Application of The Pavement Surface Cracking Metric to Quantify Distresses from Digital Images

Danilo Balzarini, Ph.D.
Pavement Engineer
International Cybernetics Company, LP

James Erskine, P.E.
Principal Engineer
International Cybernetics Company, LP

Michael Nieminen, P.E.
Chief Executive Officer
International Cybernetics Company, LP

Jason Trotter
Director of Business Development
International Cybernetics Company, LP

Paper prepared for presentation at the Innovations in Pavement Management, Engineering and Technologies session of the 2022 TAC Conference & Exhibition, Edmonton, AB

ABSTRACT

The advancement of new laser technologies in recent years has changed the resolution of pavement data captured during collection, creating the opportunity for a fully automated approach to condition evaluation. Inspired by the Universal Cracking Indicator proposed by William Paterson in 1994, and developed by the ASTM E17 working group, this paper will present the application of the Pavement Surface Cracking Metric (PSCM). By using quantitative definitions in order to ensure consistency of the results, this method removes the subjectivity that happens with human rating of pavement distresses. The repeatability and reproducibility of the method were assessed by collecting multiple runs of pavement data on three separate asphalt sections. The application of the Pavement Surface Cracking Index (PSCI) to convert the PSCM value, which is a physical property of the pavement, into a 100-0 score of the pavement section is also presented. Finally, the use of the PSCM to classify the pavement distress and the inclusion of potholes and patching in the metrics are also discussed.

Keywords: Pavement condition evaluation, Pavement cracking metric, Pavement cracking index.

INTRODUCTION

The in-situ pavement condition is measured to provide the data which is the driving force in the decision-making process to determine the treatment decisions and allocations of funds for pavement preservation and rehabilitation. Implementing and maintaining a pavement maintenance program, according to the theory of preservation pavement [1,2], delivers both economic and safety benefits: The use of the right treatment, applied at the correct time results in reduced traffic congestion, safer roads and long-term savings, as these activities prevent structural degradation and expensive reconstructions. Significant monetary investments are made to ensure road safety and ride quality; for example, in Florida, according to the 23rd Annual Highway Report on the Performance of State Highway Systems [3], the maintenance disbursement per state-controlled mile is $80,165.

To perform effective maintenance, accurate and high-quality data collection is critical. It allows for the identification of the areas where pavement maintenance is most needed, and the data is used to plan the appropriate maintenance intervention as well as evaluate the effectiveness of previous maintenance actions.

Pavement condition data collection and ratings have traditionally been based on walking field surveys, windshield surveys, or image reviews, all of which require manual rating. The distress protocols were developed and applied based on human observation, limiting the accuracy of information such as crack width or depth.

The advancement in sensors and technology used for data collection have dramatically improved, impacting collection methodologies. Data collection can now be fully automated, enabling consistency in the results, improving safety for the operators, and saving time, money, and human resources

Existing pavement distress protocols, such as the ASTM D6433 “*Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys*” [4], have been most commonly used but were designed based on a human walking survey. The ability to adapt automated data collection to match these historical distress protocols has created a significant challenge.

Subjectivity in the distress interpretation often leads to inconsistencies between different human raters. Many of the definitions reported in [4] rely on the pavement evaluator’s judgement to be repeatable and consistent, as the distresses are defined qualitatively. In order to pass the StreetSaver pavement rater certification, as described in [5], the following requirements must be met after rating up to 24 designed pavement sections, that have both flexible and rigid pavements:

- For the inspected sections, at least 50 percent of the PCI values must be within +/- 8 PCI points of the reference, or “ground truth,” PCI values.
- For the inspected sections, no more than 12 percent of the PCI values can be greater than +/- 18 PCI points of the reference, or “ground truth”, PCI values.

Herein, the Pavement Surface Cracking Metric (PSCM) is presented, and its use is applied on three pavement sections. The PSCM methodology is used to quantify the pavement surface condition leveraging the latest technology to ensure repeatable and consistent results. It was developed by the ASTM E17 working group and inspired by “*Proposal of Universal Cracking Indicator for Pavements*” from William Paterson [6] Multiple runs are used to test the repeatability, and different equipment resolutions are used to test the reproducibility.

The PSCM offers a number of key features, including:

- **Clarity and Determination**: The method provides quantitative mathematical definitions, eliminating subjectivity in pavement distresses definitions and pavement condition evaluation.
- **Repeatability and Reproducibility:** The method yields consistent results on the same roads, within tolerances, independent of the rater.
- **Usefulness**: The method, combined with other metrics, can be useful for pavement management decisions.
- **Simplicity**: The method has a physical intuitive meaning.
- **Continuity**: The method avoids binning to eliminate discontinuities in results.

To date, cracking metrics that can be calculated automatically from sensor data are not in widespread use among municipal and county-level road agencies, as far as the authors are aware. The continued reliance on either manual surveys or manual editing of automated survey data to achieve agency-specific goals is the state of the practice. For agencies looking for data accuracy and consistency in year over year measurements, the PSCM and PSCI metrics have several features that make them attractive for adoption.

DEFINITION OF THE PAVEMENT SURFACE CRACKING METRIC

The pavement surface cracking metric (PSCM) is defined as the percentage of pavement surface area affected by cracking. A crack is defined as a fissure of the pavement material at the surface that is a minimum of 1 mm (0.04 in) in width and 0.1 m (0.33 ft) in length.

The PSCM of any pavement area is calculated as:

$$PSCM = 100 \cdot \frac{\sum_i^n l_i \cdot w_i}{A} \qquad (1)$$

Where

l_i is the length of the crack i

w_i is the average width of the crack i

A is the pavement area where the PSCM is calculated

n is the number of cracks present in the pavement area.

