Potential of road roughness data from smartphones as an input to spring weight restriction decision-making

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Paper prepared for presentation
at the Innovations in Pavement Management, Engineering and Technologies Session

of the 2017 Conference of the
Transportation Association of Canada
St. John's, NL

ACKNOWLEDGEMENTS

The authors acknowledge the funding support of the New Brunswick Innovation Foundation (NBIF) Research Assistanceship Initiative (RAI), and the in-kind support of Coady Cameron from Total Pave Inc. The authors also thank Corey White, George Thompson, and Ralph Campbell of the New Brunswick Department of Transportation and Infrastructure, and Drs. Eric Hildebrand, Xiomara Sanchez, and James Christie of UNB Civil Engineering and Dr. Philip Garland of UNB Mechanical Engineering for helpful comments on the work. Finally, the authors acknowledge UNB Civil Engineering Research Technician Dr. Dennis Connor for assistance in collecting data.

ABSTRACT

One challenge facing transportation agencies employing Spring Weight Restrictions (SWR) is the ability to broadly monitor the road network for critical real time changes in road strength. Some agencies employ a subjective assessment of road roughness changes as a proxy to changes in strength and the need for further weight restrictions, though the geographic scope is limited to the travel of the road supervisor. Smartphone devices have been shown to be effective and accurate mobile platforms for collecting accelerometer data that can be converted into International Roughness Index (IRI) values. These devices have the potential to expand the extent and frequency of roughness monitoring over spring thaw if instrumented on fleet vehicles or crowd-sourced. This could support the development of objective trigger values for changes in roughness that would support the decision-making by a district engineer regarding imposing additional weight restrictions or focusing strength testing. If changes in roughness could be correlated with changes in strength, it may be possible to isolate specific areas of road weakness at high speed and in real-time.

This research explored the potential of using smartphones to monitor road roughness changes on 1 km sections of two proximate collector and local highways over the SWR period in New Brunswick from March 15 – May 17, 2015. IRI values were calculated from an average taken from four runs on 26 different days at a speed of 80 km/h, reduced to 60 km/h on the local highway due to excessive road heaving. IRI values doubled from baseline to peak on both sections (collector and local baseline (peak): 1.35 m/km (2.54 m/km); 3.34 m/km,(6.60 m/km)) within the first two weeks of SWR, returning to baseline values two weeks before SWR ended. Data collection twice a week would capture the majority of significant changes in IRI values between observations. The change from a baseline IRI to the peak IRI and back occurred within the SWR window, suggesting the dates were appropriate if roughness was correlated with strength. Further work should explore trigger values that initiate a protocol to respond to drastic weather changes and the relationship between road strength and IRI.

INTRODUCTION

Many transportation agencies annually impose Spring Weight Restrictions (SWR) to reduce allowable heavy vehicle loads during spring thaw when roads are most susceptible to traffic damage; however, agencies can be constrained in their ability to monitor network response to unanticipated climatic changes during the SWR window. The result may be situations where restrictions are either insufficient to fully protect infrastructure, or are no longer necessary thereby negatively impacting the trucking industry. Monitoring of the load bearing capacity of pavements is commonly performed to support decision-making with respect to adjusting SWR dates and percentage load reductions, and most quantitative methods heavily rely on the collection of pavement performance data and subsurface measurements (Chapin *et al*. 2009). The challenge is that collecting strength data is expensive and time consuming to the point where some agencies, such as the New Brunswick Department of Transportation and Infrastructure (NBDTI), have reduced routine strength monitoring to case-by-case bases.

In addition to thaw weakening during the spring thaw, pavements are also subject to frost heave which translates into a rougher road surface. The monitoring of surface roughness (quantified through the International Roughness Index or IRI) could be used indirectly to quantify frost heave as an indicator of thaw-weakening, but is typically collected by an expensive specialized vehicle and only when the road is the strongest. Given that consumer smartphone devices have demonstrated potential as low-cost mobile data collection platforms for IRI (Hanson, *et al*, 2014), it may be possible for these devices to enable network monitoring of roughness during the spring thaw. This system could then be used to highlight significant changes in roughness that may warrant a strength test, permitting agencies to focus their testing resources. No research has tested the ability of smartphone devices to monitor roughness changes over time.

This paper presents the results of a study using the accelerometer output of a smartphone device to monitor changes in IRI values on 1000m stretches of two secondary highways (one collector, one local) in New Brunswick over the period of SWR from March 15 – May 17, 2015. Data were processed by TotalPave Inc. based on the process developed by Cameron (2014) and outlined in Hanson, *et al.* (2014). The goal was to determine

whether the devices could successfully monitor changes in IRI and whether this could be observed on two roads of different anticipated roughness levels during spring thaw.

BACKGROUND

Smartphone devices are cellular phones with integrated computer capabilities, typically having touchscreen interfaces, internet access and the ability to run software applications and store data (Dictionary.com n.d.). The potential of using these devices for low-cost, network pavement roughness data collection has been recognized by several researchers (Ericksson *et al*. 2008) (Islam *et al*. 2014) and has beget a number of commercial efforts (DataInformed 2013). The accelerometer data and location data from these devices have been used to identify the location of specific surface distresses, primarily potholes (Ericksson *et al*. 2008), and has also been transformed into International Roughness Index (IRI) values (Hanson *et al*. 2014) (Islam *et al*. 2014).

