive one since it delivered more data during this period, while NIRA data were negatively affected on road 158 in March and April; see Figure 11. The positive effect from the commercial part of the fleet is probably due to a higher demand for home delivery brought on by travel restrictions to avoid crowded stores. The negative effect on the E18 is probably due to less travel between the cities for work since NIRA includes both private vehicles and rental cars on the E18.

In general, slippery road conditions appear not to generate a higher amount of data in comparison with a day when the two suppliers have dry, non-slippery conditions; see Figures 2 and 3. Even when there were two periods with severe road conditions on the E18 (see Figure 3), this did not cause peaks in data delivery for the corresponding time periods (see Figure 2). As shown in Figures 3, 8, and 13, the relative order of the suppliers when comparing the daily friction average is almost constant, where NIRA often indicated slightly higher friction on average in comparison with RoadCloud. The difference in amplitude could be caused by the calibration, or more likely by different behaviours for the two techniques. Even though there are differences between them, both of the suppliers indicate the same changes in the road conditions, and can distinguish variations along the road.

The locations of friction events shown in Figures 4, 9, and 14 indicate that there are differences between the suppliers regarding the locations of low-friction events. For the E18 and road 158, RoadCloud shows that there was low friction at least once during the day for each road section along the roads, while NIRA measurements show that the low-friction events were concentrated towards the city centres, ramps and exits; see Figures 4 and 14. As mentioned earlier, one reason for this is the different positionings of the sensors; RoadCloud measures close to the left-hand wheel track, while NIRA often measures within the wheel tracks. The Swedish regulations for the three roads used as examples state that the friction level should be above 0.35 and that there should not be any snow on the roadway during fair weather [33]. Both suppliers therefore measure at useful positions that complement each other. For the busier road, the E6/E20, the locations of the low-friction events are very similar for both suppliers; see Figure 9. This is probably due to more frequent lane-changing and shorter distances between ramps and exits, which means that both suppliers spread the measurements across the road in multiple lanes.

6 | DISCUSSION

The two different methods of using FCD and vehicle fleets for road friction estimation complement each other for the full coverage of the road system. If the vehicle fleets are chosen wisely, it is possible to use vehicle data to monitor the road conditions in a large area, or even a whole country. The results presented herein indicate that a mixture of commercial and private vehicles could cover a larger share of the road network, and more hours in a day than a more homogeneous fleet. FCD could show the big picture of the road conditions, and could be used to indicate where the critical road sections are located. Another interesting discussion is over the locations of the most important measuring points on the road, and this question can be seen from several perspectives. The first perspective is that there is a requirement in Sweden for the road to be snow and ice free after a certain number of hours following precipitation. However, this is expensive to ensure, and the wheel tracks are usually snow and ice free. But this can produce different results, depending on whether the measuring takes place in the wheel tracks such as NIRA or between the wheel tracks, as for RoadCloud. The measurements in the wheel tracks represent what most road users actually experience, which is where most people drive, while measuring between the wheel tracks captures the worst conditions seen over the entire roadway. But such a discussion leads to the balance between safety and cost, which those responsible within the Swedish Transport Administration must decide between. But from a user perspective, measurements in the wheel tracks are probably preferable as they reflect how the vehicles experience winter conditions. One way to get better support for this decision is that the information from the FCD could be implemented together with accident statistics. Then the decision is not focused to facilitate improved road maintenance, but also with the possibility to save lives and move further towards the goal of Vision Zero.

Using vehicle data to monitor the friction on the road will lead to a completely new way of working for winter road maintenance. This is because the Swedish Transport Administration will be able to follow up its contractors in a completely different way compared to previously, when about 300 friction measurements were performed on the state road network in 2019, with about 200,000,000 measurements with FCD data. But it also means that the Swedish Transport Administration must adapt its requirements for friction, as the current regulations focus on measurements performed by some kind of trained personnel. With FCD data, the data will no longer be subjective, that is the driver will not be able to influence the result by driving on a particular section or part of the road. Data will also not be affected by who performs the braking, but data will show the general frictional state on the road. It will give a picture of how the “customer,” the road user, experiences the road conditions.
Vehicles will then report the situation in each lane as well as between the lanes while overtaking.

