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Proposed severity ranking for ASTM E3303-21 protocol to quantify asphalt pavement cracking from automated 3D surveys

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Abstract. Cracking is one of the essential indicators to evaluate pavement surface conditions; however, it is challenging to rate pavement cracking automatically from 3D digital images. Recently, a two-level automated crack rating system was proposed for pavement management in Singapore where Level 1 provides detailed crack information including cracking extent, types, and severity. Level 2 is a macro-indicator ranging from 0 to 5 based on crack extent over a 10-m length pavement section, with 0 being excellent condition and 5 being very bad condition. On the other hand, the new ASTM E3303-21 standard has introduced the Pavement Surface Cracking Metric which is a dimensionless measure equivalent to crack density and the Pavement Surface Cracking Index which provides ratings of pavement cracking ranging from 0 to 100, with 0 being the worst possible condition and 100 being the best possible condition. This study was conducted to compare and potentially bridge the gaps between the two mentioned cracking rating methods. Cracking data were collected from the Singapore road network using the Laser Crack Measurement System-2 (LCMS-2). Based on the study findings, three severity ranks (low, medium, and high) were proposed to facilitate the inclusion of the ASTM E3303-21 cracking protocol into Pavement Condition Index calculations.

1. Introduction

Pavement structure is aged over time and deteriorated due to exposure to the environment, vehicle loadings, and wear. Such deterioration is eventually seen in pavement distress, such as cracking. A crack is defined as a "*fissure of the pavement material at the surface with minimum dimensions of 0.04 in. (1 mm) width and 1 in. (25 mm) length*" [1–3]. Therefore, cracking can be used as one of the essential indicators to evaluate pavement surface conditions. There are existing many methods to identify and quantify pavement surface cracking, including 1) manual, 2) semi-automatic, and 3) fully automatic approaches [4]. Among the manual methods, the Pavement Condition Index (PCI) has been widely used for a long time for pavement management in which cracking is rated as low, medium, and high severity. PCI is a composite index comprising around 19 distresses such as surface cracking, rutting, ravelling, bleeding, and so on [5].

One of the recent trends in pavement survey is to shift from manual to automatic data collection or to utilize automatic data collection to support tedious manual surveying thanks to the development of pavement survey technologies, resulted in higher efficiency. A recent survey in the USA has shown that the number of State Highway Agencies (SHAs) that are using the semi-automated and automated technologies for cracking data collection and processing are more dominant compared to the manual surveys [4]. However, the disparity between manual and automatic cracking surveys has led to a poor correlation between the two methods [4]. For example, many crack types (and pavement distresses) are not easily identified by machines and sensors, such as the interconnectivity of cracks, the existence of crack spalling and sealant. Thus, there are requirements for new standards/protocols [4] to define, identify, and classify not only the type, length, and width of the cracks but also the location and orientation, as well as the presence of other cracks.

Recently, Tan et al. [6] have developed a two-level automated crack rating system for pavement management in Singapore where Level 1 provides detailed crack information, including cracking extent, types, and severity. Level 2 is a macro-indicator ranging from 0 to 5 based on crack extent over a 10-m length pavement section, with 0 being excellent and 5 being the worst case. On the other hand, the new ASTM E3303-21 - Standard Practice for Generating Pavement Surface Cracking Indices from Digital Images [3] has introduced the Pavement Surface Cracking Metric (PSCM), and the Pavement Surface Cracking Index (PSCI). PSCI provides a rating of pavement cracking ranging from 0 to 100, with 0 being the worst possible condition and 100 being the best possible condition.

While cracking severity can be easily interpreted using the former method, the ASTM E3303-21 standard does not specify the levels of low, medium, and high cracking conditions, which are required input for PCI calculation based on the ASTM D6433 for Highway [5]. Therefore, this study was conducted to compare and potentially bridge the gaps between the two mentioned cracking rating methods. Cracking data were collected using Laser Crack Measurement System-2 (LCMS-2) from the Singapore pavement network. MATLAB programming was used to develop algorithms and functions to process cracking data. The study findings have proposed three severity ranks (low, medium, and high) to facilitate the inclusion of the ASTM E3303-21 cracking protocol into PCI calculations. With the established correlation between the Level-2 crack ranking and PSCI, both methods can be justified for practical applications in automatic cracking rating in the network scale.

2. Literature review

ASTM D6433 for Highway [5] has been developed and widely used to monitor and quantify road conditions through visual inspection/survey using the PCI. The precedent of highway application is ASTM D5340 - Standard Test Method for Airport Pavement Condition Index Surveys [7]. These standards are being adapted in Italy to collect urban road distresses [8]. PCI is one of several composite indices that aggregates multiple types of condition data into a single index to represent the overall condition of a pavement. This is different from individual index such as International Roughness Index (IRI) [9], cracking index, rutting index, patch index, or even the recent Bus Ride Index (BRI) [10], and so on. The standard PCI rating scale (from 0 to 100) contains seven severity ranks which can be further combined into three severity ranks as good, fair, and poor when $PCI \geq 70$, $70 > PCI > 55$, and $PCI \leq 55$, respectively (see Figure 1). Fundamentally, individual pavement distress is also classified into three severity ranks as the inputs for PCI calculation.

