Longitude profiling as a tool for evaluation of frost action active pavement section

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ABSTRACT: In seasonal frost regions frost action is a major impact factor on pavement deterioration. Normally frost damage evaluation has been carried out by visual inspection in late spring in order to separate frost action related damages from other pavement damages. The drawback of this methodology is the labour cost, subjective judgement of damages by the personnel and work safety. This approach is not suited for monitoring the condition of on a road net level. Laser scanning has been used for decades as an efficient tool to monitor the rutting development on the road net. The monitoring technique requires a snow and ice free surface to get accurate results. Thus has the use of this technology been limited in the winter seasons. In a few regions longitude profiling measurements have been introduced during for quantify winter conditions. More development is needed in the field of evaluation and techniques to relate the measurements to frost related processes. In this study has data from longitude profiling in four monitoring lines in from summer and late spring been analysed for a number of road sections. Spatial data analysis has been applied to match the acquired measurements in between the monitoring directions along the road and the different seasons. The difference in roughness between the seasons has been used as a measure to identify and qualitative grade the amount of frost action. The methodology and its applicability as an objective frost damage classification tool are discussed.

1 INTRODUCTION

1.1 Frost action on pavements

In cold regions the seasonal frost and thaw cycle have a major impact on the road net. If the road is constructed upon on frost susceptible soil, has insufficient quality of the unbound materials or suffers from poor drainage its lifetime will be reduced due to frost action. During winter time ice lenses are formed causing frost heave. Typical frost heave damages are increased roughness of the pavement surface, pavement cracks, culvert and block heave. During the thawing season the excess water from the ice lenses in combination by insufficient drainage capacity decreases the bearing capacity and decreases the lifetime of the pavement. Other thaw related damages are settlements caused by thaw consolidation. (Andersland and Ladanyi 2004, Doré and Zubeck 2009, Fradette et al. 2005, Lundberg 2001)

Especially on the low-volume road net in e.g. the Nordic countries frost action is a major contributor to pavement distress. In the initial surveys prior to pavement rehabilitation actions one of the major concerns is to identify pavement damages caused by frost action. Frost mitigation actions are in general relatively expensive since the major options includes complete reconstructions, e.g. replacement of frost susceptible soil, superstructure material or frost insulation.

Commonly identification and classification of frost damages are performed by manual inspection. Man-
ual inspection is a proven methodology. Today it is often performed in combination with automatic documentation by e.g. photos and filming. But there are some limitations and drawbacks by manual inspection. The result is based on a subjective classification of the engineer in the field. The result will be dependent on the individuals experience and may also be influenced of the expectations on the outcome the later construction works, (Berglund 2010). Automatic classification has been tested to automatically classify pavement distress. The data was useful as a support for interpretation but insufficient for classification of pavement damages, (Johansson 2012).

1.2 Road profiling and winter monitoring

Road surface profiling is commonly used as quality control of pavement works and to monitor rutting development and distress propagation over time. The surveys are in most countries conducted during the thawed season, i.e. from late spring to autumn in the seasonal frozen regions. The collected data is stored in Pavement Management Systems for further analysis and use. One of the most common measures used in the evaluation of the pavements is the International Roughness Index (IRI). The IRI-measure was developed by the World Bank in 1982 and was established in 1986 as quality measure aimed to describe road quality in mainly undeveloped countries, (Sayers et al. 1986). The IRI measure is defined as:

\[
IRI = \frac{1}{L} \sum_{i=1}^{n} |Z_s - Z_u|
\]  

(1)

where;

\( Z_s \) position of sprung mass,

\( Z_u \) position of the vehicle frame axle,

\( L \) length of the profile, and

\( n \) number of points in the longitudinal profile.

The IRI is the summation of relative vertical displacement over a given distance, commonly expressed in e.g. [mm/m].

Surface winter profiling is conducted during the frozen season when the pavement suffers from frost action. If laser scanning is used for profiling the pavement surface needs to be free from ice and snow. This is usually the case just prior the start of the thaw weakening season. If the results from the winter profiling is compared by the results from the unfrozen season the relative effect of heave or consolidation may be identified.