Defining the total crack length within the area as

$$L = \sum_i^n l_i \qquad (2)$$

And defining the average weighted width as

$$\bar{w} = \frac{\sum_i^n l_i \cdot w_i}{\sum_i^n l_i} \qquad (3)$$

The PSCM can be conveniently expressed as

$$PSCM = 100 \cdot \frac{L \cdot \bar{w}}{A} \qquad (4)$$

The fact that the PSCM has a physical meaning, representing the “open” percentage of the pavement surface, allows the use of multiple analysis areas which can be combined at any point. Given any pavement section, the PSCM can be calculated for its entirety, or the section can be divided into multiple analysis areas, and the PSCM calculated for each one. The section PSCM can then be calculated as

$$PSCM = \frac{1}{A_{section}} \sum_{j}^{m} A_j \, PSCM_j \tag{5}$$

Where
A_j is the surface of the analysis area j
$PSCM_j$ is the PSCM of the analysis area j
$A_{section}$ is the section pavement area
m is the number of analysis areas in which the section is divided into.

The section PSCM value does not depend on the choice of the number or shape of the analysis areas the section is divided into.

DESCRIPTION OF PAVEMENT SECTIONS

Data was collected on three sections, with multiple runs, as described in Table 1 and **Figure 1**.

Table 1. Description of the pavement sections

Road	Number of runs	Pavement type	Section description	Section length
Airport Dr. – Jackson, MS, Southbound	3	HMA	Several areas show block and alligator cracking	5.13 km (3.19 mi)
114th Ave. – Largo, FL, Eastbound	13	HMA	Three distinct parts: one subsection with block cracking, one with new pavement, one with alligator cracking	1.48 km (0.92 mi)
5th Ave. N – Largo, FL, Westbound	8	HMA	Good conditions, has areas with light severity cracking	1.32 km (0.82 mi)

(a) *(b)* *(c)*

Figure 1 - a) Airport Dr., b) 114th Ave., c) 5th Ave.

Using a second-generation Laser Crack Measurement System (LCMS-2), the data was collected on 114th Ave. and 5th Ave. The data has been collected using different laser longitudinal resolutions of 1, 2 and 3 mm and a transverse resolution of 1 mm. The resolution indicates the spacing between the points collected; a resolution of 1 mm provides a higher level of detail than 3 mm resolution.

CALCULATION OF THE PAVEMENT SURFACE CRACKING METRIC

The road has been divided into 5 zones, similar to that indicated in AASTHO R85-18 [7], for each of the sections. A width of 3.28ft (1m) is assigned to the central zone and the two-wheel path zones, while the width of each edge zone depends on the actual lane width. A 6ft (1.83m) length and a width equal to the road zone width make up the analysis area to be used, also referred to as tiles, as shown in **Figure 2**. The central zone width of 3.28ft is different from that indicated in [7], but this only affects the visual representation of the results and has no effect on the section PSCM value.

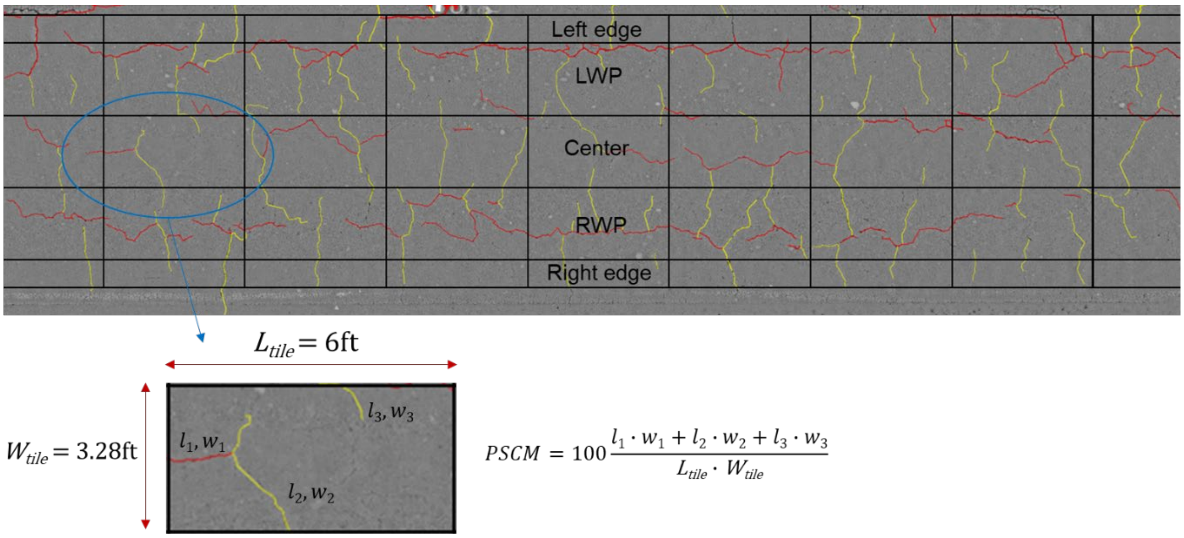


Figure 2 - Analysis areas and PSCM calculation

To ensure the visual representations is clear, since the width of the edge zones can be very small, only the wheel paths and the central zone are shown in the following figures. The PSCM values of all zones are still used for the calculations.

A breakdown of 114th Ave. is shown in **Figure 3**. Using homogeneous pavements, the road is divided into three homogeneous subsections: the first is affected by block cracking, the second is a new pavement while the third subsection has alligator (fatigue) cracking. Examples of the right of way and pavement range images are also shown for each subsection. The pavement range images are greyscale images showing the distance of the pavement from the laser system, the further the pavement is away the darker the pixel.

In **Figure 4** the repeatability of the PSCM at a tile level can be observed, where the three runs on the third subsection of 114th Ave. are shown. The PSCM values are indicated using a gradation of colors from green to red. The maximum PSCM observed on 114th Ave. is on a tile with severe alligator cracking, and the value is less than 10%.

The presence of alligator cracking can be observed from the figure: The tiles with higher cracking density are on the left and right wheel paths, while the center zone shows mostly PSCM values <2%. It is also easy to identify from the figure the areas with high severity alligator cracking (red and black tiles).

The PSCM is calculated for every single tile, and then combined using Eq. (5) to determine the PSCM of the entire section. **Figure 5** shows the repeatability of the PSCM at the section level. To confirm the repeatability of the LCMS measurements, the runs have been conducted on different days, at a different time of the day.