From ASTM D6433, three severity levels of fatigue/alligator cracking are illustrated in Figure 2, showing a series of interconnecting cracks caused by fatigue failure of the asphalt concrete surface under repeated traffic loading. This crack type is measured in square meters of surface area; however, it is challenging in case of different severity levels existing within one distressed area. The connectivity can be considered one of the key parameters to define these crack types using automatic equipment. For other crack types, the crack width is the main indicator for severity ranking.

Figure 1. Two examples of (left) standard PCI rating scales and (right) custom PCI rating scales [7].

Figure 2a. Low severity (fine, longitudinal hairline cracks; no spalling) [5].

Figure 2b. Medium severity (light alligator cracks into a pattern or network of cracks) [5].

Figure 2c. High severity (network or pattern cracking; spalled at the edges) [5].

At the national level in the USA, there are many existing protocols to identify and quantify pavement surface cracking, from 1) manual protocols such as ASTM D6433 for Highway, ASTM D5340 for Airfield, FWHA LTPP; to 2) automatic protocols such as AASHTO R 85-18, AASHTO R55-10, FWHA NPS and SCANNER (see the summary in Table 1). The AASHTO PP 67-16 [11] is replaced by the recent AASHTO R 85-18 with a similar concept, the most widely implemented protocol for automated cracking surveys in the USA. At the same time, many SHAs also developed their cracking protocols for automated pavement condition survey technologies, which can be diversified and not comparable across different agencies [4]. Due to this issue, the National Cooperative Highway Research Program (NCHRP) project 01-57A has developed standard definitions for common cracking types for asphalt and concrete pavements to help survey providers and pavement engineers at SHAs conduct objective cracking measurements [4].

Even being popular, the AASHTO R 85-18 requires the total cracking length and average cracking width of each cracking type reported for each of the five zones, resulting in 30 values (2 attributes × 3 types × 5 zones) that characterize the crack measured for each summary section [11]. This led to a certain level of complexity, where 24/33 SHA respondents (73%) indicated AASHTO R 85-18 had not been implemented for cracking quantification [4]. The ASTM E3303-21 [3] cracking protocol is the most recent standard, based on a study by Balzarini et al. (2020) [12] and inspired by Paterson's study in 1994 [13]. Cracking is quantified for any pavement type, based on PSCM (0 to 10%) and PSCI (0 to 100) as numerical and dimensionless ratings. As for PSCM: 0 means no cracking, 10 is heavy cracking, and for

PSCI: 0 is worst condition, and 100 means best condition. Like AASHTO R 85-18, the surveyed lane width is divided into five road zones with sizes and dimensions, as shown in Figure 3. However, the recent ASTM E3303-21 protocol does not classify cracking types but simply integrates them all into PSCM and PSCI ratings. There is a correlation between PSCM and PCI, as investigated in a recent study [12].

Table 1. Summary of the national level crack protocol in the USA [4].

Protocols	Automation	Pavement and Cracking Types
FHWA LTPP	No	• Asphalt: fatigue, block, edge, reflection, longitudinal, and transverse cracking. • JPCP: corner break, "D", longitudinal, and transverse cracking. • CRCP: "D", longitudinal, and transverse cracking.
ASTM D6433-16 for Highway	No	• Asphalt: alligator, block, edge, joint reflection, longitudinal/transverse, and slippage cracking. • PCC: corner break, "D", linear on non-reinforced slabs, linear on reinforced slabs, shrinkage cracking, and divided slab.
ASTM D5340-12 for Airfield	No	• Asphalt: alligator, block, joint reflection or longitudinal/transverse, and slippage cracking. • PCC: corner break, cracks (longitudinal, transverse, and diagonal), "D", shattered slab/intersecting cracks, and shrinkage cracking.
AASHTO R 85-18	Yes	• Asphalt: longitudinal, transverse, pattern, and other cracking.
AASHTO R 55-10	Yes	• Asphalt: wheel path and non-wheel path cracking.
FHWA NPS	Yes	• Asphalt: alligator, longitudinal, and transverse cracking • PCC: longitudinal and transverse cracking.
UK SCANNER	Yes	• Any Pavement Type: carriageway cracking intensity and intensity of wheel track cracking.

Note: SCANNER is the Surface Condition Assessment for the National Network of Roads from the UK
FHWA NPS is Federal Highway Administration National Park Service
FHWA LTPP is Federal Highway Administration Long Term Pavement Performance
AASHTO is American Association of State Highway and Transportation Officials

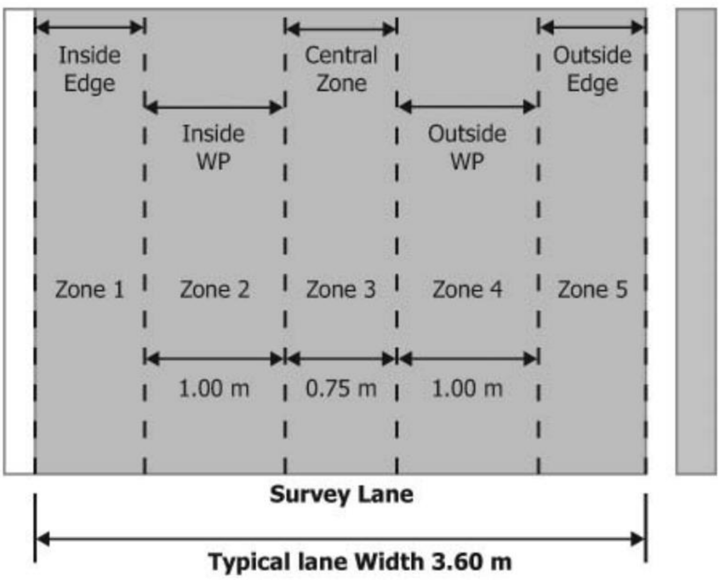

Figure 3. Five road zones.