Therefore, of course, the measurements will have a completely different spread, which will mean that the requirements must be adjusted so that they produce a certain amount of the measurements that may be below a limit for the approval of winter road maintenance. Today, there are also no requirements for friction levels during, for example, ongoing snowfall. This is also something that may need to be investigated in more detail as it will also generate more data, but winter road maintenance is also a cost, so here there is of course the need to balance cost against safety.

With this drastic change of follow-up, contractors will need to adapt their working methods as well, they will need to use FCD data in their planning and also in their own follow-up. This is highly likely to increase the costs of winter road maintenance for a period and then decrease them when all of the different stakeholders have adapted to the new conditions.

Also notable is that FCD always need to be implemented in some kind of system or GUI, independent of user. For entrepreneurs some kind of forecast system together with weather parameters and weather forecasts. For administration the friction data needs to be incorporated together with the regulations and weather parameter to be useful. Just friction data by itself of course provides information but mainly to the driver out on the road at that time and then if it can be distributed to other drivers to warn about slippery road stretches.

In the future, there will be a higher number of new vehicles from multiple manufacturers with the systems already installed, which will generate even more data than is available today. But there is still work to be done and questions to be answered. How well will the FCD cover low-traffic roads? What will happen the next time driving patterns change, as they did during the Covid-19 pandemic? Will driving patterns ever go back to how they were before the pandemic, or will we have a new normal, with less public transportation and less unnecessary travel? How will autonomous vehicles contribute to, and use, the FCD for friction estimation in the future?

7 SUMMARY

The aim of this paper was to investigate how floating car data (FCD) can be utilised for road friction estimation. The investigation focused on coverage and on whether the FCD can detect harsh weather conditions with decreasing road friction. Two different methods were studied, one continuous and one slip-based. Different approaches on how to build the vehicle fleet to collect the FCD have also been tested, one using utility vehicles, such as buses and trucks, and one that uses taxis and private vehicles.

The results show that both methods detect low-friction road events and that for roads with high annual average daily traffic (AADT), the data collection using slip-based methods and larger fleets gives more data points than smaller fleets do using continuous methods, and the opposite is true for lower AADT. The results also show some differences between the two fleets in terms of coverage in the weekly and daily distributions, but overall, the method of using FCD for road friction estimation seems promising for the follow-up of winter road maintenance. Depending on AADT, the method using FCD could generate, around 100,000 to 1,000,000 measurements per day for a single road section when combing two vehicle fleets such as in Digital Winter. This is in comparison to the 50–100 measurements per month in an operating area performed using a spot-wise method such as the Coralba.

ACKNOWLEDGMENTS

The findings presented are based on the results of the Digital Winter project initiated and funded by the Swedish Transport Administration.