The ability to collect IRI values at a reasonable accuracy with a low-cost consumer device (when compared to Class 1 profilers) led Hanson *et al* (2014) to suggest using the devices to monitor road roughness changes over time on seasonally weakened pavements. They theorized that this approach may permit network monitoring of the progression of road roughness as a proxy for thaw weakening, enabling agencies to prioritize their strength testing and supporting their decision-making with respect to seasonal weight restrictions. This would have application in jurisdictions such as the Province of New Brunswick, where resourcing constraints has led the Department of Transportation and Infrastructure (NBDTI) to end its routine strength data collection program, instead relying on historic strength data as well as collaboration with surrounding provinces to support seasonal weight restriction decision-making (C. White, personal communication, 2015). While historic strength data has practical use in understanding the general applicability of restriction timeframes, the lack of routine data limits the ability of an agency to be proactive in responding to dramatic temperature changes or weather events.

The need for seasonally adjusted maximum allowable commercial vehicle weights

Any transportation agency that has roads subject to Freeze Thaw Cycles (FTC) may face the issue of seasonally weakened pavements. While it is possible to design all-weather roads, many agencies will enact a seasonal load restriction, typically a Spring Weight Restriction (SWR) to reduce allowable commercial vehicle loads on the roads subject to weakening. Under critical thaw conditions, these pavements are unable to properly transfer traffic load through the structure, resulting load-induced damage can be 1.5 to 3 times higher than the average annual damage (Salour and Erlingsson 2012). The use of SWR can result in an increase in average life expectancy of pavements between 6% and 14% (Baïz *et al.* 2008), while decreasing allowable weights by 20% and 50% can increase pavement life by 65% and 95%, respectively (Kavanagh and Shalaby 2013). While beneficial to highway agencies, SWR have an economic impact on trucking agencies causing indirect effects to any industry with high reliance on trucking (Levinson *et al.* 2004; CSHRP 2000; Chapin *et al.* 2009), such as the forest industry, operating during the restriction window. This introduces a dynamic that puts additional pressure on public agencies to minimize the extent and duration of restrictions.

Canadian approaches to setting Spring Weight Restrictions

Canadian jurisdictions expend considerable effort to develop SWR that ensure infrastructure protection while minimizing disruptions to the trucking industry, though there is variability among their approaches. Some undertake strength monitoring, surface and subsurface temperature monitoring, and some employ indices based on air temperature. A thorough list of practices will be available when the Transportation Association of Canada (TAC) releases its new Load Management Guide in 2016 (TAC 2014). The most common method to establish SWR is the limitation of pavement deflections or stiffness modulus estimated from deflections, which was the practice in New Brunswick until routine monitoring ended in 2013 (C. White, personal communication, 2015). Pavement deflections are monitored over the thaw-weakened period once or twice a week using apparatus such as the Falling Weight Deflectometer (FWD), Benkelman Beam or Dynaflect (Tighe and McLeod 2011). Restrictions are placed once deflections reach a specified threshold value and lifted when deflections fall below the threshold; values found in literature indicate 80% of fully recovered baseline moduli as an acceptable

threshold value (Kavanagh and Shalaby 2013; Kestler *et al.* 2011). Current methods of deflection data collection are time-consuming and costly, limiting opportunities to increase data collection (Chapin *et al.* 2009).

Other approaches used to set SWR include monitoring of subsurface temperatures with sensors such as thermistors and thermocouples, and sensors that indicate the state of ground (frozen or thawed) such as frost tubes and resistivity probes. Common practice is to impose SWR when near-surface temperatures rise to 0ºC; while these sensors are useful in predicting the onset of thaw, their usefulness for determining when to lift the restrictions is limited during the strength recovery period. Moisture can be used as an indicator of modulus. The dissipation of moisture within the pavement structure indicates that the road is no longer highly susceptible to damage and SWR can be lifted (Kestler *et al.* 2011; Kestler 2003). The price of acquiring a system varies widely based on requirements, their major downfall is that they are site specific (Yu *et al.* 2009; Kestler 2003).

Indices such as the Freezing Index (FI) and Thawing Index (TI) have been developed to quantify the intensity of a freezing or thawing season to assist practitioners in implementing and lifting SWR. The depth of frost present in a pavement structure depends in part on the amount and duration of the temperature differential below or above freezing at the ground surface allowing the use of daily air temperature to predict thaw. Indices can be useful but are more applicable on a broad scale rather than for evaluating the suitability for SWR on a single road.