2.1. ASTM E3303-21

To quantify cracking, ASTM E3303-21 uses the concepts of "*analysis interval*" and "*analysis tile*" to divide the pavement section into element units with a recommended length of 2.0m or slab length. If the total crack length within one tile is greater than 2.5 times of the tile length, that specific tile can be affected by fatigue cracking. The PSCM for any analysis tile is calculated as follows:

$$PSCM = 100\frac{L.w}{A} = 100.\rho.w \tag{1}$$

where: PSCM is pavement surface cracking metric; A is analysis tile area; L is the total length of cracking in analysis tile area A; w is the average weighted width of cracking in tile area A, and ρ is crack density (l/A).

The PSCM for the whole pavement section is the weighted average of the PSCM of each analysis tile, for which the PSCI is calculated:

$$PSCI = 100 \times e^{-0.45PSCM} \tag{2}$$

where: PSCM is PSCM for the whole pavement section, and PSCI is the pavement surface cracking index.

Figure 4 illustrates a pavement section of 16m in length with analysis tiles of 2m in length. Based on the borders of analysis tiles, cracks will be split into smaller segments. For example, in the centre zone crack #1 becomes #1A and #1B with specific crack length (L) and crack width (w). In this example, the PSCM = 0.030%, PSCI = 87.3 for the section length of 16m, section area of 56.8m^2 [3].

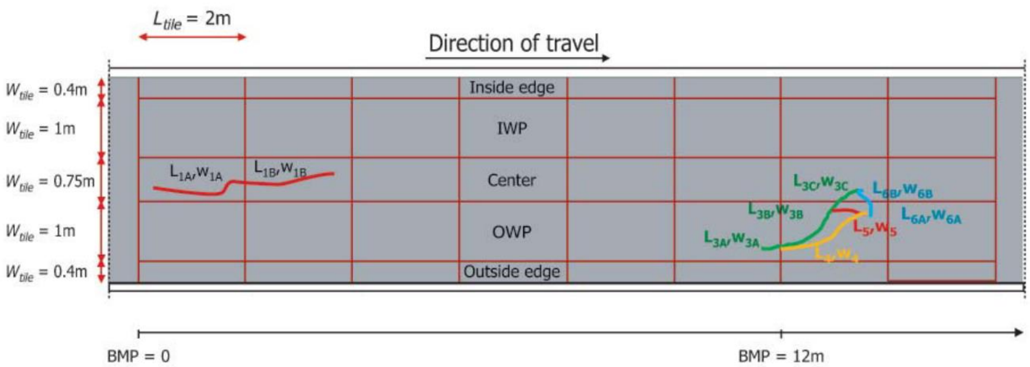

Figure 4. Example of a Pavement section (16m length) with analysis tiles (2m length).

2.2. Pavement cracking protocol in Singapore

Developed by Tan et al. [6] in Singapore, the current cracking quantification system can be considered an SHA cracking protocol in the USA, where each local transport authority customizes cracking distress to their needs. The flowchart of crack rating concepts in Singapore is illustrated in Figure 5. Cracks are identified, classified, and quantified for every 10m of road section (or 4m width x 10m length = 40m^2). There are two levels of crack ratings:

- Level-2 crack rating is based on the percentage of cracks (or crack extent) over a 10-m length pavement section. It is rated from 0-5 with 0 being excellent and 5 being very bad (as shown in Table 2). This rating is intended as a macro-indicator (or a management-level index) of a pavement section's general cracking condition. The concept is similar to the MAP-21 cracking thresholds [14] used in the USA to categorize AC pavement conditions as good, fair and poor if the cracking percent <5%, from 5-20% and >20%, respectively. This is one of the final rule-making, performance measures for different types of pavements for Highway Performance Monitoring System (HPMS) reporting.

