Case Study: Developing a Surface Condition Indicator from Laser Crack Measuring System Data for Pavement Asset Management

Authored by:

Aziz Salifu, M.Sc., P. Eng.,
Sr. Materials Standards Engineer
Saskatchewan Ministry of Highways and Transportation

Nichole Andre, P. Eng.,
Sr. Asset Management Engineer – Roads
Saskatchewan Ministry of Highways and Transportation

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Abstract

The Saskatchewan Ministry of Highways and Infrastructure (SMHI) adopted Laser Crack Measuring System (LCMS) technology for collecting road condition data in 2016. LCMS data has replaced a visual assessment method for identifying cracking and other surface distresses. This paper discusses the methodology used to determine type, severity, extent and aggregation of LCMS distress data. To better analyze the data, SMHI developed the Surface Condition Indicator (SCI) to support asset management decision making for setting performance measures, optimize budgets, and identify pavement preservation candidates.

The paper covers:

- The use of LCMS generated crack maps and a Bayesian sorting methodology to develop severity ranges for pavement distresses.
- The methodology used to identify the type and severity of LCMS measured distresses that map to treatment triggers for rejuvenating fog seals (CRF™ and Reclamite™), graded aggregate seal coat, chip seal, fiber-reinforced chip seal, microsurfacing rut fill with a seal coat cape, and functional repaving.
- The methodology for setting the SCI threshold values (Good to Fair and Fair to Poor).
- The development of SCI formulas for Asphalt Concrete and Granular Pavements.
- The process of calibrating SCI values with field observations and "blind" testing the SCI numbers in the field to confirm results for the SCI metric.
- The benefits of adopting the SCI for finding good pavement preservation candidates and ruling out locations that are too late for fog or seal coat treatments.
- The benefits of adopting the SCI for setting performance measures and communicating trade-offs in investing for pavement preservation projects.

SMHI's SCI values range from 0 through 100+ in a progression that reflects the amount and severity of pickouts and cracking that develops as pavements age. SCI60 values are categorized as good, fair or poor. Pavement segments with fair SCI60 are light treatment preservation candidates. Pavement segments in the poor category are too late for a light preservation treatment. SCI60 values over 45 require a heavy preservation treatment.

Laser Crack Measuring System (LCMS) Data Standards

The Saskatchewan Ministry of Highways and Infrastructure's (SMHI) adoption of the Laser Crack Measuring System (LCMS) technology started with a trial in 2014. It became clear that the accuracy, repeatability and automated collection method had significant advantages over manual windshield surveys. LCMS data standards were developed and a contract for road condition data collection was secured for three seasons beginning in 2016.

As part of a network-wide data collection initiative, 17,000 lane kilometers of pavements were surveyed initially. Saskatchewan has two types of pavements: granular pavements, which are constructed with a double seal coat over unbound layers of base and subbase, and asphalt concrete pavements, which have an asphalt concrete cement surfacing layer. Figure 1 illustrates the asphalt concrete and granular pavements surveyed in red and blue respectively. Table 1 summarizes the LCMS reported distresses.