Winter profiling has mainly been tested and analysed in Canada, but minor studies has also been conducted in other countries e.g. Sweden, (Lundberg 2001). (Fradette et al. 2005) studied the winter roughness and concluded that the IRI increased substantially for the analysed road sections. It was possible to correlate distress to pavements sections of high IRI. By comparing smoothed the data to unfiltered data it seemed possible to estimate the relative importance of the frost action mechanisms. In (Bilodeau and Doré 2013) winter roughness (IRI) is related to the subgrade soils variability and is implemented as a part of a design model for serviceability of roads in Quebec, Canada.

1.3 Aim and goal of the study

In this study a comparison of roughness measurements from unfrozen and frozen conditions of 10 roads been studied. The objectives of the study are to a) compare the interpretation of roughness classification of manual inspection with IRI, b) evaluate the use different measures of IRI and their use, c) evaluate the use of the use of a 2-laser system for road profiling.

2 METHODOLOGY

2.1 Road surveys

Ten road sections was selected for the study. The roads were in different phases in their life cycle. The roads was new constructed, reconstructed, subjected to pavement overlay or under evaluation ahead of evaluation actions. The list of analysed road sections are summarised in table 2.1. The surveys comprised summer and winter profiling and visual inspection in the early thaw season.

2.2 Data collection

The data collection has been carried out in the season 2015/2016. During summer conditions road profiling was conducted by a standard road profiler with 17 lasers according to the monitoring requirements of the Swedish Transport Administration, (STA 1997). The monitoring was done by three passages in both directions of the road. Two of the monitoring lines in each direction has been evaluated representing the inner and outer wheel path in both directions. Winter roughness was evaluated by using a portable 2-laser profilometer during the beginning of the thawing season. The profilometer system consists of the same laser types as the standard road profiler and fulfils the same requirements of accuracy as the the full system. Two monitoring lines in each direction has been evaluated independently of the number of lasers used. The data was postprocessed to IRI [mm/m] at a sample interval of 0.1 m in the longitudinal direction for each monitoring line. The accuracy requirements in the survey are 0.08 % deviation based on three 400 m monitoring lines.
Table 1: Road sections included in the study. All objects are situated in the northern part of Sweden

<table>
<thead>
<tr>
<th>Object</th>
<th>Length [m]</th>
<th>Type of object</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6700</td>
<td>New construction</td>
</tr>
<tr>
<td>2</td>
<td>11000</td>
<td>Reconstruction</td>
</tr>
<tr>
<td>3</td>
<td>10200</td>
<td>Reconstruction</td>
</tr>
<tr>
<td>4</td>
<td>10300</td>
<td>Maintenance</td>
</tr>
<tr>
<td>5</td>
<td>8000</td>
<td>Maintenance</td>
</tr>
<tr>
<td>6</td>
<td>17000</td>
<td>Maintenance</td>
</tr>
<tr>
<td>7</td>
<td>99,14900</td>
<td>Maintenance</td>
</tr>
<tr>
<td>8</td>
<td>3200</td>
<td>Maintenance</td>
</tr>
<tr>
<td>9</td>
<td>17700</td>
<td>Maintenance</td>
</tr>
<tr>
<td>10</td>
<td>16700</td>
<td>Evaluation</td>
</tr>
</tbody>
</table>

An ocular inspection was conducted during the early thawing season in 2015 according to the Swedish Transportation Administration guidelines (STA 2013). In the ocular inspection frost related damages was identified, classified and documented. A correlation of the frost related damages were conducted.

2.3 Analysis of data

The data has been analysed on basis of 0.1 sampling interval and precomputed IRI-values by the Scientific Python distribution Anaconda in Python 3.5.

The data for each road sections provided for this study consists of four files; summer IRI in positive longitudinal direction, summer IRI in negative longitudinal direction winter IRI in positive longitudinal direction and winter IRI in negative longitudinal direction. In the data management process prior analysis the data was merged and adapted to a common chainage.

Different concepts were tested to merge the data into a common chainage; linear matching by sparsing and cross correlation fit.

Linear matching was applied as follows. The dataset of the shortest chainage was chosen as baseline. The other three remaining datasets where linearly sparsed by removing the excess length by uniformly over the length remove singular data points. The error generated by this process was evaluated by studying the effect of sparing the data-sets. A 6 km length of the dataset was chosen. Sparsing was applied on this dataset in steps of 50 m down to 5 km. The IRI data was compared for 5 km in each step by comparing the original IRI values by the sparsed. Three measures was used to quantify the effect of sparsing compared to the original dataset; the Euclidian distance, the Pearson correlation and the difference in percent.