The potential for road roughness metrics to enhance network monitoring over the spring thaw

Road roughness is typically quantified through International Roughness Index (IRI) values, which is a measure of a standardized vehicle's vertical suspension travel over a horizontal distance (m/km) (Sayers *et al.* 1986). Measuring road roughness (or surface frost heave) as a means to determine thaw duration was discussed in the recommendations of a Minnesota study by Van Deusen *et al.* (1998) and has seen application in research in Quebec (Fradette *et al.* 2005) and Japan (Kameyama *et al.* 2002). While road roughness can increase with time for all roads, frost susceptible roads can experience marked increases and decreases in roughness annually in response to seasonal weather changes, with some research showing maximum IRI values twice the value of the baseline roughness (Corley-Lay and Mastin 2009; Kameyama *et al.* 2002; Doré and Savard 1998). Seasonal monitoring of pavement roughness in Quebec has shown increases in roughness early in the winter (December) as the freezing front progresses through the structure and causes heaving of transverse cracks (Fradette *et al.* 2005). Road roughness progresses over the course of the spring thaw due primarily to differential soil movement caused by FTC, though can exacerbated by existing distresses present over the freeze-thaw process including rutting, fatigue and thermal cracking (Qiao *et al.* 2013). Distresses resulting from frost action reach their peak during the critical thaw conditions and usually become less pronounced as the structure recovers (St-Laurent 2012; Schaus and Popik 2011; Kestler *et al.* 2005; Janoo and Barna 2002; Doré and Savard 1998; Raad *et al.* 1998). A study by Kameyama *et al.* (2002) reported that IRI values are at their maximum just before the maximum depth of frost penetration is achieved. Reduction of road roughness to near pre-freeze levels occurs when the thaw front has reached the subgrade soil (Fradette *et al.* 2005), though residual roughness can remain after the spring thaw possibly caused by new distresses formed during the process (Corley-Lay and Mastin 2009; Kameyama *et al.* 2002; Doré and Savard 1998).

The literature indicates that monitoring the seasonal progression of roughness could be useful in understanding the various stages of the freeze-thaw processes. This could potentially be used as a proxy for changes in road strength over this timeframe, though further research is needed to describe the relationship between changes in strength and roughness. It did not appear any of the profiled research compared road strength measurements with road roughness. These findings do suggest that a link between road strength and road roughness exists; consequently, there would be considerable value in an approach to collect road roughness data on a network basis during the spring thaw. This is something that could be facilitated at a reasonable level of accuracy by the smartphone platform tested by Hanson, *et al.* (2014), but further research was needed to determine whether the smartphone devices could monitor changes in IRI values over time and differentiate between roads of varying perceived strength.

METHODOLOGY

The goal of this research was to apply the methodology and approach outlined in Hanson *et al.* (2014) to determine whether accelerometer output from a smartphone device could be used to monitor changes in roughness over the course of the spring thaw. The results would be used to inform spring weight restriction policy in the absence of network wide routine strength data.

Study approach

The equipment and study approach were selected to replicate expected field conditions if this data collection method was to be performed by a highway agency such as the NBDTI: a popular smartphone device, installed in a typical highway agency vehicle, was to be used to collect accelerometer data on two different road classes at highway speeds (80 km/h) multiple days per week throughout the duration of NBDTI's spring weight restrictions in 2015. The selection of equipment for this research was guided by the results of scenario tests conducted by Cameron (2014) and reported in Hanson *et al.* (2014).

The Apple iPhone 5C was selected as the test device. While it was not the best performing smartphone in the 2014 University of New Brunswick (UNB) study by Hanson *et al.* (2014), Apple iPhones were among the most widely available devices and its performance was sufficiently close to the Class 1 profiler values in the 2014 UNB study to warrant its testing. The same 2008 Ford F250 owned by the UNB Department of Civil Engineering and used in the previous UNB study was used as the data collection vehicle. A device-specific windshield bracket (iGRIP) was used.

Data were collected three times a week over the time period NBDTI employs restrictions during the spring thaw. NBDTI's 2015 SWR became effective at midnight on March 15th; the end date was initially set for May 10th for the southern part of NB but was extended until May 17th (NBDTI 2015). Data were collected for a total of nine weeks beginning a few days prior to the posting of the restrictions. Ideally data collection would have been performed on a daily basis, however due to schedule limitations and equipment availability data collection was limited to three times a week. Monitoring roads three times a week was deemed to be more realistic from a highway agency operating point of view. It is a considerable improvement in resolution from current practices given that NBDTI currently employs a 3-year cycle for the collection of surface roughness and structural capacity data (Cunningham, *et al*. 2010). Data were collected during non-peak hours (9 to 11 AM or 1 to 3 PM) to minimize transverse wandering of the vehicle due to traffic. Varying vehicle wheel paths causes variations in IRI between runs, transverse wandering of the vehicle can result in a 5-10% difference in IRI values for a divergence of 30 cm (Corley-Lay and Mastin 2009).

IRI conversion procedure

Vertical acceleration caused by anomalies in the road profile was logged in the field using a third-party smartphone application SensorLog. Raw accelerometer data collected in the field at 32 Hz were processed into IRI values by Total Pave, a private company using the numerical method procedure developed by Cameron (2014) and described in Hanson *et al* (2014). The process involves creating a displacement dataset approximating the road profile, which is converted to IRI values processed through ProVAL software developed by the U.S. Federal Highway Administration. Total Pave has automated this multi-step process allowing for quick processing of the large amount of data collected for this study. IRI values were calculated and reported in m/km for the entire 1 km length. While it is possible to report IRI values calculated by this method at shorter intervals (e.g. 100 m), it does considerably increase the amount of data that would need to be transferred wirelessly and processed for analysis. Further work could explore whether a finer resolution than 1 km would be necessary to support network level monitoring.