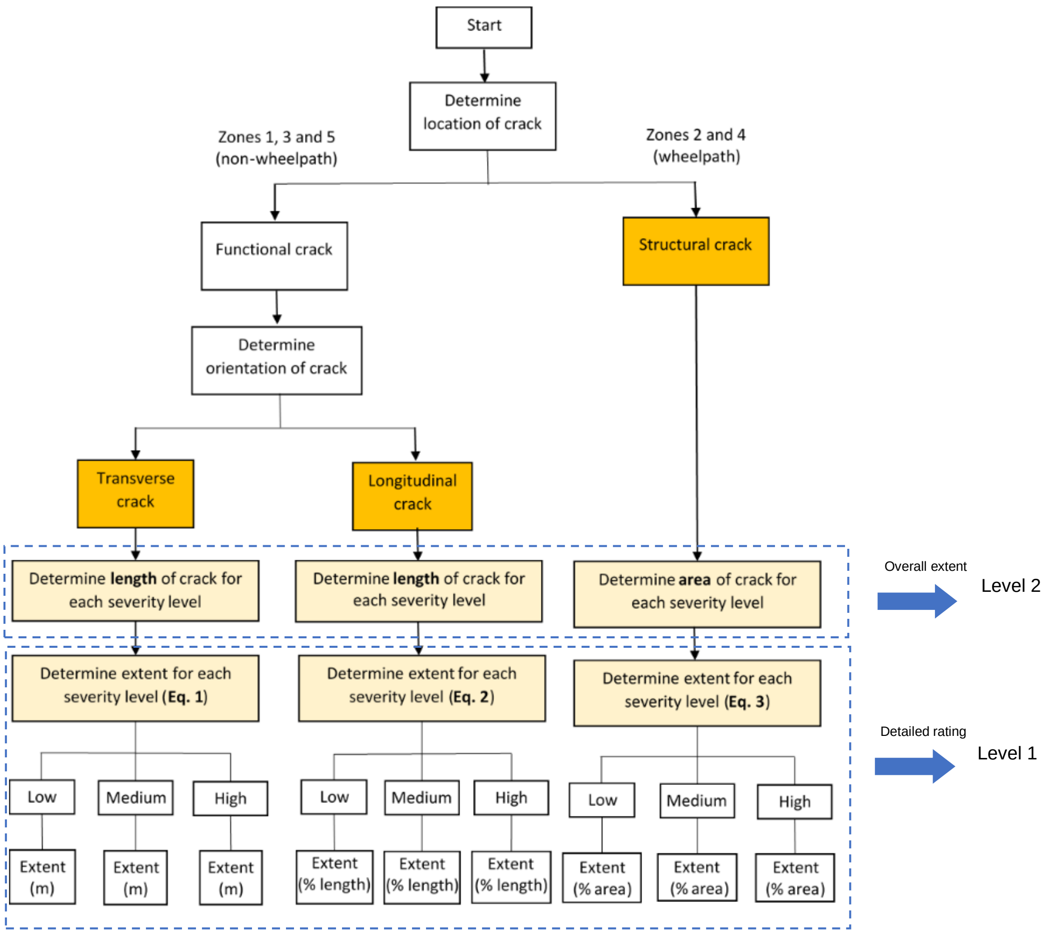

Figure 5. Flowchart of the crack rating process.

Table 2. Level-2 crack rating: thresholds and ranking.

Overall Extent, E (%)	Ranking (0-5)	Meaning
$E > 25$	5	very bad
$15 < E \leq 25$	4	bad
$10 < E \leq 15$	3	fair
$5 < E \leq 10$	2	good
$0 < E \leq 5$	1	very good
$E = 0$	0	excellent

- Level-1 crack rating provides decision-making when it comes to repairing action, scheduling, and allocation of budget. This level of rating contains detailed information, including cracking extent, crack types and severity. The severity of longitudinal and transverse cracks uses the definition in FWHA LTPP cracking protocol for asphalt pavement by using crack width (w) as the primary indicator. Transverse and longitudinal cracks are categorized into low, medium, or high severity levels if $w \leq 6$mm, 6mm $< w <$ 20mm, and $w >$ 20mm, respectively. On the other hand, structural crack (or wheel path crack) is defined similarly to fatigue cracking in ASTM D6433 cracking protocol by using interconnectivity between cracks as the main indicator. Structural cracks are classified as low severity when the area of cracks sealed or unsealed with no or a few interconnections, and medium severity when the area of interconnected lightly spalled cracks. It is high severity when the area of interconnected medium to highly spalled cracks with a well-defined pattern; also, some of the pieces may rock under traffic resulting in potholes. Detailed information can be found in [6].

It can be observed that the overall extent of Level 2 crack rating only takes the percentage of all crack types into account, which is similar to the PSCM concept. On the other hand, the final rating from 0 to 5, with 0 being excellent condition and 5 being very bad condition, is opposite to PSCI ranging from 0 to 100, with 0 being the worst possible condition and 100 being the best possible condition. The three severity levels of cracking can be interpreted from Level-2 crack rating. There is the need to quantify cracking as low, medium, and high severity to include ASTM E3303-21 cracking protocol into PCI calculations.

3. Methodology

Survey work was done in Singapore road network by using the Laser Crack Measurement System-2 (LCMS-2) shown in Figure 6a. The 3D images are collected from advance optics sensor equipped with laser line projectors, allow to automatically measure, detect and quantify all key functional parameters of pavement in a single pass [15]. The LCMS-2 is able to collect data at sampling rate of 28,000 profiles/s, vehicle speed from 0 to 100 km/h, with transversal resolution at 1 mm (4,096 points/profile) [16]. This unique 3D vision technology allows for automatic pavement condition assessment of all types of asphalt and concrete surfaces. High quality video images for verification of pavement condition were also collected from front camera. This LCMS-2 system has been used in Singapore to collect surface distress data of over 5,000 lane-km of pavement annually for the local PMS to maintain the road network. Similar system has been used to inspect the runway and taxiway pavement condition of several airports in Netherlands, Germany, Poland, France, Hong Kong, and Malaysia.

Collected data was processed using RoadInspect software to detects surface distresses. Figure 6b shows a grey-scale image (on the left) before overlaid with color coding (on the right) to visualize cracking conditions by different widths as green, orange, and red when crack width $w \leq 6$mm, $6 < w < 20$mm, and $w \geq 20$mm, respectively. To estimate Level 1, Level 2 ratings, PSCM and PSCI, MATLAB programming was used to develop related algorithms and functions. It is noted that MATLAB-based code was applied widely for data processing in pavement automatic survey, such as to determine the pavement cracking percentage [17], or to detect cracks and patches for PCI calculation in airport pavement [18]. Level 2 crack rating was compared with the PSCI to derive three cracking severity levels. Cracking data is based on 10-m unit road section, including Rank 0: 749 sections, Rank 1: 2749 sections; Rank 2: 227 sections; Rank 3: 102 sections; Rank 4: 115 sections; and Rank 5: 79 sections. The dominance of Rank 0 (excellent) and Rank 1 (very good) has demonstrated that pavements are generally in very good condition.