The cross correlation was done by using the central monitoring lines in positive and negative direction by first match the summer and winter data separately and then finally match summer and winter data into the final analysis data set. The cross correlation of each data begun with ocular inspection of common spikes an sequences occurring in both data sets to delimit sequences to use for cross correlation. The delimited sequence was analysed by cross correlation and the lag in distance between the datasets was identified. Finally the lag was adapted to adjust the datasets to match.

Different measures of IRI were computed and evaluated on basis of their use in evaluation. $\Delta IRI$, as a measure of differential frost heave, defined as:

$$\Delta IRI = IRI_w - IRI_s$$  \hspace{1cm} (2)

where;

$\Delta IRI$ Measure of differential frost heave [mm/m].

$IRI_w$ IRI from winter survey [mm/m].

$IRI_s$ IRI from winter survey [mm/m].

$|\Delta IRI|$ as an alternative to visualise the difference in frost heave, and the ratio between $IRI_w$ and $IRI_s$ defined as;

$$IRI_r = \frac{IRI_w}{IRI_s}$$ \hspace{1cm} (3)

To avoid division by 0 values of $IRI_s$ was set to 0.1.

2.4 Ocular inspection

The manual inspection was conducted according the Swedish Transportation guidelines, (STA 2013). The damages were documented by photos and filming. The roughness was evaluated at a speed of 30 km/h. The pavement distress are graded on scale of 1-5 based on criteria for cracks and roughness.

The roughness classification was compared by the results of the IRI-measurements.

3 RESULTS

3.1 Correlation of datasets

The analysis on the effect of sparing the data-sets showed that sparsing could be applied down to 0.2 % of the total length at a initial resolution of 0.1 m
in chainage. At 0.2% sparsing the Pearson correlation coefficient is about 0.5 which is a common limit in statistics for correlation. The analysis shows that the deviation between the original data set and the sparsed is less than 0.6%. A comparison of the effects of sparsing was conducted on rolling means and it had insignificant effect down to a rolling mean of 5 m. When comparing the effect on the measures $\Delta IRI$ and $|\Delta IRI|$ the error of $|\Delta IRI|$ is lower.

The procedure of using autocorrelation by matching the roughness resulted in unique matches for all data sets in the study. An example of matching result is shown in figure 1. The upper two plots in the figure shows the correlated monitoring lines and the bottom plot the Pearson correlation of the data sets. As expected the Pearson correlation coefficient is relatively low, about 0.5 in all data sets included in this study, since roughness is different between frozen and unfrozen conditions. The distribution of the Pearson coefficient shows in all analysis that there is an unique matching correlation.

The distribution of the collected IRI, computed $|\Delta IRI|$ and $IRI_r$ is right skewed as expected. The distribution of $\Delta IRI$ is uniformly distributed. The basic summary statistics presented in table 2 for the used IRI-data, $|\Delta IRI|$, and $IRI_r$. The summary of IRI and shows that in general the mean and standard deviation are almost equal indicating that most observation is in the range from 0 to two times the standard deviation. The range between the 75% percentile shows that there are extreme outliers. For $IRI_r$ it can be observed that for all objects the set maximum level is reached. An interesting observation is that for object 10, where the other measures indicates that the pavement is in poorest condition of all objects the summary of $IRI_r$ indicates the opposite.

4 ANALYSIS

4.1 Winter roughness measures

$\Delta IRI$ and $|\Delta IRI|$ are basically the same measure. But $|\Delta IRI|$ has the same type of distribution as the original IRI data and quantifies the relative winter roughness of the pavement. It is thus easier to compare the results if $|\Delta IRI|$ with the original readings. $\Delta IRI$ has the advantage in defining either the change in roughness is either heave or depression. Since it both can be positive and negative the mean of $\Delta IRI$ may be misleading. $IRI_r$ is efficient in displaying differences between summer and winter conditions. Since individual readings from both summer and winter monitoring may be 0 computational means to avoid infinity or extremely large ratios. It could thus be discussed if summary statistics are meaningful. The results in table 2 of object 10 shows that despite high IRI the $IRI_r$ still may be low if the roughness in summer conditions is high.

The three different computed measures of winter measures for a pavement section is compared, figure 2 at a rolling mean of 5 m. As seen the $IRI$, is the most sensitive measure. $IRI_r$ and $|\Delta IRI|$ provides similar information but at different y-scales. $\Delta IRI$ also displays the relative heave is positive or negative.