Study area

Roughness values were collected on two New Brunswick provincial highways in the Fredericton area to allow the comparison of roughness progression on two types of road. In order to be consistent with previous methods and

align with the standard method of IRI data collection, the following criteria were used when selecting the test sections:

- Speed limit of 80 km/h or higher;
- Safe turnaround locations for the data collection vehicle;
- Approximately 1 kilometre in length;
- Limited changes in grade and horizontal alignment;
- Perceived variability in longitudinal roughness;
- Maintained by NBDTI;
- Posted with spring weight restrictions.

The first test section was a recently resurfaced asphalt section with few visible surface distresses located on Route 105 (NB Collector Highway) northwest of Fredericton. This section was used in previous research at UNB (Hanson, *et al*, 2014) where a standard inertial profiler measured the test section's average IRI at 2.60 m/km prior to resurfacing, with the smartphone device returning similar values at the time. It was expected that baseline IRI values collected on this section in this research would be less than prior to resurfacing. The second test section was an asphalt surface with considerable visible surface distresses, including rutting and cracking, on Route 616 (NB Local Highway) northeast of the Route 105 test section. Both roads were posted to an 80% weight restriction by NBDTI and data logging occurred in one lane only. For future reference, the test sections will be referred to as R105 and R616.

Pilot test

The required sample size for test runs was estimated using the following equation (Dowdey & Wearden, 1983):

$$n = \left(\frac{Vt}{E}\right)^2$$

Where:

n = number of samples required

V = coefficient of variation

t = student "t" test statistic

E = acceptable error

The assumed parameters were t = 1.96 (5% level of significance) and an acceptable error of ±10%. The previous UNB research found a coefficient of variation (COV) to be 7.33% on Route 105 using the same parameters. The required sample size was calculated to be 3; however, this method assumed that the COV remains constant in every run. This is unlikely to be the case due to random experimental errors. In order to account for the possibility that the standard deviation is higher in subsequent tests, 4 runs per observation were performed. A test run validated the sample size, with COV of 3.71% and 3.24% observed on R105 and R616, respectively. The testing procedure ensured a consistent operating speed, device set up, tire pressure and start and stop location for data collection. A two-sample t-test assuming equal variances (F-test at 0.05 did not reject null hypothesis of equal variances) rejected the null hypothesis that the mean IRI values between the two roads during the pilot test was the same, indicating the device could successfully differentiate between two levels of roughness for both roads.

Approach to analysis

A paired t-test was used to compare average IRI values between sections for the 26 data collection days; the paired t-test allows the comparison of means of independent pairs. Data collected over the observation period were analyzed using two-sample t-tests assuming equal variances to identify if there were any significant changes in IRI between the two road sections, as well as between readings on each individual road. Since the number of days between consecutive data collection efforts varied on a weekly basis, observations were paired

with consecutive IRI readings measured 1 to 7 days later to determine whether significant differences could be observed between a reading and a reading "n" days later.

RESULTS AND ANALYSIS

Summary observations

Data were collected on 26 occasions over the study period from March 12th to May 15th, 2015. The maximum observed IRI values and Baseline IRI values are profiled in Table 1, with local highway R616 being the rougher of the two roads (as expected). Both test sections experienced differentials greater than 1.0 m/km, which according to research in Quebec indicates that the IRI deterioration rate is above normal and heaving is a problem (St-Laurent 2012). The difference observed at the R616 was twice that of R105, also confirming that anticipated seasonal effects are more pronounced on sections with measurable rutting and cracking. Ideally, baseline values would have been collected the September prior to the data collection period (due to residual increases in IRI found to remain after the spring thaw); however, the project timeline did not allow for data collection in the fall of 2014.

Change in data collection speed

Travel speeds were initially at 80 km/h for both roads; however, the roughness progression on R616 was severe enough that travel speeds were reduced to 60 km/h on R616 for safety reasons beginning April 2nd. Previous research by Hanson et al. (2014) found that IRI values collected with this method at speeds of 50 km/h and 80 km/h were not significantly different; however, R616 was a considerably rougher road than R105 used in the 2014 study. Both R105 and R616 were run at 60 km/h and 80 km/h to determine the impact of speed on calculated IRI values. A t-test (alpha = 0.05) confirmed that the observed changes in IRI values due to the speed change were only significant for R616, not for R105. Even then, the p-value was only 0.04 for the observations on R616, meaning that while the change was statistically significant at 0.05, it likely did not represent a practical difference for the purposes of using this device for its intended purpose as a network screen. The results from this finding were that when comparing values for analysis, values observed after the change in data collection speed could not be compared statistically to values before.