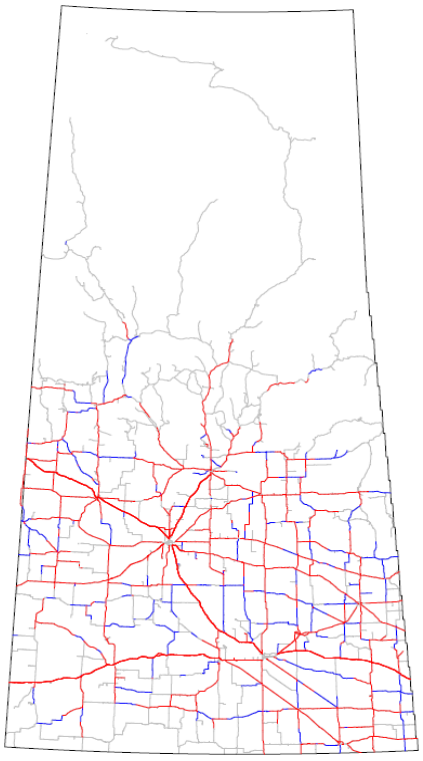

Figure 1: SMHI AC and Granular Pavements

Table 1: LCMS Reported Distresses

LCMS Measured Distress	Severity	Length	Area	Count	Wheel Path
Transverse Cracks	X	X		X	
Meandering Cracks	X	X	X		
Block Cracking	X		X		X
Pick Outs	X		X		X
Raveling (ARI)	X		X		X
Bleeding			X		X
Macrotexture (sand patch)	X		X		
Centerline Cracking	X	X	X		
Shoulder line Cracking	X	X	X		
Shoving	X			X	X
Potholes & Delamination	X			X	
Water Traps		X		X	X
Sealed Cracks		X			
Bumps & Dips (5m IRI)	X			X	
Wheel Path IRI : Average, Max, Min, Standard Deviation					
Wheel Path Rutting : Average Depth, Max Depth, Min Depth, Depth Standard Deviation, Cross Section Area, Volume, Rut Type (multiple wheel, shallow, deep)					

The LCMS data delivery includes crack map images as well as 129 unique distress measurements. The high definition LCMS crack map images span 10 m sections of road and allow the user to see where the distresses are located. Distress measurements are reported for 50 m long survey intervals, which include transverse, meandering, longitudinal, centerline, edge and block cracking. Surface defects including macro-texture, ravelling, pick outs, bleeding, shoving, delamination and potholes are also included in the LCMS data.

Cracks are reported by type, severity and location. Cracks are located between the wheel paths, in the wheel paths, along the shoulder, and at the centerline. As seen in Figure 2, crack maps are color coded by crack width.

The block crack density determines severity of block and fatigue cracking. Block Crack density is a measurement of how tight or concentrated the cracks are over the area covered. Crack severity is summarized in Table 2.