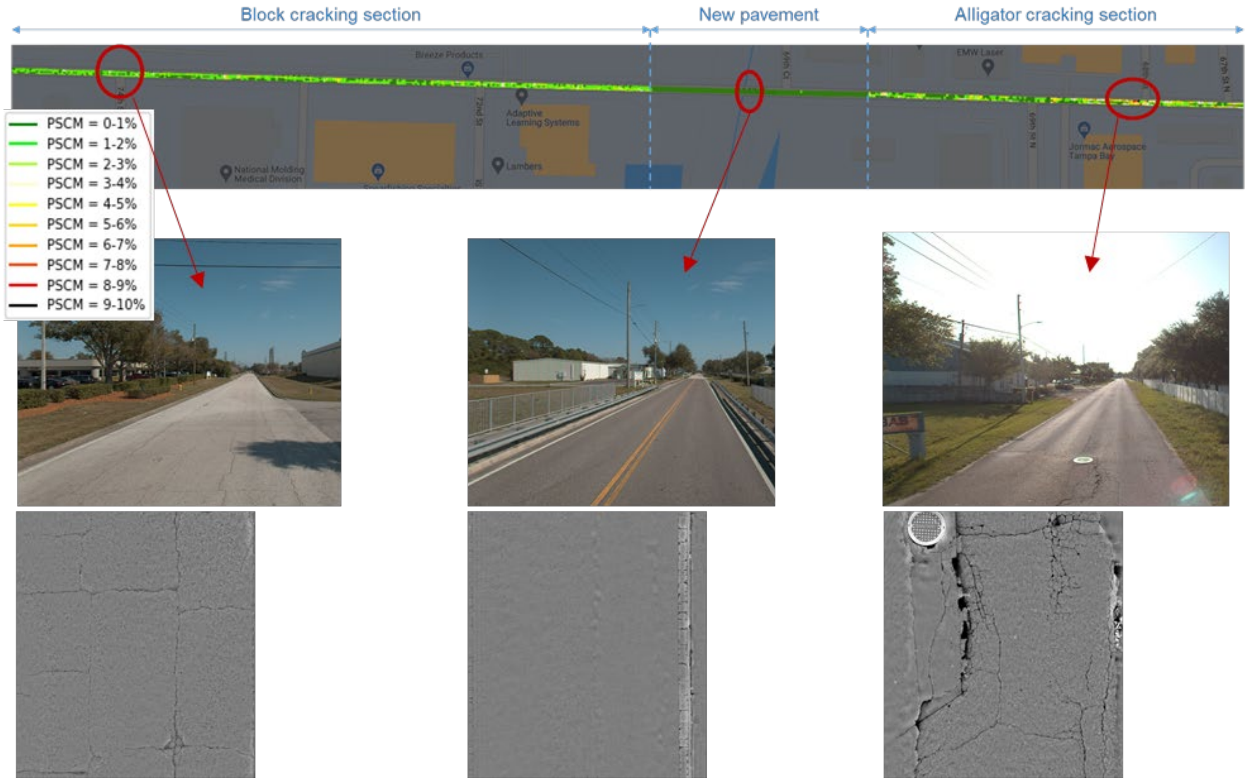


Figure 3 - PSCM calculation on 114th Ave.

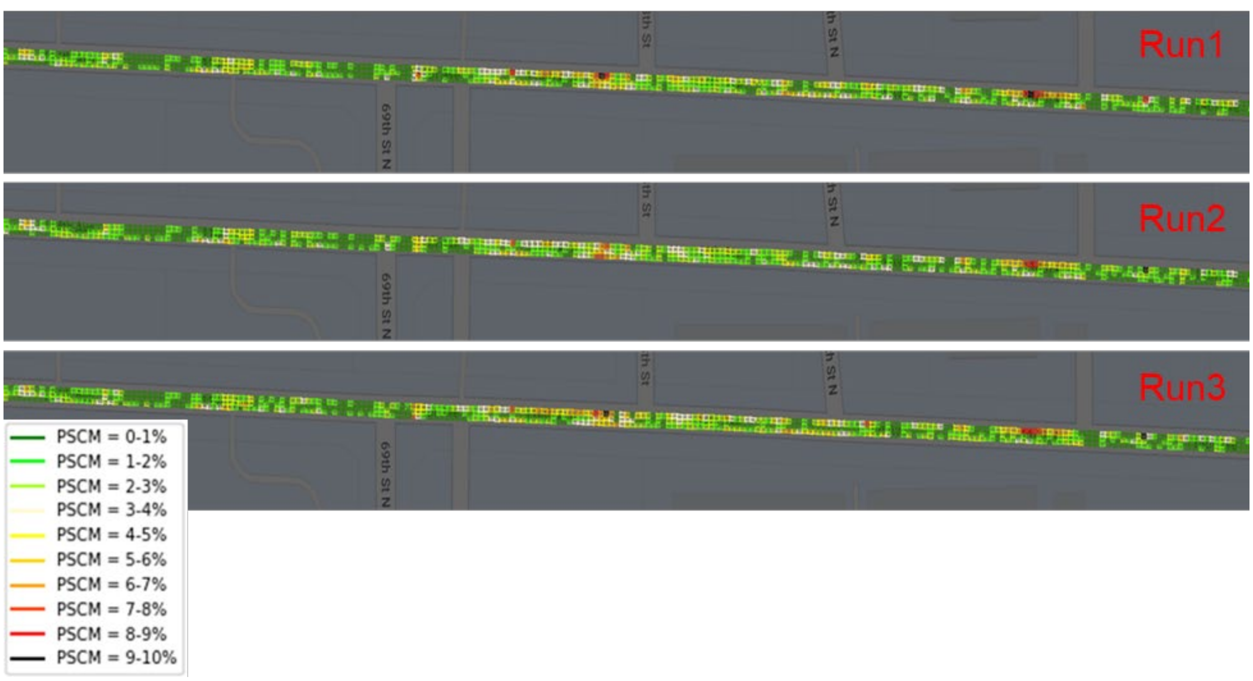
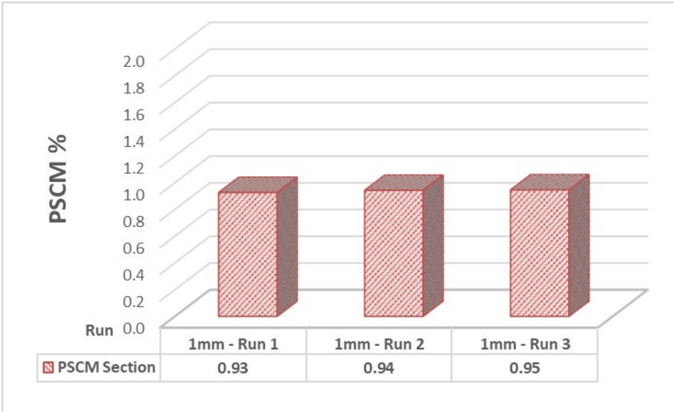
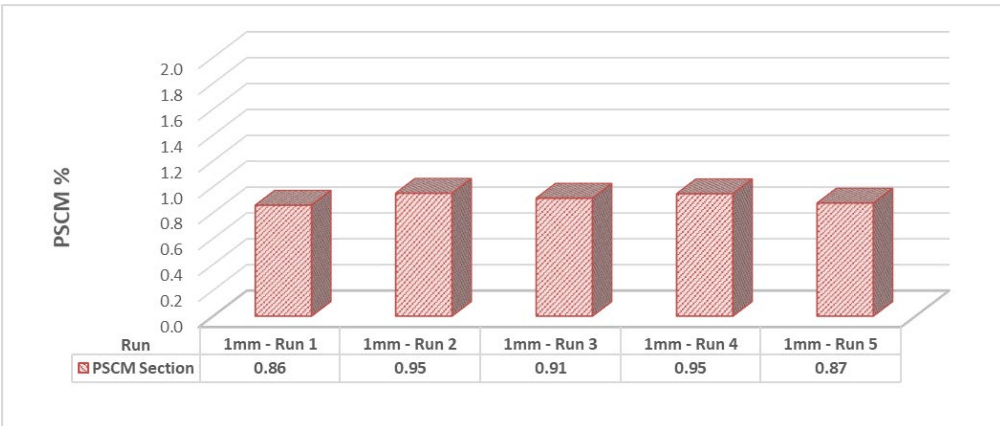