Figure 6a. An LCMS-2 equipment in operation.

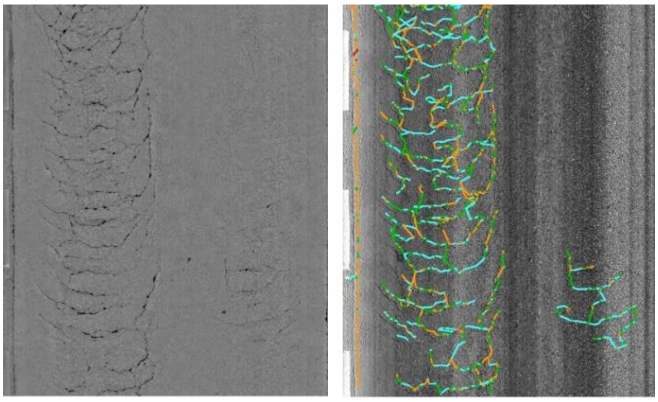

Figure 6b. (left) 3D range image, (right) with color overlay for cracking rating based on crack width.

4. Results and Discussion

4.1. Proposed severity cracking levels for ASTM 3303-21

LCMS-2 survey collects 3D images with the sizes of 4m width x 5m length, which were aggregated into 10m unit section (or 4m width x 10m length). This is the standard length for data format in the local PMS to monitor cracking and other surface indices. For each image, the whole area of $20m^2$ is subdivided into 10 small tiles to calculate PSCM and PSCI according to ASTM 3303-21 (see Figure 7). It is noted that the tile length of 2.5m (= 5.0m / 2) is slightly longer than ASTM 3303-21 recommendation of 2m but is within acceptable length.

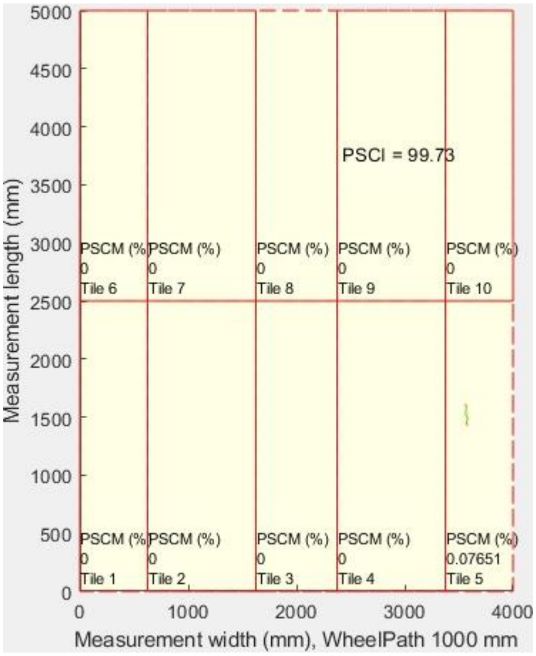

Figure 7a. Image 0346**,** PSCI = 99.73.

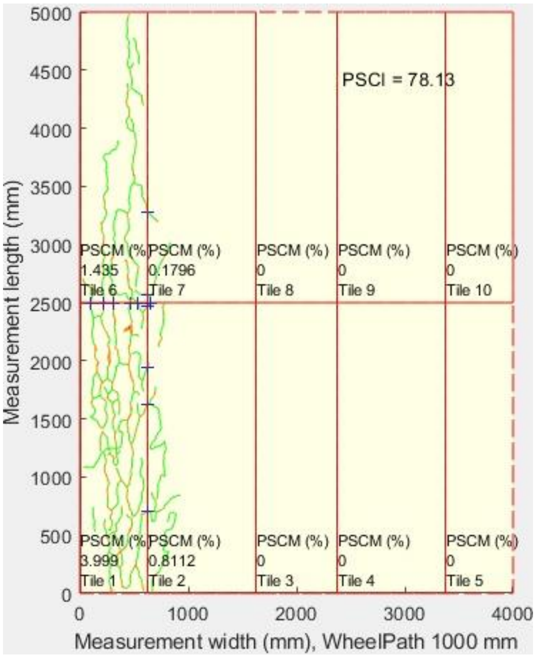

Figure 7b. Image 0373, PSCI = 78.13.