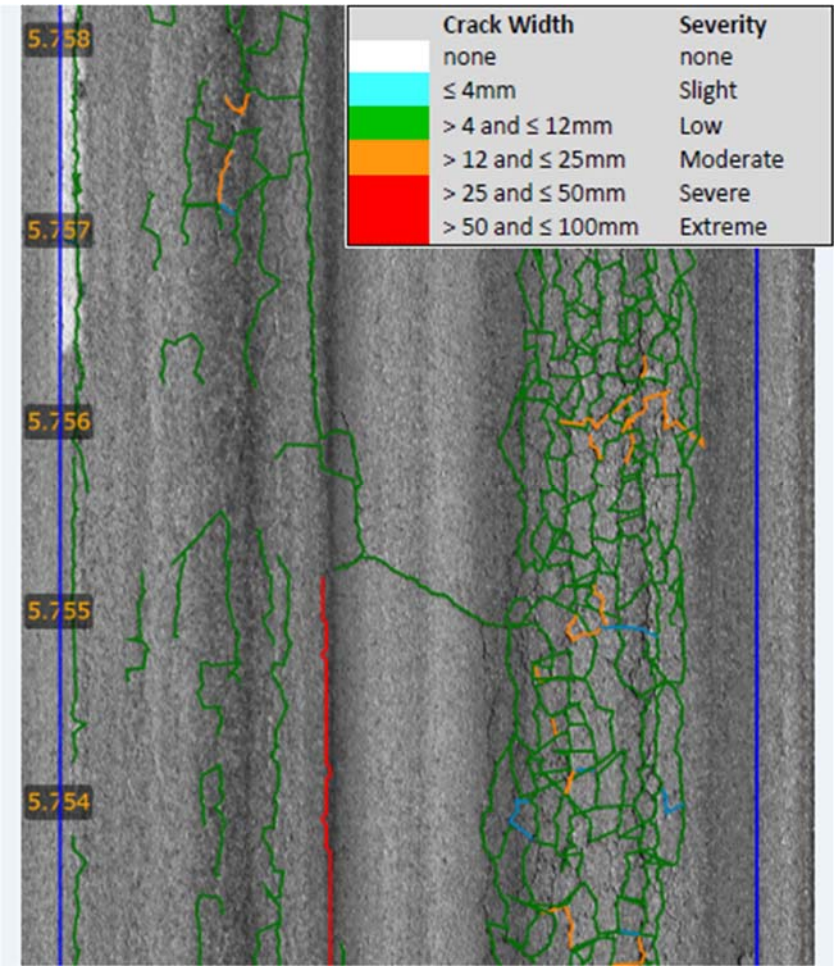

Figure 2: LCMS Crack Map

Table 2: Crack Severity Classification

Single Crack Severity	Width (mm)	Block Crack Severity	Crack Density (m/m^2)
Slight	≤ 4	Multi	<0.9
Low	>4 ≤ 12	Block	≥0.9 and <1.8
Moderate	>12 ≤ 25	Fatigue	≥1.8
Severe	>25 ≤ 50		

Developing SMHI's Surface Condition Index (SCI) Value

The key components to an effective asset management program for pavements are applying a pavement preservation treatment at the right time, on the right project, with quality materials and construction. Like all provincial agencies, the seal coat program for Saskatchewan provincial highways has limited funding. Treating a pavement too soon can lead to a missed opportunity for optimizing dollars spent by treating in a more suitable location. Treating too late means the full benefit of the treatment is lost. Missing the optimum treatment window can result in:

- A shorter pavement life span;
- Higher maintenance costs;
- Reduced level of service for road users, and
- An earlier demand for expensive rehabilitation.

SMHI developed the Surface Condition Indicator (SCI) values to support asset management decision making for setting performance measures, optimizing budgets, and identifying pavement preservation candidates. The goal in developing the SCI was to utilize the LCMS data to optimize light preservation treatments across the province's road network.

As a starting point for the SCI's development, SMHI's asset managers developed approximate SCI values for predicting treatments. Table 3 lists the predicted SCI values that incorporate treatment timing windows for rejuvenator fog coats, seal coating and functional repaving.

The presence of stone pick outs and slight cracking trigger rejuvenator fog coats. Seal coats are triggered as cracking severity becomes low to moderate. Fiber reinforced seal coats are triggered from more extensive low and moderate severity cracking. Functional repaving is triggered when the block and fatigue cracking is extensive. A sliding scale with trigger points for different types of treatments created a framework for the LCMS data.

Table 3: Predicted Treatment Timing Framework for SCI Development

Pavement Condition	SCI Value	Treatment Window	Performance
Perfect condition	0	Do nothing	**GOOD**
Pickouts and slight cracking	~10	Rejuvenator fog seal	**FAIR**
Low to moderate cracking	~15	Seal coat	
Moderate and severe cracking	~25	Too late to seal – Do nothing	**POOR**
Block and fatigue cracking	~50	Ready for repaving	
Fatigue cracking and potholes	~75	High risk of failures	

The development process for SCI followed a typical Bayesian modelling approach which is described in the steps below and illustrated in Figure 3.

Step 1: Develop a model using parameters from expert knowledge (LCMS Crack Maps & the Goldilocks Principle).
Step 2: Condition the model given expert observations (Distress Correlation & Weighting).
Step 3: Evaluate fit of the model to the full data set (Field Reviews, Performance Models, Project Selection).
Step 4: Alter or expand the model (Rejuvenator Fog Seals & Pavement Types).