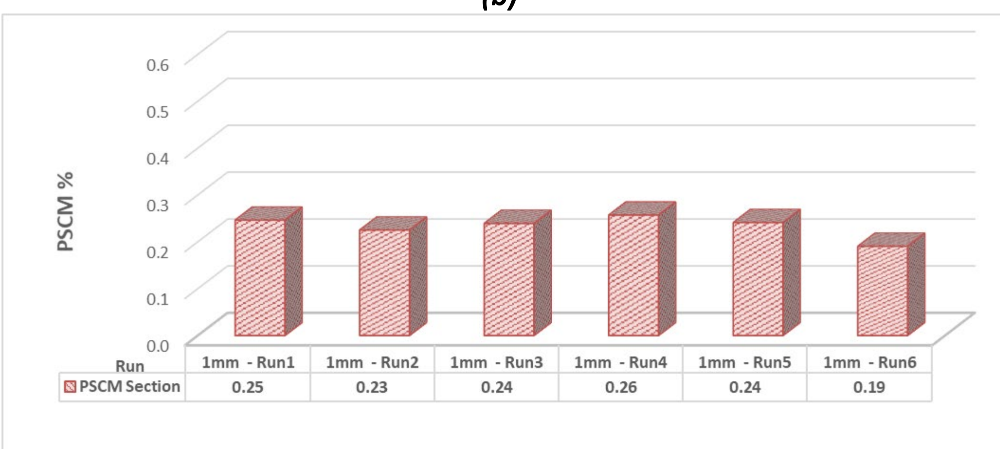
Figure 4 - Repeatability of the PSCM at a tile level on the third subsection of 114th Ave.



(a)



(b)

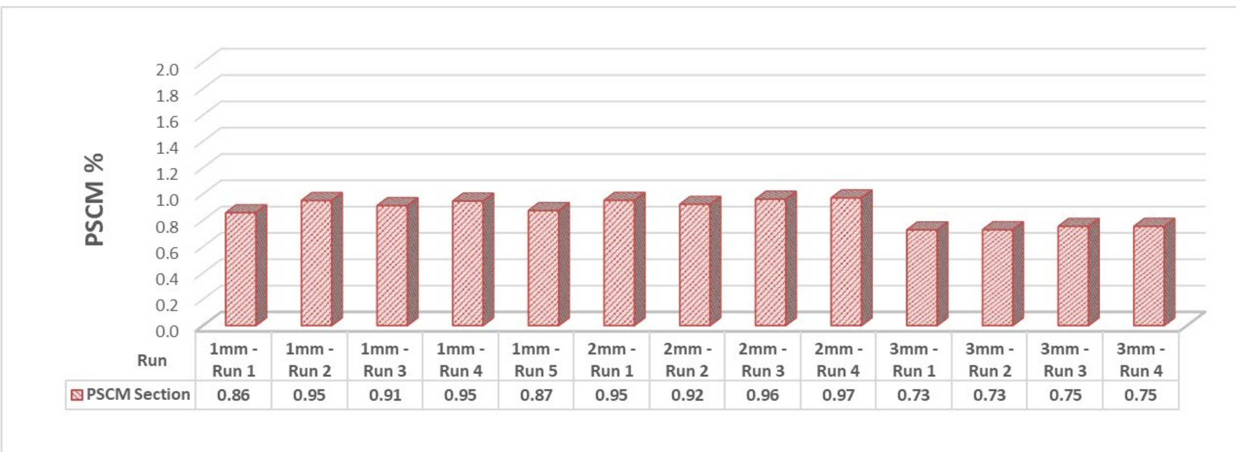


(c)