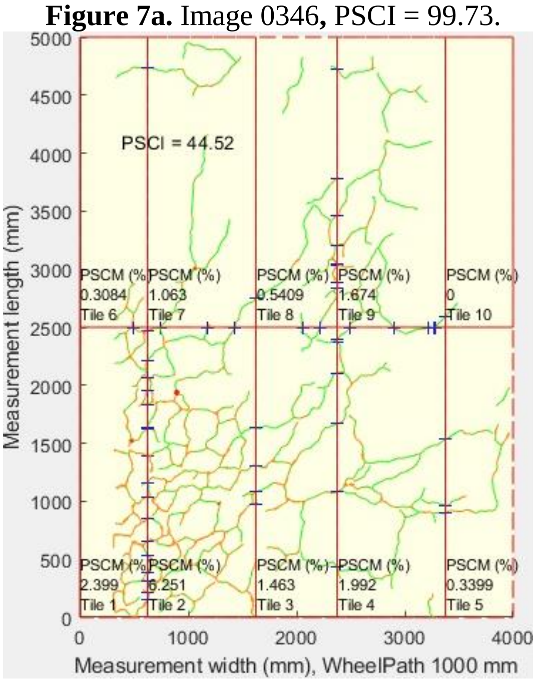

Figure 7c. Image 0315, PSCI = 44.52.

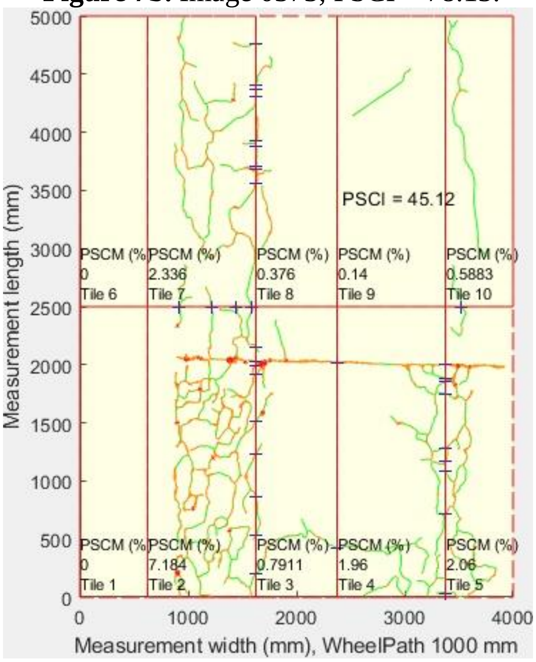

Figure 7d. Image 0298, PSCI = 45.12.

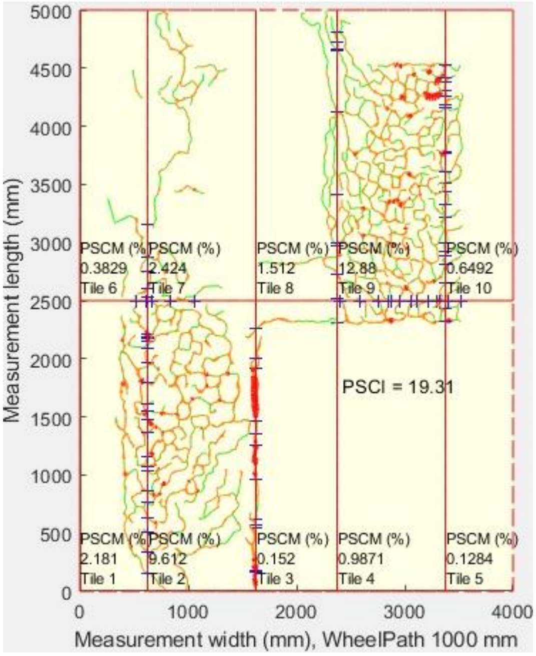

Figure 7e. Image 1545, PSCI = 19.31.

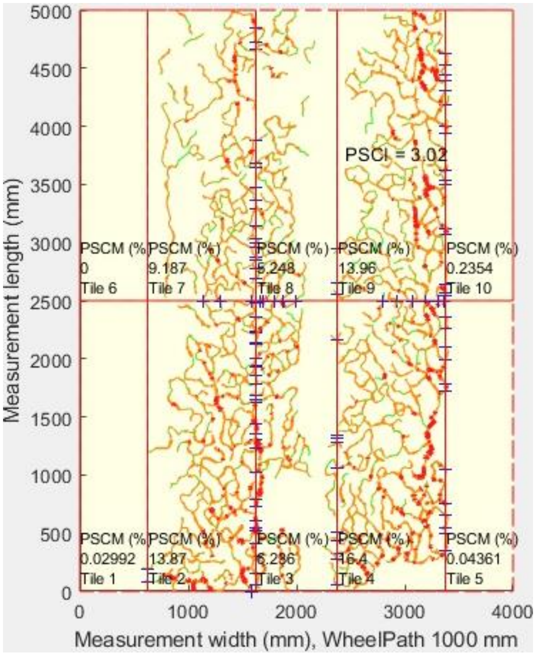

Figure 7f. Image 0232, PSCI = 3.02.

Figure 7a-7f illustrate PSCI results from LCMS-2 data at various low to high cracking conditions. The "**blue +**" sign depicts the intersection of cracks and tile border, where that crack is split into two sections. PCSM (%) value is shown at the bottom of each tile, whereas there is only one PSCI value for the whole area. The results of PSCM for each tile and PSCI for 20m^2 of asphalt pavement section are summarized in Table 3 based on ASTM 3303-21. For the purpose of this study, Figures 7a and 7b were selected to represent good pavement surface, while Figures 7e and 7f were selected to show heavy cracking with high-level interconnectivity under the two wheel-paths (tiles 2, 4, 7 and 9).

Table 3. Summary results of example data based on ASTM 3303-21.