Roughness progression over the SWR period

Figure 1 shows the progression of IRI values at both test sections over the study period relative to the start of SWR on March 16th, 2015. The large drop in IRI values and discontinuity in baseline values observed at R616 17 days into the SWR period (April 2nd) is explained by the change in data collection speed to 60 km/h. A 60 km/h data collection speed returned IRI values that were statistically lower than those collected at 80 km/h, though with a 7% difference, within the 10% tolerance for the work. The roughness at the test sections reflect seasonal influences, where higher values of roughness were experienced in March followed by decreases as spring progressed until IRI values stabilized around the end of April.

Roughness peaked on R105 eight days into the SWR period (March 24th) and one week later on R616, though the second highest IRI values on R616 were observed on the same day as peak values on R105 and were only 1% lower than the peak value. The minimum IRI value at R105 occurred 53 days into the 62 day SWR period (May 8th) and six days later at R616 on (May 14th), though the second lowest IRI values on R616 were observed on the same day as the lowest values on R105. The precision limitations of the equipment mean that maximum and minimum IRI values could have occurred at approximately the same time on both roads. The implication is that if the road roughness progression curves of two different road classes in proximity are aligned, it may be possible to infer roughness progression according to a baseline IRI value and road class, eliminating the need to monitor all roads.

Daily weather data obtained from the Fredericton CDA CS weather station included maximum temperature, minimum temperature, mean temperature and total precipitation. Daily mean temperature data from March 9th to May 17th were plotted against the IRI values and displayed in Figure 2. The expected trend is visible

where IRI values increased with lower temperatures due to frost heave and decreased with increasing temperatures until it stabilized to the baseline conditions.

Table 2 summarizes the weekly IRI values observed over the study period and the standard deviations associated with these averages. Higher standard deviations were observed in weeks 4 and 5, and 5 and 6 for R105 and R616 indicating that changes in IRI were likely greater during those weeks of the SWR period.

Analysis of IRI changes

The 26 days of observations were organized into pairs of observations collected between 1 to 7 days apart to determine whether significant changes to IRI could be observed depending on time from an initial reading (Table 3). The goal was to develop recommendations for data collection frequency for a transportation agency. These pairs of observations were analyzed by road class and by week of data collection. The largest differences were observed between weekly readings (-0.51 m/km on R105 and -1.44 m/km on R616). The majority of changes observed were not significant when observations were less than four days apart, though there were some statistically significant differences between observations taken two days apart.

IRI changes over the SWR timeline

The data pairs were further broken down over the study time period to identify when significant changes in IRI occurred relative to the SWR timeline. The data pairs were divided into ten bins, where each bin represents a period of one week before or after the implementation of the SWR on March 16th, 2015. The data pairs were placed into bins according to the date of the second observation. Table 4 summarizes for each data pairs with "n" days between readings during which weeks significant changes were observed. If any significant differences were observed between any of the data pairs, it was denoted with a "Y" (yes) in Table 4; otherwise it was denoted with an "N" (no).

The data from Table 4 can be interpreted in two ways: propensity to observe statistically significant changes in IRI values over the course of the SWR; propensity to observe statistically significant changes in IRI values between consecutive readings. Significant changes in IRI values were observed in 8 of the 9 weeks of SWR for R105 and 7 of 9 weeks for R616. The majority of statistically significant changes were experienced between weeks 4 – 6 on R105 and 4 – 7 on R616. Statistically significant changes were most likely to be observed between readings taken 4 days apart on R105 and 1 week apart on R616. It did not appear that IRI values would change significantly on a daily basis during the course of the SWR period, though one observation in the week prior to SWR was found to be statistically significant.

Potential of mobile IRI data to compliment frost depth models

Some transportation agencies, including the NBDTI, employ frost depth models in areas without automated frost probes to estimate the extent of frost progression and the point when the road begins to thaw and weaken. These models are network-specific and typically only applicable when mean air temperature is below 0°C. The model shown in Equation 2 is used in New Brunswick to predict frost depth based on the CFI calculations using air temperatures:

$$FD = CF\sqrt{CFI}$$

Where:

FD = frost depth (cm)

CFI = Cumulative freezing index (ºC-days)

CF = Frost depth coefficient (5.612 is used for NB)

Typically, these calculations are performed using forecasted air temperatures, these calculations performed post facto use the recorded daily mean temperatures. Frost depths were estimated using the frost depth coefficient of 5.612 for New Brunswick and plotted against the calculated IRI values found for R105 and R616 at the beginning of the data collection period where IRI was increasing. The maximum estimated frost depth was

found to occur on March 25th after which mean temperatures rose above 0°C. This coincides with the maximum IRI value at R105 and the second highest at R616 observed on March 24th (no observations were made on the 25th) after which both sections began experiencing decreases in IRI values. The dotted line after March 25th was used to symbolize thawing with its curve following fluctuations in mean air temperatures as thawing would be expected to occur but does not represent actual frost depths estimations. Figures 3 and 4 show that the calculated IRI values closely follow the predicted frost depth progression.

While road roughness is a lagging indicator in this case, there does appear to be sufficient alignment between the frost depth model and IRI values to consider exploring the use of network-wide mobile road roughness data to refine frost depth models at a project level for use the following year.