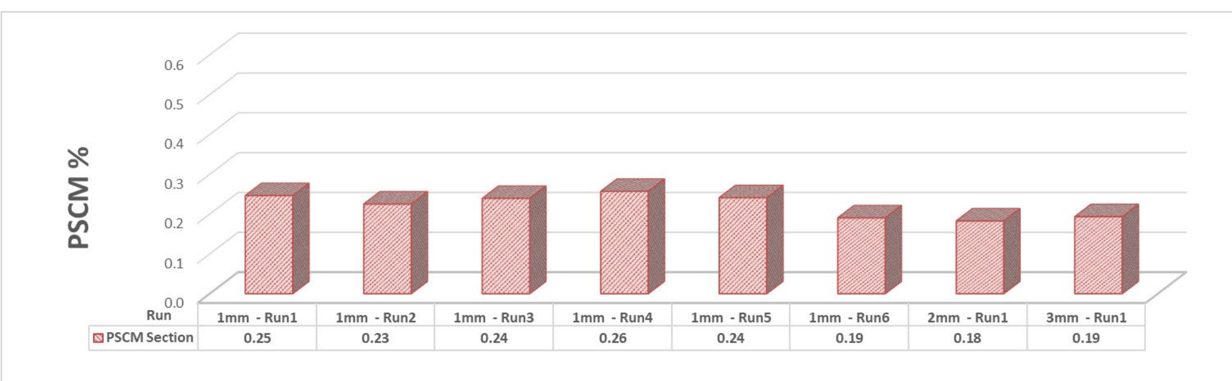
Figure 5 - Repeatability of the PSCM at the section level using 1 mm resolution for a) Airport Dr., b) 114th Ave., c) 5th Ave.

Repeatability using different equipment resolution

As there are a variety of sensor type and resolution that are commercially available, a series of runs at 2- and 3-mm laser resolutions were conducted on 114th Ave. and 5th Ave. to investigate how the resolution of the measurement equipment could affect the results. While the section PSCM values are consistent within the same laser resolution, as showing in **Figure 6** less cracks are detected at 3 mm resolution on 114th Ave. The percent of cracked pavement for that road reduces from 0.93% of the total area when using a 1- or 2-mm laser resolution to 0.74% using the 3 mm resolution. Although only one run was conducted at 2 and 3 mm on 5th Ave., the results look more consistent on that section. A more detailed analysis of 114th Ave. showed that the crack detection at 3 mm was less accurate in the alligator cracking areas, where some "alligator tiles" were only partially detected. There is no alligator cracking on 5th Ave.



(a)



(b)

Figure 6 - Repeatability of the PSCM at the section level using different laser resolution for a) 114th Ave., b) 5th Ave.

DEFINITION OF THE PAVEMENT SURFACE CRACKING INDEX

The PSCM represents the cracked percentage of the pavement area and, therefore, its value will increase over time as the cracks develop in length and width. The Pavement Condition Index (PCI) [4] has been widely adopted, and large efforts have been made by the engineering community to educate and inform non-technical decision makers about the importance of pavement preservation and how timely planned maintenance can save money over time [8, 9]; the idea of a pavement condition rated on a 100-0 scale, where 100 represents an "as new" condition is understood and well accepted.

To assist in the consideration of historical data and to provide continuity, the Pavement Surface Cracking Index (PSCI) is an index to converting the PSCM to a 100-0 scale.

To determine the PSCM-PSCI conversion, a simulation was done for 10,000 imaginary sections, and for each section the PCI defined in ASTM D64-33 and the PSCM defined above were calculated. Each section was assumed to be 2,500 sq ft (PCI sample unit), and on each section, random amounts of linear cracking (0-50), alligator cracking (0-15), block cracking (0-15), and slippage cracking (0-5), were simulated.

To each linear crack a random length (0-15 ft) and width (0-4 in) were assigned, and used to determine the severity levels, density and calculate the PCI deduct value for each severity level. To each area distress a random area (0-30 sq ft) and average crack width (0-4 in) were assigned; the severity level has been associated to the average crack width, and the crack length to be used for the PSCM calculation has been assumed to be a multiple of the area which depends on the type of distress and its severity.

Only the above listed surface distresses are simulated to be present for the sections.

For each section, the PCI has been calculated according to [4]. The PSCM has been calculated using Eq. (1).

The relation between the PSCM and PCI is shown in **Figure 7** for the simulated sections. To relate the PSCM and PCI, the best fit exponential function is here proposed as the PSCI equation. A larger weight has been given to the (0,100) point to ensure that the curve passes by point PSCM=0, PSCI=100. PCI values of 20 or below are indicative of a pavement in very bad condition and such a pavement would be in strong need of maintenance regardless of the actual PCI value, therefore having an asymptote for the PSCI curve at the value of 15 is acceptable.

$$PSCI = 15 + 85 \cdot e^{-0.64PSCM} \qquad (6)$$

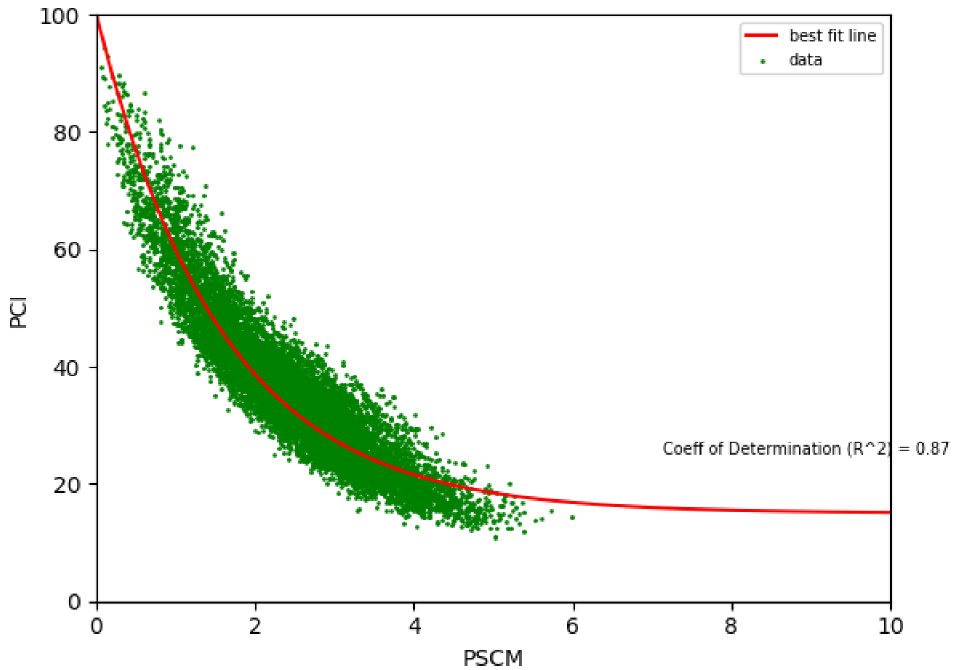


Figure 7 - PSCM vs PC

With regards to the random generation of the pavement data, it must be noted that the complete random generation of distresses may can lead to situations which would not happen on a real pavement, where exist implicit relations between the number, length, and width of cracks. It would be uncommon for a real pavement to only have one high severity alligator distress in the entire section with no other defects, for example. Or to have high severity cracks that are very short in length.