LCMS-2 3D image	PSCM (%)										PSCI
	Tile 1	*Tile 2*	*Tile 3*	*Tile 4*	*Tile 5*	*Tile 6*	*Tile 7*	*Tile 8*	*Tile 9*	*Tile 10*	
0346	-	-	-	-	0.076	-	-	-	-	-	99.73
0373	4.00	0.812	-	-	-	1.435	0.180	-	-	-	78.13
0315	2.40	6.251	1.463	1.992	0.340	0.308	1.063	0.541	1.674	-	44.52
0298	-	7.184	0.792	1.960	2.060	-	2.336	0.376	0.140	0.588	45.12
1545	2.181	9.612	0.152	0.987	0.128	0.383	2.424	1.512	12.88	0.649	19.31
0232	0.030	13.87	6.236	16.40	0.044	-	9.187	5.248	13.96	0.235	03.02

Using all collected data and results (4,021 sections of 10m length), a boxplot is used to investigate the relationship between Level-2 crack ratings and PSCI. From Figure 8**,** the interquartile range of the boxplot covers values from 25th percentile to 75th percentile with the median at 50th percentile. At Rank 0 (excellent), PSCI = 100, and PSCI is decreased with the increased ranks. The interquartile range of rank 5 (very bad surface) is right below PSCI = 50, whereas, both rank 3 (fair surface) and rank 4 (bad surface) are well inside PSCI ranging from 50 to 75. Therefore, three severity cracking levels can be inferred from the boxplot based on PSCI values:

- PSCI $\geq$ 75 : low severity (excellent, very good and good surface)
- 75 > PSCI > 50 : medium severity (fair and bad surface)
- PSCI $\leq$ 50 : high severity (very bad surface)

It is noted that the above proposed severity ranking is quite similar to the simplified PCI rating scale from ASTM standards, in which pavement surface condition is rated as good, fair and poor condition when PCI ≥ 70, 70 > PCI > 55, and PCI ≤ 55, respectively.

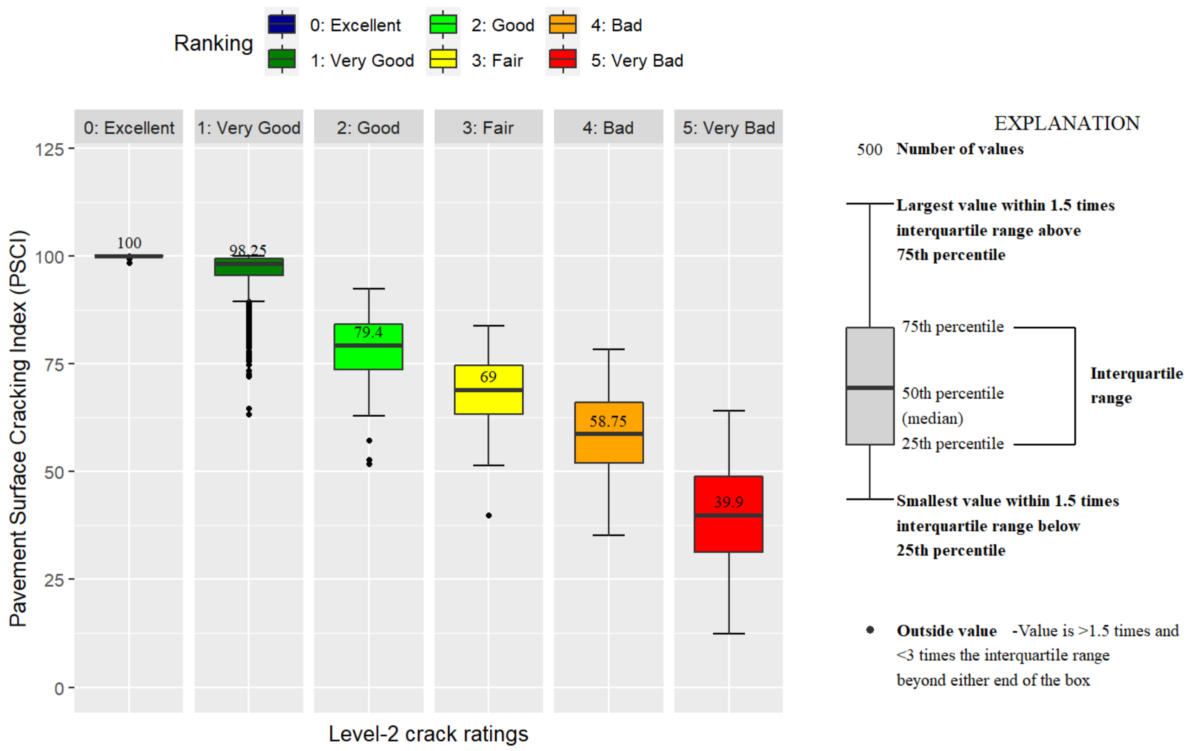

Figure 8. Boxplot showing the relationship between Level-2 crack ratings and PSCI.

4.2. Visualization example

A trial survey was conducted in an industrial area in Singapore which is subjected to heavy loading and traffic to demonstrate the proposed severity ranking thresholds. The surveyed track, around 11km, was selected as it covers a wide range of pavement asphalt surface conditions from very good to extremely cracking, mostly due to heavy traffic and truck loading. Figure 9 illustrate the results comparing Level-2 crack ratings (based on crack extent and 0-5 rating) with the proposed severity rankings for ASTM 3303-21 (based on 0-100 PSCI). Along the route, there are several locations (highlighted in dash boxes) with clusters of high surface cracking levels. LCMS-2 photos of two 10m unit sections are also included on the left side as examples of 3D digital images and cracking detection. The results expressed by color codes are quite identical between the two crack rating methods along the surveyed track.