CONCLUSIONS

This research employed a smartphone device to record vertical acceleration associated with road roughness on two New Brunswick highways subject to spring weight restrictions on 26 occasions between March and May 2015. Accelerometer data were transformed into IRI values by a third party company, which were then used to compare observations. The smartphone device was able to return values that identified statistically significant changes in IRI values over time and between the two road classes. IRI values calculated from the device reflected seasonal influences, peaking in March followed by decreases in April until IRI values stabilized around the end of April. IRI values observed increased up to 1.88 times higher than baseline values on R105 and up to 1.98 times higher on R616, which was consistent with literature suggesting IRI values during spring thaw could be twice that of baseline values. The IRI values observed suggest that the SWR dates chosen for 2015 aligned with the expected strength of the two road sections, though further research is needed to better understand the relationship between road roughness and strength. Demonstrating this relationship would expand the opportunities for using the mobile roughness data.

Maximum and minimum IRI values were observed around the same time on both sections, and the progression of roughness followed a similar trend at both roads regardless of road class. If roads of different classes (collector vs. local) within a specific geodesic distance behaved the same way, this suggests that once a baseline is established for all roads in a certain area, only a subset may need to be routinely monitored using this method.

This research also identified several operational considerations for agency adoption which will be explored in further work. The most notable findings were that the majority of statistically significant differences between observations occurred two to seven days apart, indicating that changes are generally not significant on a daily basis. The data suggests that performing data collection twice a week would capture the majority of significant changes in observations. Another finding was that excessive frost heaving impacted the ability to safely maintain a consistent monitoring speed throughout the course of the testing. The impact of the speed change was statistically significant on values from the rougher road (R616), but resulted in only a 7% difference in calculated IRI value, within the 10% tolerance assumed for this work. The number of runs per observation (which was four) would be impractical for a single vehicle, therefore additional work could explore the impact on accuracy of reducing the number of runs or increasing the number of instrumented vehicles. Additional research could explore the use of “trigger values”, where changes in IRI values could be used to trigger a strength test, or perhaps, further weight restrictions.

The monitoring of road roughness using mobile devices on highway agency vehicles over the course of the spring thaw could have multiple applications for agencies looking to expand their network monitoring at an anticipated lower cost than with road instrumentation. While predictive models for enacting SWR remain an ever-present goal, this type of approach could permit a real-time monitoring of network conditions and help focus resources, such as strength testing, on apparent problematic areas. It could also assist in the evaluating the applicability of network-wide models (such as frost depth) to project-level situations.

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TABLES

Table 1 Summary of IRI values

Test Section	Max IRI (m/km)	Baseline IRI (m/km)	Ratio of Max IRI to Baseline IRI
R105	2.54	1.35	1.88
R616	6.60	3.34*	1.97

*Note that data collection speed changed from 80 km/h to 60 km/h due to impact of road heaving on test vehicle. Baseline IRI collected at 60 km/h was 3.10

Table 2 Summary of weekly IRI values

Weeks from SWR	Dates	R105		R616	
		Average IRI	Standard deviation	Average IRI	Standard deviation
-1	Mar 9 – 15	2.26	0.08	6.00	0.02
1	Mar 16 – 22	2.45	0.05	6.29	0.21
2	Mar 23 – 29	2.51	0.04	6.54	0.03
3	Mar 30 – 5	2.37	0.03	-	-
4	Apr 6 – 12	2.10	0.12	5.84	0.08
5	Apr 13 – 19	1.72	0.17	5.43	0.30
6	Apr 20 – 26	1.31	0.05	4.05	0.35
7	Apr 27 – 3	1.31	0.05	3.31	0.02
8	May 4 – 10	1.27	0.08	3.06	0.06
9	May 11 – 17	1.25	0.00	3.07	0.11

Table 3 IRI changes at R105

# of days between data pairs	# of data pairs	R105 # of significant ΔIRI data pairs	Max significant ΔIRI (m/km)	# of data pairs	R616 # of significant ΔIRI data pairs	Max significant ΔIRI (m/km)
1	6	1	-0.12	6	0	-
2	9	4	-0.21	8	4	-0.36
3	7	3	-0.18	6	3	-0.72
4	9	7	-0.33	9	3	-0.70
5	8	7	-0.39	8	6	-1.08
6	7	3	-0.30	7	3	-0.71
7	13	9	-0.51	11	8	-1.44

Table 4 Statistically significant changes in IRI values over the SWR timeline

Weeks from SWR	Dates	Significant ΔIRI data pairs by "n" days from initial reading (Y/N)													
		R105							R616						
		1	2	3	4	5	6	7	1	2	3	4	5	6	7
-1	Mar 9 – 15	Y	-	-	-	-	-	-	N	-	-	-	-	-	-
1	Mar 16 – 22	N	-	Y	Y	Y	-	Y	N	-	Y	N	N	-	Y
2	Mar 23 – 29	-	N	-	Y	-	N	N	-	N	N	N	-	N	Y
3	Mar 30 – 5	N	N	N	N	Y	Y	Y	N	-	-	N	N	N	N
4	Apr 6 – 12	N	Y	Y	-	Y	Y	Y	N	N	N	-	Y	Y	-
5	Apr 13 – 19	-	Y	N	Y	Y	Y	Y	-	Y	N	Y	Y	Y	Y
6	Apr 20 – 26	-	N	Y	Y	Y	-	Y	-	Y	Y	Y	Y	-	Y
7	Apr 27 – 3	N	-	N	Y	N	N	N	N	-	Y	Y	Y	Y	Y
8	May 4 – 10	-	Y	-	Y	-	N	N	-	N	-	N	-	N	N
9	May 11 – 17	N	-	-	-	-	N	N	N	-	-	-	-	N	N