REFERENCES

1. Litman, T.: Autonomous vehicle implementation predictions—Implications for transport planning, pp. 1–45. Victoria Transport Policy Institute, Victoria (2020)
2. Pili Shvola, E., Leviakangas, P., Hautala, R.: Better winter road weather information saves money, time, lives and environment. In: Proceedings of the 16th SIRWEC conference, Helsinki, Finland, 23–25 May 2012
3. Edwards, S., et al.: Wireless technology applications to enhance traveller safety. IET Intel. Transport Syst. 6(3), 328–335 (2012)
4. Berrocal, V., et al.: Probabilistic weather forecasting for winter road maintenance. J. Am. Stat. Assoc. 105(490), 522–537 (2010)
5. Norrman, J., Eriksson, M., Lindquist, S.: Relationships between road slipperiness, traffic accident risk and winter road maintenance activity. Clim. Res. 15, 185–193 (2000)
6. Ye, Z., et al.: Vehicle-based sensor technologies for winter highway operations. IET Intel. Transport Syst. 6(3), 336–345 (2012)
7. Hinckka, V., et al.: Integrated winter road maintenance management – new directions for cold regions research. Cold Reg. Sci. Technol. 121, 108–117 (2016)
8. Erguloglu, G., Alexander, L., Rajamani, R.: Friction coefficient measurement for autonomous winter road maintenance. Veh. Syst. Dyn. 47(4), 497–512 (2009)
9. Casselgren, J., Bodin, U.: Reusable road condition information system for traffic safety and targeted maintenance. IET Intel. Transport Syst. 11(1), 230–238 (2017)
10. Autioniemi, J., et al.: Intelligent Road. (INTEREG IV A North program for interregional cooperation, 2015)
11. Hu, Y., et al.: Modeling road surface temperature from air temperature and geographical parameters—implication for the application of floating car data in a road weather forecast model. J. Appl. Meteorol. Climatol. 58(1), 1023–1038 (2019)
12. Odellius, J., et al.: Internet application services for efficient winter road maintenance. J. Qual. Maint. Eng. 23(3), 355–367 (2017)
13. Brockfeld, E., et al.: Benefits and limitations of recent floating car data technology—An evaluation study. Proceedings of the 11th World Conference on Transport Research, Berkeley, 24–28 June 2007
14. Jenelius, E., Koutsopoulos, H.N.: Travel time estimation for urban road network using low frequency probe vehicle data. Transp. Res. B 53(1), 64–81 (2013)
15. Vignisdottir, H.R., et al.: A review of environmental impacts of winter road maintenance. Cold Reg. Sci. Technol. 158(1), 143–153 (2019)
16. Perrier, N., Langevin, A., Campbell, J.F.: A survey of models and algorithms for winter road maintenance, part iv: Vehicle routing and fleet sizing for plowing and snow disposal. Comput. Oper. Res. 34, 258–294 (2007)
17. Federal Highway Administration (FHWA). Ten-year averages from 2007 to 2016 analyzed by Booz Allen Hamilton, based on NHTSA data. https://ops.fhwa.dot.gov/weather/q1_roadimpact.htm (2020). Accessed 30 April 2020
18. Trafficanalys: Vägtrafiksåkador 2009 (Statistik 2010:17). TRAFA (2010)
19. Trafikanalys: Vägtrafiksåkador 2010 (Statistik 2011:15). TRAFA (2011)
20. Trafikanalys: Vägtrafiksåkador 2011 (Statistik 2012:14). TRAFA (2012)
21. Trafikanalys: Vägtrafiksåkador 2012 (Statistik 2013:9). TRAFA (2013)
22. Trafikanalys: Vägtrafiksåkador 2013 (Statistik 2014:8). TRAFA (2014)
23. Trafikanalys: Vägtrafiksåkador 2014 (Statistik 2015:8). TRAFA (2015)
24. Trafikanalys: Vägtrafiksåkador 2015 (Statistik 2016:12). TRAFA (2016)
25. Trafikanalys: Vägtrafiksåkador 2016 (Statistik 2017:12). TRAFA (2017)
26. Trafikanalys: Vägtrafiksåkador 2017 (Statistik 2018:12). TRAFA (2018)
27. Trafikanalys: Vägtrafiksåkador 2018 (Statistik 2019:11). TRAFA (2019)
28. Trafikanalys: Vägtrafiksåkador 2019 (Statistik 2020:10). TRAFA (2020)
29. Swedish Government, 1997: Nollvisionen och det trafiksäkra samhället (Vision Zero and the road traffic safety society). Swedish Government Bill 1996/97:137
30. Belin, M., Tillgren, P., Vedung, E.: Vision zero—A road safety policy innovation. Int. J. Inj. Control Saf. Promot. 19(2), 171–179 (2012)
31. Ali, M., Falcone, P., Sjöberg, J.: A predictive approach to roadway departure prevention. In: 21st IAVSD Symposium on Dynamics of Vehicles on Roads and Tracks, Stockholm (2009)
32. Kilpeläinen, M., Summala, H.: Effects of weather and weather forecasts on driver behaviour. Transp. Res. Part F Psychol. Behav. 10, 288–299 (2007)
33. Swedish Transport Administration: Standardbeskrivning Vintervåghållning för Baunderhåll Väg (SBV). Trafikverket 1–10 (2017)
34. Swedish Transport Administration. ‘Trafikverket’. Accessed 30 April 2020, https://www.trafikverket.se/
35. Casselgren, J., Sjödahl, M., LeBlanc, J.P.: Model based winter road classification. Int. J. Veh. Syst. Model. Test. 7(3), 268–284 (2012)
36. Bruzelius, F., et al.: Evaluation of tyre to road friction estimators, test methods and metrics. Int. J. Veh. Syst. Model. Test. 1(5), 213–236 (2010)

How to cite this article: Sollén S, Casselgren J. Large-scale implementation of floating car data monitoring road friction. IET Intell Transp Syst. 2021;15:727–739. https://doi.org/10.1049/itr2.12039