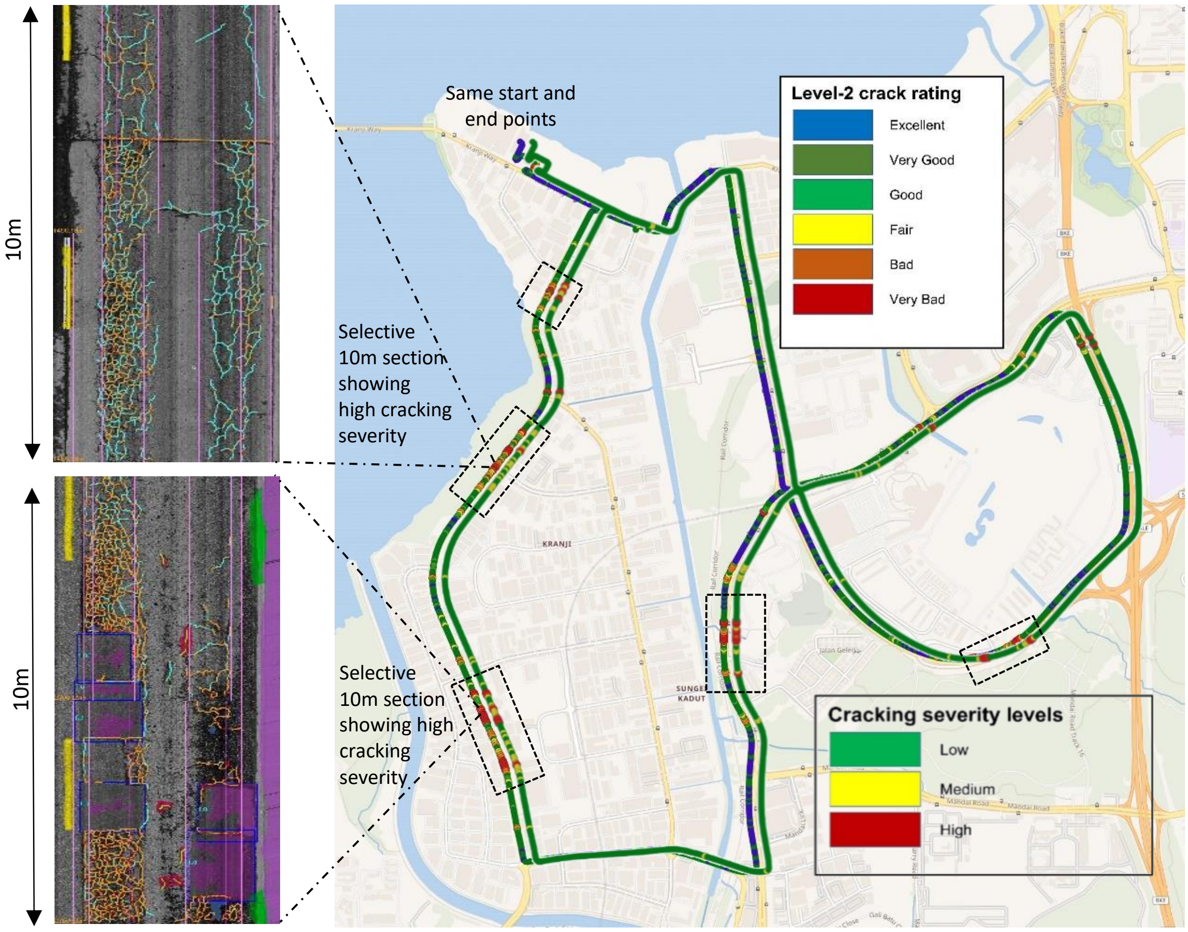

Figure 9. Visualization of Crack rating using Level-2 scale (left route with blue color) and proposed ASTM 3303-21 severity (right route). Data is offset for clarity.

5. Conclusion

Crack classification and quantification are important for pavement monitoring and management. With the development of technology, automatic survey equipment is dominant to the manual survey. This study was conducted to compare the two current methods (ASTM 3303-21 and local cracking protocol in Singapore) and potentially bridge the gaps between them. The main similarity is rating overall cracking conditions based on the percentage/extent of cracking regardless of crack types to simplify the rating protocols. From collected 3D images, crack locations, lengths, and widths are extracted for further processing. Using MATLAB programming, the crack quantification by recent ASTM standard is implemented in Singapore road network for potential use in the local PMS in the future. The developed algorithms and functions can be simply customized for different section unit (e.g., 20m or 50m) and integrate other distresses (e.g., rutting, ravelling) to calculate any composite pavement index.

The study has proposed three levels of cracking severities: low, medium, and high, based on PSCI value as PSCI ≥ 75, 50 < PSCI < 75 and PSCI ≤ 50, respectively. With the proposed thresholds, the cracking quantification results from ASTM 3303-21 standard can be included in PCI calculations in ASTM D6433. However, the results may only apply to fatigue cracks under the wheel-paths with different levels of connectivity. For other crack types (e.g., longitudinal, and transverse cracking), using crack width as recommended by FWHA LTPP is sufficient for the quantification and classification purpose.

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