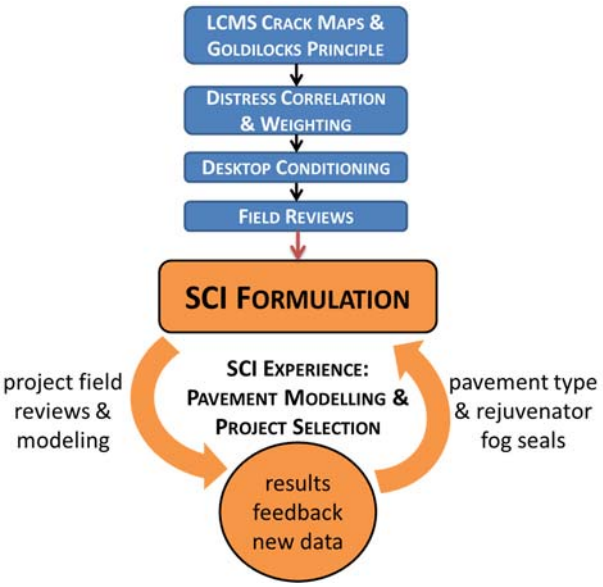

Figure 3: SCI Development Process

Adjusting the SCI model based on feedback was an iterative process. Cycles of adjusting the formulas in the SCI model were followed by applying the changes to the LCMS data across the network. The results obtained was validated through desktop analysis as well as field pavement conditions assessments. Figure 4 is a conceptual illustration of how the distribution of data changes through a Bayesian model development process.

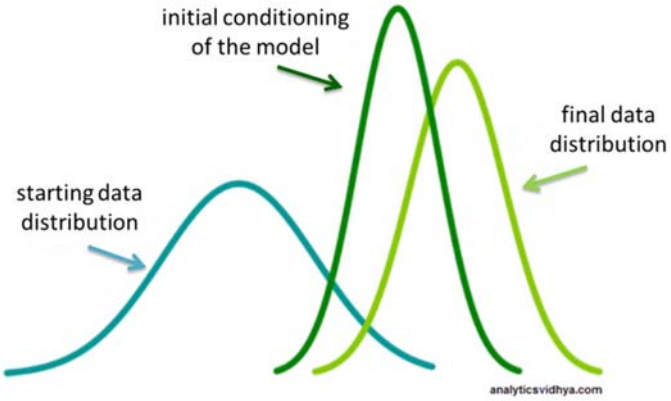

Figure 4: How the SCI Data Distribution Evolved During Bayesian Model Development

LCMS Crack Maps & the Goldilocks Principle

To create the SCI value, it was necessary to match the LCMS data to expert knowledge about pavement distresses and the right timing for seal coat treatments. A sampling technique to collect expert knowledge was an important aspect of determining crack types and evaluating crack severity. The crack types and crack severity data gathered though expert sampling were used for setting the thresholds for seal coat application. Our Subject Matter Experts (SMEs) are responsible for selecting and programing

preservation projects and included a team of materials engineers, preservation planners, and project engineers. Twelve SMEs were invited into a room to sort through LCMS crack map images using the Goldilocks Principle as shown in Figure 5. The engineers looked at the crack maps and had to categorize the crack maps into one of five bins, deciding if it was too early to seal, too late, just right, or if fibre reinforced seal or repaving was better suited.

Options:

None
0- Too Early To Seal
1- Just Right to Seal
2- Fiber Reinforced Seal
3- Too Late to Seal
4- Repave