4.2 Comparison of IRI-based results and ocular inspection

An comparison of the roughness distress from the ocular inspection and the $|\Delta IRI|$ is shown in figure 3. The induced roughness is classified by a scale from 0-5. In the figure the the highest class 3 represents an estimated differential heave up to 30 mm. As seen in the figure an extraction of the highest registered IRI-measures shows a high correlation with the classified roughness.

4.3 Effect of resolution for interpretation of winter roughness

Rolling means is commonly used to collapse large datasets to enhance the interpretation in the graphs and is commonly used in Pavement Management systems. An analysis was conducted to compare the effect of applying different rolling means on the data sets. In figure 4 rolling mean of 5 m, 10, m and 20 m are compared with the original resolution of 0.1 m of the data. The measure used in the plot is $|\Delta IRI|$. In the figure is the 80% percentile of the original data indicated as a dashed line and the mean value as a solid line. The 80% percentile indicates the limit of the correlation of winter roughness is found from the ocular inspection. As seen, all the investigated identifies the clusters of spikes in the data sets. But above the rolling mean of 5 m the risk of missing increased roughness is obvious since frost action related damages usually are local.

5 DISCUSSION

A matching procedure for the different profiling measurements are necessary to perform since the profiling is done separately in both directions and at different occasions. In this study the positioning of the measurements relies on trip distance. The method used, sparsing and autocorrelation could be applied without changing the overall interpretation of winter roughness. But in order to exact positions of e.g. block heave or heave in drums a more accurate methodology is recommended. Ideally coordinate positioning would be preferable, but to start the match by use of the road profile data would increase the accuracy.

Both the measures $\Delta IRI$ and $|\Delta IRI|$ are displaying differential frost heave. To be accurate the matching of the summer and winter data should be as accurate as possible. The analysis shows that the $|\Delta IRI|$ is slightly less sensitive for mismatch and thus preferable. $IRI_r$ is more sensitive for variations than the
Figure 1: The final result of matching the IRI data by autocorrelation. The two upper plots shows the correlated data from the outer wheel path in positive chainage direction. The example shows chainage 0-1000 m for road object number 1.

Table 2: A selection of summary statistics of IRI and $|\Delta IRI|$ for the pavement sections in the study.

| Number | IRI [mm/m] | $|\Delta IRI|$ [mm/m] | $IRI_r$ [-] |
|--------|------------|-----------------------|-------------|
| Mean   | Std        | 75%-perc. | Max | Mean | Std | 75%-perc. | Max | Mean | Std | 75%-perc. | Max |
| 1 | 0.79 | 0.84 | 1.06 | 29.0 | 0.82 | 0.8 | 1.15 | 29.5 | 3.1 | 7.2 | 2.4 | 50 |
| 2 | 0.78 | 0.75 | 1.1 | 35.8 | 0.82 | 0.78 | 1.18 | 19.1 | 2.9 | 6.9 | 2.3 | 50 |
| 3 | 0.75 | 0.71 | 1.0 | 16.7 | 0.98 | 0.91 | 1.4 | 17.6 | 3.7 | 7.4 | 6.7 | 50 |
| 4 | 0.78 | 0.69 | 1.3 | 16.4 | 0.89 | 0.91 | 1.4 | 24.2 | 2.9 | 6.8 | 2.2 | 50 |
| 5 | 0.86 | 0.69 | 1.3 | 17.3 | 0.89 | 0.77 | 1.3 | 16.9 | 3.1 | 7.1 | 2.4 | 50 |
| 6 | 0.81 | 0.77 | 1.2 | 40.7 | 1.0 | 1.3 | 1.4 | 40.4 | 2.6 | 6.5 | 1.9 | 50 |
| 7 | 1.45 | 1.49 | 2.1 | 35 | 1.7 | 1.8 | 2.4 | 47.0 | 2.9 | 7.0 | 2.2 | 50 |
| 8 | 0.98 | 0.81 | 1.4 | 13.9 | 1.2 | 1.2 | 1.7 | 14.0 | 1.5 | 2.7 | 2.0 | 50 |
| 9 | 1.5 | 1.4 | 2.0 | 29.4 | 1.6 | 1.7 | 2.3 | 50.0 | 3.0 | 7.2 | 2.3 | 50 |
| 10 | 2.9 | 14.5 | 4.3 | 49.9 | 2.3 | 10 | 5.0 | 49.8 | 1.5 | 0.8 | 1.7 | 50 |
Figure 2: Comparison of the winter roughness measures $\Delta IRI$, $|\Delta IRI|$ and $IRI_r$. The plot shows chainage 1-1000 m of road object 1 at a rolling mean of 5 m.