The proposed equation can be improved, and a better equation that relates PSCM and PCI can be found, but it is important and necessary to clarify that the PSCI is not an attempt to convert the PSCM to PCI, but is just an attempt to ensure the PSCI has a similar trend and can be related to the PCI for the familiarity and convenience of practitioners. The assumptions made for generating the random sections have a significant effect on the results and on the PSCI equation.

There is not a direct correlation between PSCM and PCI for several reasons:

- Binning: Because of the PCI severity levels, a single 9.9 mm width crack will result in a PCI much lower than a 10.1 mm crack, but a 50 mm crack has the same PCI as a 10.1 mm one. The PSCM increases linearly with the crack dimensions.
- Crack classification: The PSCM of 10 ft of cracking with 10 mm width will always give the same score regardless of the classification of the crack, while the PCI would depend on the classification of those 10 ft of cracking.
- Only surface distresses are accounted for in PSCM, while greater number of distresses accounted for in PCI calculation. In this sense, it can be said that the PSCI is determined as the most likely value of the PCI if only the surface distresses are considered.

The PSCI only has meaning at the section level, which is different than the PSCM, which starts at the tile level. Additionally, the PSCI of different analysis areas cannot be aggregated.

Repeatability of the PSCI

The PSCM results shown in **Figure 5** have been converted into PSCI values by the use of Eq. (6); the results are shown in Table 2. The standard deviation and coefficient of variation of the section PSCI value are low, indicating good repeatability and consistency of the results.

Table 2. PSCI values based on the 1 mm resolution runs on all sections

Road	Run number	PSCM Section	PSCI Section	Standard deviation PSCI	Coefficient of Variation
Airport Dr.	1	0.93	62.0	0.31	0.5%
	2	0.94	61.5		
	3	0.95	61.4		
114^{th} St.	1	0.86	64.1	1.27	2.0%
	2	0.95	61.3		
	3	0.91	62.4		
	4	0.95	61.4		
	5	0.87	63.6		
5^{th} Ave.	1	0.25	87.6	1.10	1.3%
	2	0.23	88.6		
	3	0.24	87.9		
	4	0.26	87.1		
	5	0.24	87.8		
	6	0.19	90.2		

APPLICATIONS OF THE PSCM

Use of PSCM to classify cracking

Pavement management applications typically look for the type of distress present in order to determine appropriate preservation, maintenance, and rehabilitation decisions. The pavement surface condition metric can also be used to classify the types of distresses that are present. Several criteria and multiple tile dimensions have been tested to determine which tiles are affected by alligator cracking. Utilizing the expected results (based on human rating) on 114^{th} Ave and Airport Dr., these were compared against the results of the classification. The criterion that showed the best results in distinguishing between alligator and non-alligator cracking is based on the density of cracking within the tile, without considering the crack width. To consider a tile to be affected by alligator cracking, the total length of cracking within the tile will be greater than 2.5 times the length of the tile. The tile used is 6ft (1.83m) in length and is 3.28ft (1m) or less (edge zones) in width.

Aggregation of tiles in larger analysis area is still achievable, however the criteria proposed for the identification of alligator cracking should be applied only to tiles of the specified dimensions and might not work for different analysis tiles. The section area affected by alligator cracking can be calculated as the sum of the alligator tile areas.

By having the length of the tile at nearly twice the width reduces the chance of block cracking being detected as alligator cracking, as shown in **Figure 8**. With the PSCM, the crack width is not part of the criteria, so the PSCM is not directly related to the crack classification. As an example, a tile with high severity (large crack width) block cracking will have a much greater PSCM value compared to a tile with low severity (fine cracks) alligator cracking.

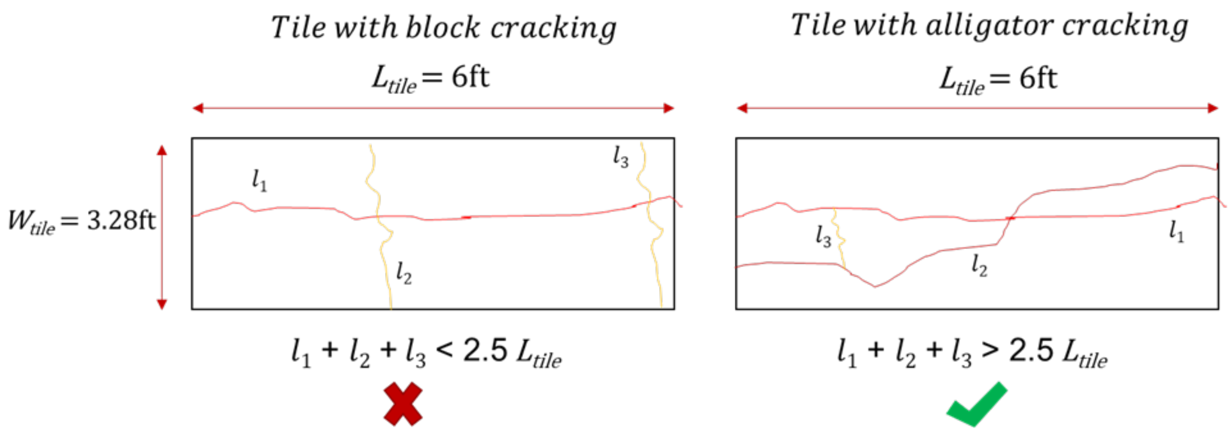


Figure 8 - Alligator classification criterion; the cracking on the right is identified as alligator cracking

The classification of distress types, using the standard, has indicated good and accurate results. The results of the criterion on 114th Ave. are shown in **Figure 9**. In the first subsection where block cracking is predominant, very few tiles were classified as alligator cracking, and within the few tiles marked as alligator the pavement shows signs of fatigue, and high crack density.