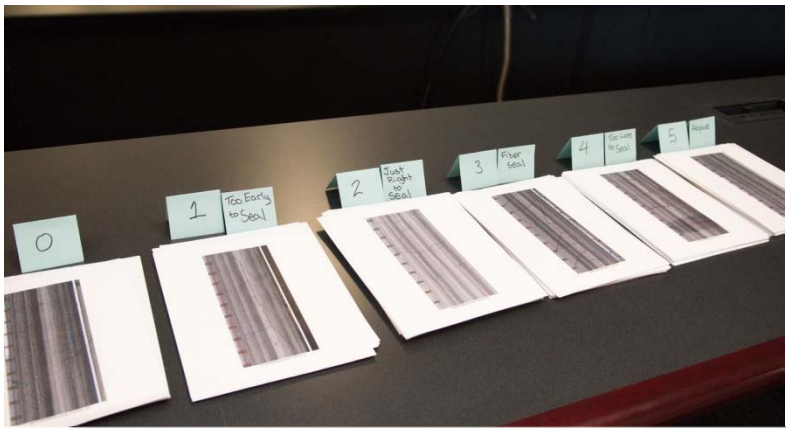

Figure 5: Sorted Crack Maps

Distress Correlation & Weighting

The sorted crack map images provided treatment recommendations for each image. Many of the images appeared in more than one pile and in this case we worked with the distribution of answers for each image. Correlation analysis was completed for distress measurements for each crack map and the recommended treatment. The next step was to apply the results of the correlation analysis to the data. Correlation of the severity, type of cracking and location (in or between the wheel paths) was checked. Table 4 is an example of some of the correlation results.

Table 4 is a comparison between the density and length of the wheel path block cracking within the block crack area. A clear trend can be seen in the median values as the treatment recommendation progresses from too early to seal through to repaving.

Table 4: Correlation of Block Cracking to SME Crack Map Treatment Recommendations

			Wheel Path Block Crack Density					Wheel Path Block Crack Length				
Bin#	Bin	image count	min	max	median	avg	std dev	min	max	median	avg	std dev
0	none	0										
1	too early to seal	2	0	0.10		0.05	0.07	0	1.06		0.53	0.75
2	seal	8	0	1.27	0.00	0.24	0.44	0	37.03	0.00	6.90	12.90
3	fiber seal	5	0	2.08	0.20	0.61	0.86	0	44.50	1.99	12.82	18.74
4	too late to seal	5	0	1.53	0.44	0.54	0.61	0	20.59	7.32	9.73	9.57
5	repave	5	0	2.19	1.89	1.41	0.85	0	47.18	46.92	35.82	20.38

Formulas used by the Ministry of Ontario (MTO) and New South Wales were referenced. Both of these agencies had generously shared drafted versions of their LCMS data collection and processing standards. The cracking index created by these agencies separated single, multiple, and fatigue cracking values from each other. This separation made it possible to apply different weights to the three categories of cracks. A second layer was then added within each category to add a weight according to the severity of the cracks. Fatigue or alligator cracking receives a higher weighting if located in the wheel paths.

The first version of the formulas for the SCI model was created by using results from the correlation along with similar weighting factors from the MTO Cracking Index formulas. The components of the model included:

- Single Cracks: transverse, longitudinal, meandering, centerline, edge, and multiple cracks where the block crack distress density was less than 0.9.
- Block Cracking: Block cracking and fatigue cracking.
- Pickouts: single and multiple pickouts.

Desktop Conditioning and Field Validation

Conditioning of the SCI model began by applying the formulas to LCMS data for the entire network of pavements and checking to see if the results made sense. Spot sampling of locations across the range of SCI values involved checking the LCMS crack map images. In the case of SCI values that fell in the range of values suitable for rejuvenator fog seals, it was only possible to identify pickouts with the LCMS images.

Joint cracking on the center and shoulder lines as well as edge cracking created a concern. A pavement with only moderate or severe joint or edge cracking, but no other distresses, was enough to generate an SCI value that categorized the pavement as “just right” to seal. Therefore, cracking in the centerline and shoulder edge bands were dropped from the single cracks formula.

The SCI formula was now ready for field validation. The team of SMEs who had completed the goldilocks sorting were invited to spend a day looking at sites in the field. The engineers spent a December day driving a route with prepared stop points to review pavement condition. The SME’s collectively decided on what the most suitable treatment at each stop point was. The engineers justified their reasoning based on the type and severity of cracking, pickouts, texture, ravelling and bleeding. Did the SCI value make sense? Why or why not? The SMEs made detailed notes of the type and severity of cracking to support their feedback.