Figure 3: Comparison of winter roughness and inspection classification of frost related roughness of a road object 10.
other measures but may be misleading if e.g. the road is rough in unfrozen conditions.

The comparison between the manual inspection and classification of frost related roughness indicates that it is the spikes of the IRI-data correlates well for roughness. The classification is subjective as pointed out in (Berglund 2010, Johansson 2012). In this study the manual inspection has been performed by the same person to reduce the variation in classification. The strong correlation was found by filtering out sections where the IRI-values exceeded the 80 %-percentile. An approach based on only the percentiles of the data is problematic to generalise since it is dependent on the overall condition of the road. The correlation of roughness in this study was better compared to (Johansson 2012) where $IRI_r$ was used. The approach of studying wavelength for correlation by different types of sources of distress as done in (Fradette et al. 2005) is preferable but for identification of winter roughness and as support for visual inspection IRI measures are useful.

An interesting observation by comparing the two methods is that in general the location or boarders of the classified damages are systematically registered slightly earlier in the manual inspection independently of the direction of the monitoring vehicle. This may be an effect of that during an manual inspection the damage is registered when it is observed and surface profiler register the roughness when it passes over it.

Figure 4: The effect aggregating winter roughness data by rolling mean in comparison by the input data. The solid line indicates the mean roughness and the dashed line the 80 % percentile of the initial data of the whole road section. The example shows the outer wheel path of chainage 0-1000 m for object 1.

Using a two line profilometer was efficient and cost effective. The short period during the thaw season when profiling in frozen conditions is difficult to cover in an efficient way by the standard profilers, especially in remote areas. A limitation of the road profiling is that only distress in the monitoring lines may be identified and classified. By adding more lasers to the vehicle more distress will be registered but at this stage an ocular inspection will still be needed. It is not obvious that more monitoring lines will add substantial more information to the visual inspection.

Applying rolling mean on the IRI data to collapse it to sections reduces the information in the spikes of the data. The comparison of the IRI results with the ocular inspection results showed that the classified roughness may shift in short distances and that it was convenient to correlate the data by the 80 %-percentile or higher. Applying rolling means for distress classification may be useful if the rolling mean is short, here 5 m, or to define a quality measure. If it is used as a quality measure it probably needs to be combined with other requirements in order to avoid short distance roughness that does not influence the rolling mean enough, e.g. a defined maximum value or variance.

6 CONCLUSION

Based on the rough profiling results compared by the outcome of the ocular inspection results both methods
has strengths and drawbacks. The main advantages by road profiling is that it is an objective measure. It is independent of external factors such as weather condition and the observance of the engineer. It is also time-effective which makes it possible to perform a range of inventories and makes it possible to study the variation of the roughness during the winter and thawing season. The methodology also has some identified drawbacks. It is not able to identify damages outside the monitoring lines in this study the wheel paths. It is not able to detect cracks. If IRI is used as a measure there is a risk to misinterpret damages such as depressions and insufficient bearing capacity.

The advantages of the ocular inspection compared to the road profiling is the accuracy in classification of the pavement damage and if it is related to frost action. It captures damages on the whole road surface, not only in the wheel paths. The drawbacks are related to the human factor, e.g. the experience, fatigue over the day (tired), the influence of the weather in viability of damages, the speed and comfort of the vehicle.

Some of the drawbacks with the use of road profiling for frost damage inspection could be addressed by increasing the number of lasers on the monitoring vehicle and analysis of other measures than IRI, e.g. wavelength.

The investigated IRI based measures to describe winter roughness all have advantages and disadvantages. $\Delta IRI$ at high resolution captures the relative displacement of the surface in both heave and depression. But at low spatial resolution depressions and heave may be underestimated. $|\Delta IRI|$ shows the differential heave and is more robust to statistical errors and does not underestimate heave at lower spatial resolution. $IRI_r$ is sensitive to relative changes between summer and winter conditions. A drawback of this measure is that at if roughness is high in summer time the winter roughness is not captured. The recommendation is to evaluate more than one measure to interpret winter roughness in combination with the IRI-data.

REFERENCES