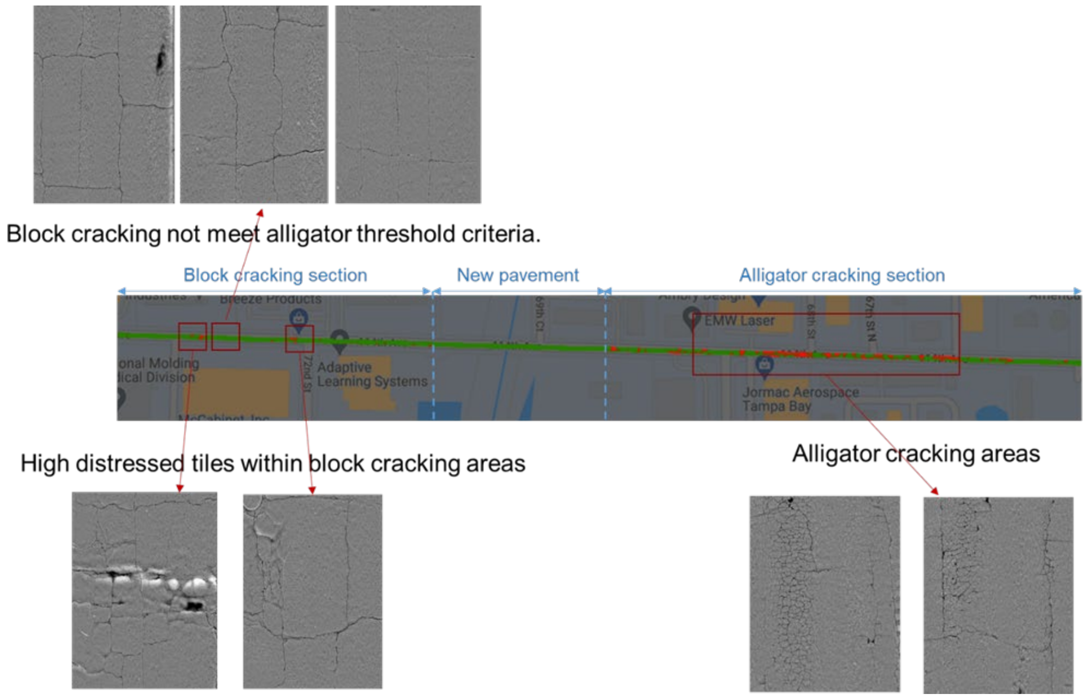


Figure 9 - Results of alligator classification on 114th Ave.

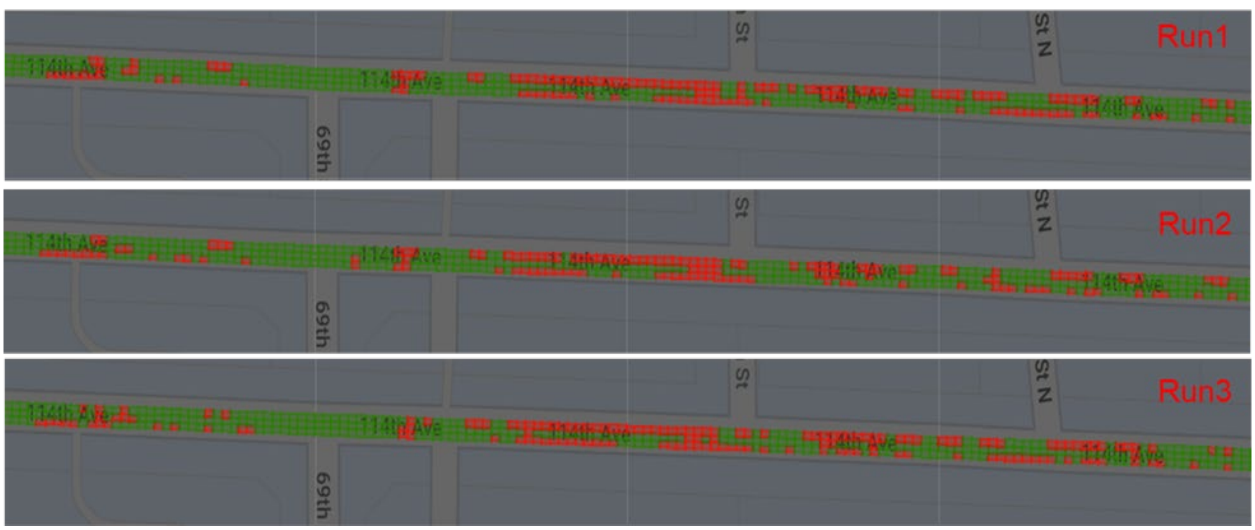


Figure 10 - Repeatability of alligator classification for three runs on 114th Ave

By applying this type of crack classification approach, it offers the advantage of providing a quantitative definition that uniquely identifies the distress and eliminates any need for interpretation, advancing and simplifying the automated processing. The use of small unit tiles that can be aggregated leaves room for customization. For example, if desired, the alligator cracking criteria can be applied to the tiles within the wheel paths only.

Additional criteria can be established for other distress classification, such as a tile with a high value of the PSCM which does not meet the alligator criteria can be considered affected by block cracking.