Adjusting and Editing the SCI Model – AC Pavement vs Granular Pavements

The processed segment level SCI data was used in performance prediction models for generating benefit cost data for the application of preservation treatments. The output data from the prediction models were used in desktop analysis as part of preservation candidates’ selection.

The pickout component, specifically for asphalt concrete pavement, of the SCI formula still needed to be adjusted. A range of pickout densities was looked at in order to adjust the trigger points for rejuvenator seal coats and chip or graded aggregates seal coats. Asphalt concrete pavements with high pickout densities would be seal coat candidates while moderate pickout densities would be rejuvenator fog seal candidates.

The formula was expanded to include a cap on the amount of pickouts that could be included in the formula. This allowed cracking to be the dominant distress when generating the SCI value for surfaces with both cracking and pickouts. The cap on the amount of pickouts also ensures that segments that have only pickouts do not generate high SCI values that require heavy preservation treatment to fix. The effects of pickouts on the final SCI values were different for AC pavements compared to granular pavements because AC pavements are more prone to pickouts.

Saskatchewan's granular pavements are built with a double seal coat as the surfacing layer. An investigation to better represent deterioration and treatment timing for granular pavements included looking for correlation in the LCMS data for bleeding, texture, shoving, and cracking. Cracks on granular pavements are missed by the LCMS because of cracks healing during the summer months when data collection occurs. Asphalt pavement cracks are more visible compared to cracks on granular pavements. Filtering settings can be adjusted on the LCMS system to increase its sensitivity to crack detection; however, this causes a higher frequency of false detection for cracking. Other pavement surface conditions which have been wrongly detected as cracking when the filtering is adjusted on the LCMS include edges of spot seals, snow plow damage, and tears in the seal coat.

While reviewing macrotecture, specifically for the granular pavements, it was discovered that the LCMS crack detection was filtering out a lot of the severe fatigue cracking when the width of the cracks was below 4 mm. This is attributed to additional filtering that happens on highly textured pavements surfaces. The values for block cracking where bleeding was evident on the section of road were found to be acceptable, but where there was no evidence of bleeding, the crack detection system was unable to differentiate between a crack and the texture of the surface.

It was determined that the SCI formulas would require a different set of weighting factors for asphalt concrete and granular pavements. Reasons for this are outlined below.

- LCMS reports lower volumes of slight cracking on granular pavements. The texture of granular pavements disrupts detection of fine cracks by the LCMS system. Filtering parameters can be adjusted to include fine cracks; however, it would also bring in much higher volumes of false cracking.
- Cracking on granular pavements manifests differently as the pavement ages. Single cracks appear between the wheel paths as the seal coat surface structure moves while it is subjected to loading, which is the opposite for AC pavements, where cracks first appear in the wheel paths.
- Transverse cracking is more prevalent for AC pavements.
- Pickouts are more prevalent in AC pavements.

Implement SCI in the Model for Pavement Asset Management

In the first year, using the SCI in pavement modelling changed what and how cracking data was being used in the Ministry.

SMHI uses two types of pavement models. The first is a deterministic model which uses a benefit vs cost analysis and a pavement deterioration curve to identify the best locations for treatment projects. The second model is a Marchov probabilistic model, which looks at pavements on a network level and predicts needed funding over time for a desired set of performance targets. This requires knowing the probability of a pavement moving from a good to poor condition in a given year for the three primary distresses modeled; International Road Roughness (IRI), Rutting and SCI.

During implementation of the SCI, a Fair category was incorporated into the models. This was a significant improvement. The models could now predict the volume of poor roads that were too late for seal coating and in need of repaving. Previous models categorized all cracked roads together into the poor category. Now roads that were candidates for a seal coat treatment were separated into the fair category. This filled a gap in understanding network performance and the ability to optimize funding needs for roads where the level of fatigue cracking required repaving even though IRI and Rutting were good. During the second year of modelling two years of SCI data was available from surveys done in 2016 and 2017. This allowed us to confirm and adjust the SCI probabilities in the Marchov strategic level models and improve deterioration curves in the deterministic models.