FIGURES

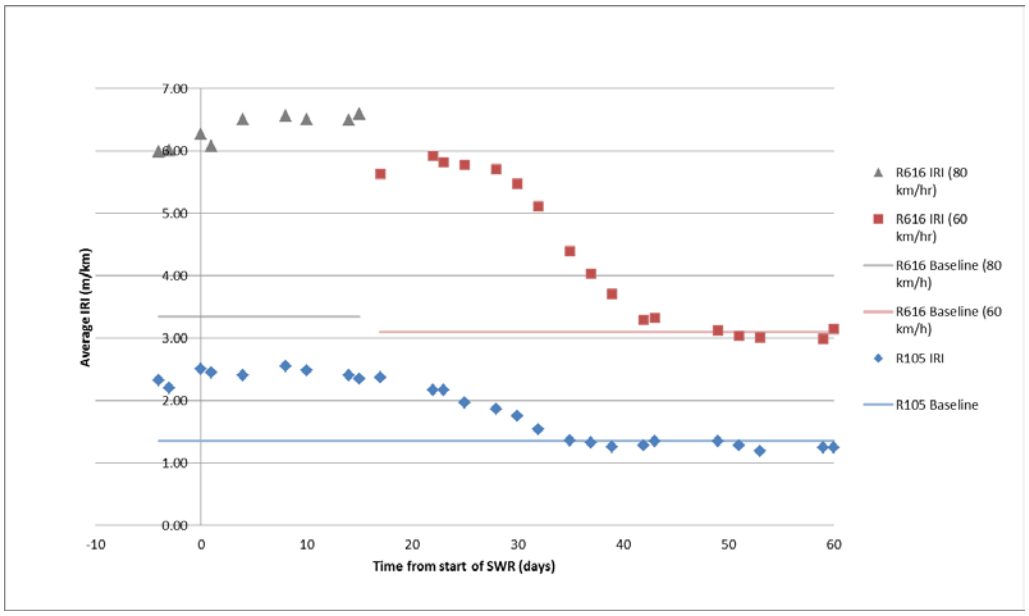

Figure 1 Roughness progression over the study period

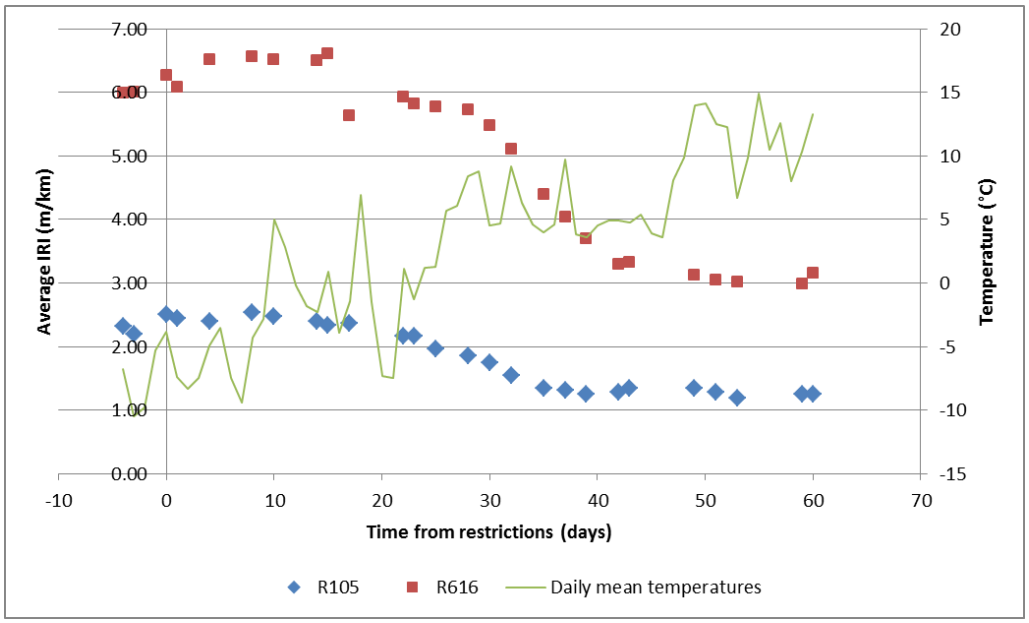

Figure 2 Air temperature and road roughness