Inclusion of potholes, patching, and sealed cracks in the PSCM

The condition index of the pavement as determined by the PSCI only uses crack detection. Untreated alligator cracking will deteriorate into potholes, which will often be repaired using patches. When observing the evolution of the PSCM/PSCI over time, these treatments will cause some steps or discontinuities, the more noticeable the smaller the analysis areas are chosen. The PSCI can only reduce with time, unless some maintenance intervention is conducted on the pavement, as more cracks are formed, or as the existing cracks widen, and the formation of potholes will be the only "natural" reason for a sudden reduction of the PSCI. For example, the PSCM of a pavement tile with alligator cracking will grow over time as more cracks are formed, and as the cracks become wider, but, when a pothole is formed, all the cracks within the pothole area will not be detected and the PSCI will suddenly increase. To ensure continuity of the PSCI, the PSCM can be modified to also include potholes and patching. Eq. (1) can be modified to include the area of the potholes as follows:

$$PSCM = 100 \cdot \frac{A_{pot} + \sum_i^n l_i \cdot w_i}{A} \quad (7)$$

Where A_{pot} is the sum of the pothole areas.

It must be noted that, regarding the addition of potholes and patching area to the PSCM calculation, while cracks are linear distresses with a length value much higher than the width value, potholes are area distresses. A single pothole would cause a significant increase of the PSCM value at the tile level, as the pothole area is greater than the product of crack width and length. Potholes are a distress that affects the quality, comfort, and safety of the ride, it is therefore acceptable for them to have a higher weight in the PSCM calculation when compared to cracks.

On the other hand, while patches could also be included in the PSCM by adding a coefficient A_{pat}, equal to the sum of the patches area, they would create a substantial increase in the PSCM, making the pavement condition index appear worse than it is. Patches are used not only for pothole repairs but are also sometimes used on larger pavement areas affected by fatigue cracking. In addition to that, the current state of technology for the automated patching detection from 2D and 3D images has room for improvement and is not always accurate. The pothole detection is more reliable and accurate than the patch detection. The arguments moved against the inclusion of patching can also be extended to crack sealing. The sealing width is not necessarily representative of the width of the sealed crack, and the automated methods of crack seal detection are not always accurate. In addition to that, cracks are defined as openings with a width greater than 1 mm, and therefore, sealed cracks are excluded. Logically, sealing methods such as chip seal, fog seal, slurry seal, etc, which cover the cracks, are not detected by the laser measurement system, and are therefore also excluded from the method. For these reasons, it is preferable to not include patching or sealed cracks in the Pavement Surface Cracking Metric and otherwise report the patched area and length of crack sealing as separate fields or as part of a different metric.

CONCLUSION

The Pavement Surface Cracking Metric (PSCM), developed by the ASTM E17 working group, is presented in this paper, and discussed as a method to evaluate the pavement surface condition. The repeatability of the metric is shown through data collected on multiple runs on three asphalt pavement sections. A different resolution of the data collection equipment collected additional runs and showed that the reproducibility of the results depends on the equipment quality. The advantage the method offers are numerous: It has a simple and intuitive physical meaning, representing the cracked pavement area, and as such can be used for any analysis area size and shape. Depending on the required level of detail, the PSCM can be used to describe the pavement condition at either the tile level or at the section level; it does not require binning and ensures continuity over time. It has been shown how the PSCM can be used to determine a mathematical definition for the classification of alligator cracking.

The comparison of the PSCM with the Pavement Condition Index (PCI) has been analyzed, and the use of a Pavement Cracking Surface Index (PSCI) has been shown, with the intent to facilitate the transition and maintain line of continuity with historical methods.

The PSCM has many potential applications in quality control and quality assurance procedures to evaluate and ensure the quality of the crack detection of automated systems and is an ideal candidate to be used in decision trees for pavement maintenance decisions, such as pavement preservation treatments. In this regard, the use of the PSCM should not limit the reporting of other information necessary for making pavement maintenance decisions. Information such as total crack length, average crack width, crack density, etc. should be reported in combination with the PSCM for each analysis area.

An important remark adapted from [6] is that "*There is no presumption that two pavements with the same PSCM under differing circumstances would behave or perform similarly or have similar priorities for maintenance. The interpretation and impact in each case rest on a diagnosis and analysis relevant to the circumstances and objective.*"

By combining with other measurements such as rutting, IRI, texture mean profile depth, raveling, patching, and more, allows for the PSCM/PSCI to take informed pavement management decisions. Citing the discussion from W. Uddin in [6], "*Perhaps a standard for deformation index should also be developed for uniform reporting of rutting, depression, faulting, and shoulder drop-off distresses.*"

Regarding the use of the PSCM on different pavement types. While only asphalt sections were used for this analysis, the method could potentially be applied to rigid pavements as well; for jointed concrete pavements using slabs as analysis areas seems an ideal solution.

However, the authors tend to agree with the comments from W. Uddin in [6]: "*PCC pavements perform differently from flexible pavements and require different types of maintenance treatments … It is suggested that a separate identifier for pavement types may be necessary*" and believe that more studies be conducted to adapt the use of a similar metric to rigid pavements.

REFERENCES

1. FHWA, "*Pavement Preservation A Road Map for the Future*", 1999. Publication No. FHWA-SA-99-015.
2. Galehouse L., J. S. Moulthrop and R. G. Hicks, "Principles of Pavement Preservation", 2003. Transportation Research Record Issue Number: 228, ISSN: 0738-6826.
3. M. G. Fields and S. Purnell, "*23rd Annual Highway Report on the Performance of State Highway Systems*", 2018. Reason Foundation Policy Study No. 457.
4. ASTM D6433-20, *"Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys",*2020. ASTM International, West Conshohocken, PA, www.astm.org.
5. Streetsaver rater certification, https://www.streetsaver.com/academy/academy-rater-certification
6. W.D. Paterson, "*Proposal of Universal Cracking Indicator for Pavements*", 1994. Transportation Research Record Issue Number: 1455, ISSN: 0361-1981.
7. AASHTO "*Standard Practice for Quantifying Cracks in Asphalt Pavement Surfaces from Collected Pavement Images Utilizing Automated Methods*", 2018. AASHTO Designation R 85-18, American Association of State Highway and Transportation Officials, Washington, D.C.
8. FHWA, "*Reformulated Pavement Remaining Service Life Framework*", 2013. Publication No. FHWA-HRT-13-038.
9. D.N. Geoffroy, "*Synthesis of Highway Practice 223: Cost-effective Preventive Pavement Maintenance*", (1996). Transportation Research Record Issue Number: 223, ISSN: 0547-5570