The Marchov transition probability model is illustrated in Figure 6.

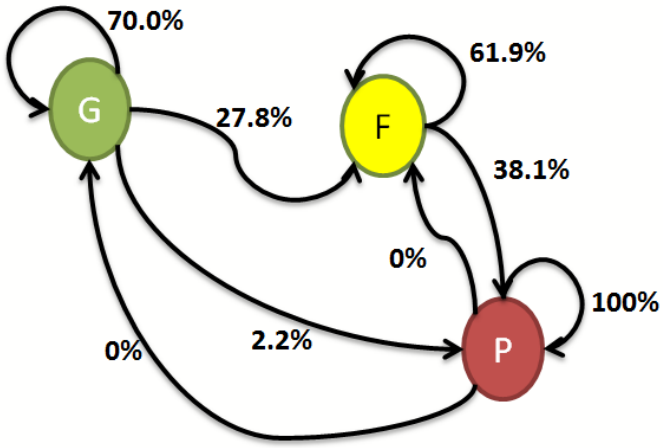

Figure 6: Marchov Probabilistic Model

Traditionally, the SMHI pavement rehabilitation program is driven by poor international roughness index (IRI) and rutting data as established in segments condition state scores. The approach of selecting pavement rehabilitation candidates based largely on IRI and rutting has resulted in severe block cracking or fatigue cracking pavement segments being omitted through desktop screening of pavement condition data for preservation treatments. Including the risk score into the segment level SCI scores enabled the selection of pavement segments that only exhibited poor SCI scores for pavement rehabilitation projects.

The final SCI categories are outlined below in Table 5. SCI values range from 0 through 100+ in a progression that reflects the amount and severity of pickouts and cracking that develops as pavements age. SCI60 is the 60th percentile value of the SCI of 50 meter sections within a segment of road. SCI60 values are categorized as good, fair or poor. Pavement segments with fair SCI60 are light treatment candidates. Pavement segments in the poor category are too late for a light treatment. SCI60 values over 45 require a heavy treatment.

Table 5: SCI60 Treatment Timing Windows

	SCI60	Treatment Candidate Window	Distresses Present
GOOD	0 to <9	good condition too early to treat	
FAIR	9 to < 22	9~13 rejuvenator fog seal	pickouts or slight cracking
		13~ 20 seal coat	low and moderate cracking
		18~22 fiber reinforced seal coat	moderate cracking
POOR	22 to 80+	22~35 too late to seal	moderate and severe cracking
		>45 repaving	block and fatigue cracking
		>80 at end of life	severe fatigue cracking

Finalized Formulas: SMHI's SCI Distress Calculation

SMHI's finalized formulas for SMHI's SCI distress calculations are outlined herein.

The finalize SCI formula has three components: pickouts, single cracking, and block cracking. The LCMS data for each 50 m section of road is analyzed for pickouts, single cracking and block cracking. Single and block cracking are added together and compare to the value calculated for pickouts. The larger value is the SCI for the 50m section of pavement.

$$SCI = \max (SCI_{pickouts}, SCI_{single} + SCI_{block})$$

Single Cracking Analysis (SCI_{single})

Single cracking includes longitudinal, meandering, transverse, and multi-cracks that are not tight enough to be classified as block cracking (crack density < 0.9 m/m^2).