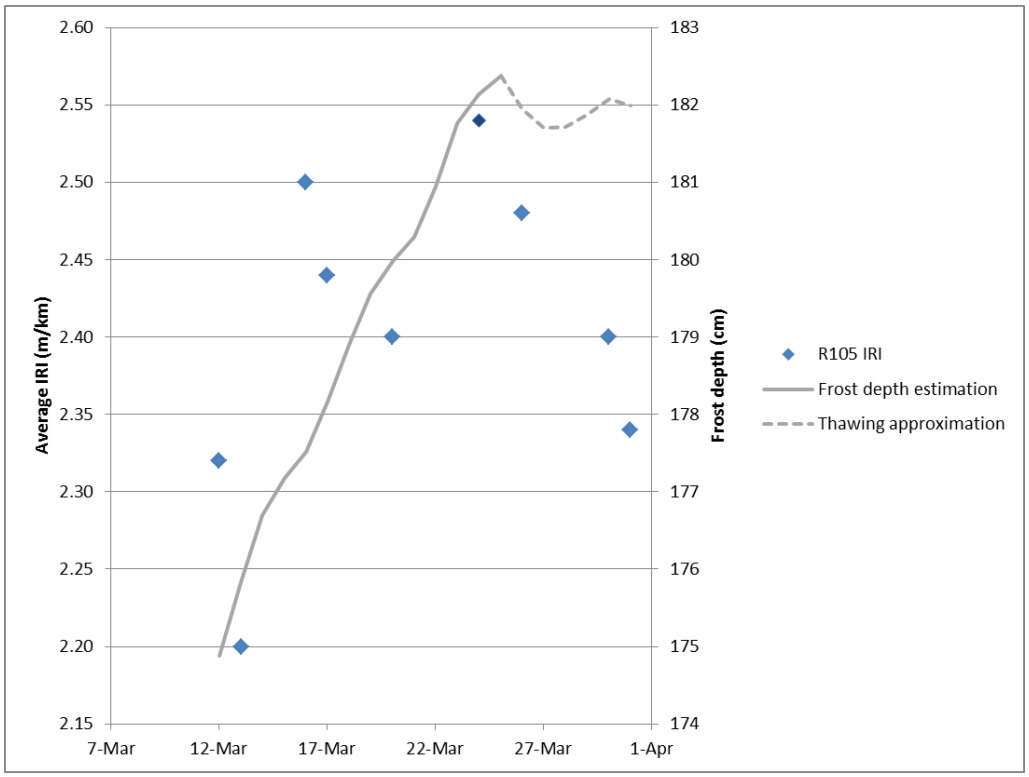

Figure 3 Average IRI values and frost depth estimations at R105

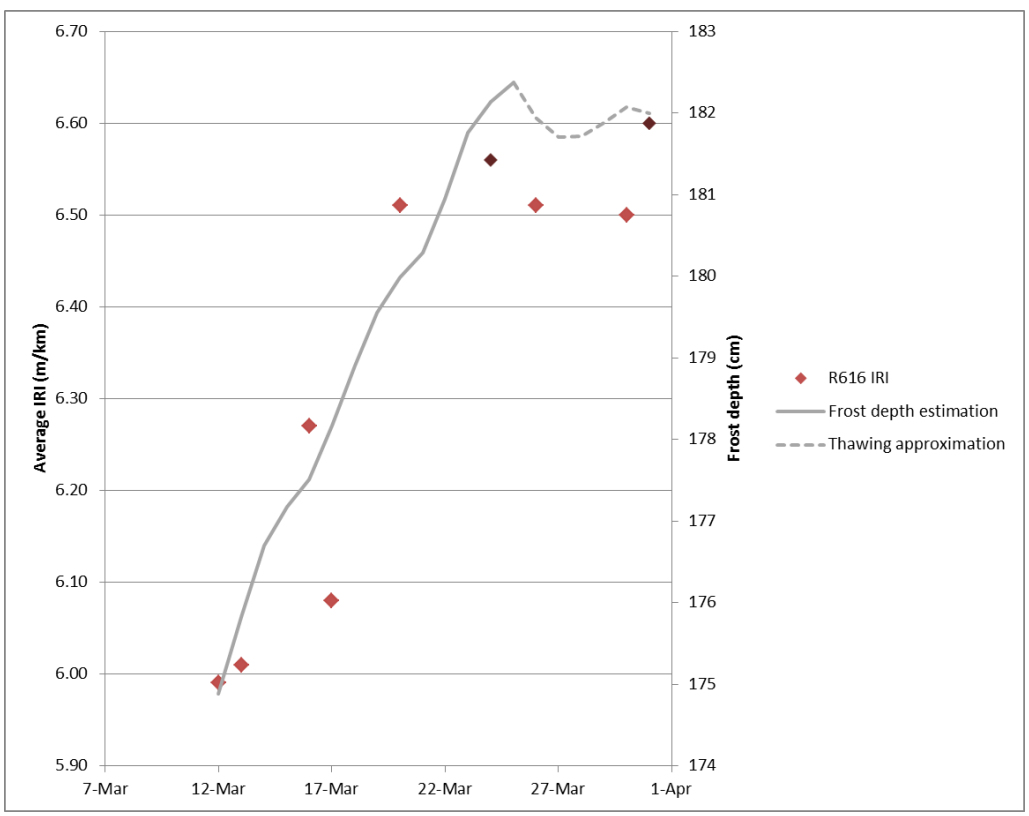

Figure 4 Average IRI values and frost depth estimations at R616