Asphalt Concrete Pavement:

DMI_{single} = 0.8 × (Slight & Low Meandering+Longitudinal+Transverse Cracks Length (m))
+1.0 × (Moderate Meandering+Longitudinal+Transverse Cracks Length (m))
+1.2 × (Severe Meandering+Longitudinal+Transverse Cracks Length (m))
+1.8 × WheelPath Multi Cracking Length (m)
+1.0 x Between Wheel Path Multi Cracking Length (m)

Granular Pavement:

DMI_{single}= 1.8 × (Slight & Low Meandering+Longitudinal+Transverse Cracks Length (m))
+4.0 × (Moderate Meandering+Longitudinal+Transverse Cracks Length (m)
+4.4 × (Severe Meandering+Longitudinal+Transverse Cracks Length (m))
+2.8 × WheelPath Multi Cracking Length (m)
+2.0 x Between Wheel Path Multi Cracking Length (m)

$$\mathrm{SCI_{Single}} = 100 \times \left(\frac{DMI_{Single}}{3.2 \times \text{Survey Section Length (m)}}\right)$$

Block Cracking Analysis (SCI_{block})

DMI_{block}= 1.2 × WheelPath Block Cracking Area (m^2)
+1.2 x NonWheelPath Block Cracking Area (m^2)
+2.0 × WheelPath Fatigue Cracking Area (m^2)
+2.0 x NonWheelPath Fatigue Cracking Area (m^2)

$$\mathrm{SCI_{block}} = 100 \times \left(\frac{\mathrm{DMI_{block}}}{5 \times \text{Survey Section Length (m)}}\right)$$

Pickout Analysis ($SCI_{pickouts}$)

$$\text{Pickout Density} = \frac{\text{Single Pickout (count)} + \text{Mutipickout (count)}}{\text{Lane Width (m)} \times \text{Section Survey Length(m)}}$$

$SCI_{pickouts}$ = **9.0** x Pickout Density $^{\mathbf{0.1227495}}$

The above formula was derived by fitting a curve to known points.

Pickout Density		**SCI**
0	→	0
1	→	9
20	→	13

Observations and Conclusion

The Saskatchewan Ministry of Highways and Infrastructure (SMHI) adopted Laser Crack Measuring System (LCMS) technology for collecting road condition data in 2016. LCMS data has replaced a visual assessment method for identifying cracking and other surface distresses. To better analyze the data, SMHI developed the Surface Condition Indicator (SCI) values to support asset management decision making for setting performance measures, optimize budgets, and identify pavement preservation candidates.

SMHI's SCI is calculated by analysing and comparing the amount and severity of cracking and pickouts. Longitudinal, meandering, transverse, block and fatigue cracks are analysed. Weighting factors are applied to each type and severity of cracking. The concentration of pickouts is fitted to a curve to produce SCI values that match the treatment timing window for rejuvenator fog seals and seal coats. Pickout analysis is only completed for Asphalt Concrete (AC) pavements.

Granular pavements exhibit cracking differently compared to AC pavements. There was a need to adjust the filtering protocol within the LCMS to accurately detect granular pavements cracking while rejecting textured pavement surface as cracking. The weighing factors were adjusted for centerline cracking and edge cracking on granular pavements in order to capture the effects of these types of cracking on granular surfaces where their presence pose a high risk of pavement failure. Additional years of LCMS data is needed to continuously evaluate the effectiveness of the SCI to accurately predict granular pavement performance.

Aggregates pickouts is a AC pavement surface distress. The score for the presence of pickouts on a section of road was capped at a maximum within the LCMS formula to ensure that a road that only shows pickouts as a distress does not generate a LCMS value as high as requiring repaving.

SCI values range from 0 through 100+ in a progression that reflects the amount and severity of pickouts and cracking that develops as pavements age. SCI60 values are categorized as good, fair or poor. Pavement segments with fair SCI60 are light treatment candidates. Pavement segments in the poor category are too late for a light treatment. SCI60 values over 45 require a heavy treatment.

The LCMS data used to generate SCI provides a more reliable and repeatable matrix in predicting pavement performance and enhancing investment decision making. Additional fine-tuning of the SCI

would be required as the effects of some of the information gathered by the LCMS on pavement performance is being investigated.

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