

# Automatic Pavement Crack Rating for Network-Level Pavement Management System



Jun Yew Tan , Teron Nguyen , S. Kapilan, Than Than Nyunt, Yeow Hoo Lim, and Yin Fong Leong

**Abstract** Cracking is one of the important distresses that can be used to trigger pavement maintenance treatments. Traditional crack rating is commonly based on the Pavement Condition Index (PCI) approach involving time-consuming visual inspection and manual classification processes. The emergence of automatic and high-speed laser imaging devices significantly improves the efficiency and productivity of pavement crack data collection but it requires suitable methods and concepts for automatic crack ratings. This paper discusses the development of an automatic pavement crack rating using crack data collected from a high speed 3D sensor. Two levels of crack ratings are proposed: Level 1 provides detailed crack information including cracking extent, crack types and severity, and Level 2 is a macro-indicator of general/overall cracking extent on a pavement section of 10 m length. The method and concept were developed and tested initially for Singapore expressway network under the effort of the Land Transport Authority (LTA) of Singapore to integrate crack data into the pavement management system (PMS).

**Keywords** Pavement crack · LCMS-2 · Automatic classification · Crack rating · Pavement management system

## 1 Introduction

### 1.1 Background

Pavement is an expensive road infrastructure asset that require suitable maintenance and rehabilitation to maintain its service life. To manage the road infrastructure, transportation agencies often use Pavement Management Systems (PMS) to store,

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analyse and visualise large datasets in the network scale. PMSs require accurate and reliable pavement condition data as critical input in order to evaluate the health of the pavement network [1, 2]. Surface distresses such as pothole, crack, rutting and roughness are important parameters that define the health of the pavement network in a PMS [3, 4].

In Singapore, pavement surface defects or distresses are typically gathered by teams of inspectors as they drive through the road network at low speed. Surface defects that require urgent attention such as potholes are marked and work orders are issued subsequently to carry out rectification works within a stipulated time. As most of the surface defects are repaired almost immediately, these are not captured efficiently into the pavement management system.

The emergence of automated equipment (semi or full) offers the opportunity to significantly improve the productivity and efficiency of pavement surface condition data collection in the current dynamic road environment [5]. Roads can now be surveyed at a much faster rate and more thoroughly, and the data is available digitally for all types of analysis. This has opened up the opportunity to use surface crack data as additional input to Singapore's PMS.

This paper discusses the development of an automatic crack rating for asphalt pavement that is suitable for network-level pavement management systems.

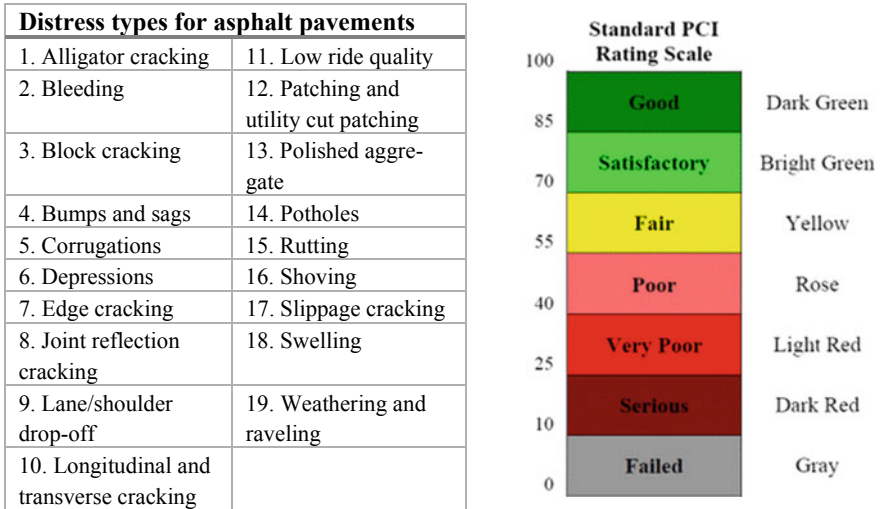
## ***1.2 Crack Rating Systems***

Crack rating is one of the key parameters of a wider pavement condition rating system. There are many pavement condition rating systems used around the world such as the Pavement Condition Index (PCI), Pavement Serviceability Rating (PSR), Pavement Condition Rating (PCR), etc.

The Pavement Condition Index (PCI) system is the most widely known pavement rating system developed by the US Army Corps of Engineers [6]. The PCI system rates the pavement condition as a range of numerical value between 0 and 100, with 100 representing the best possible condition and 0 representing the worst possible condition. The PCI system includes 19 types of pavement distresses including non-crack parameters such as ride quality, rutting, depressions, polished aggregates and weathering and raveling (see Fig. 1).

## ***1.3 Motivation***

A rating system for crack-only data is required for Singapore's pavement management system. The PCI system is the most widely used but it often involves time-consuming, laborious visual inspection and manual classification processes as some of the distresses in the PCI system is not suited for fully automatic processing. Studies



**Fig. 1** Asphalt pavement distresses considered by the PCI system and the Standard PCI rating scale [6]

have also shown that manual survey results do not correlate well with automatic classification and rating [7, 8].

In researching and developing a suitable crack rating system for Singapore condition, consideration was given to the needs of the operational as well as the management level. The operational level requires more detailed information on the crack in order to carry out the appropriate repair action. On the other hand, the management level is interested in a simple linear ranking, for example 0–5, that can be quickly and easily compared from one pavement section to the other. Therefore, the resulting crack index system must be reliable and able to meet the conflicting needs of both the management and the operational level.

An automated classification procedure needs to be developed and suited to the capabilities of the automated survey equipment within the Singapore dynamic road environment and traffic loading based on the types of crack that commonly occur here.

## 2 Approach and Methodology

### 2.1 Automated Pavement Condition Survey

In recent years, the emergence of advanced image sensor technology allows pavement condition survey to be carried out automatically and quickly. One advanced system being used is the Laser Crack Measurement System-2 (LCMS-2) shown in Fig. 2.

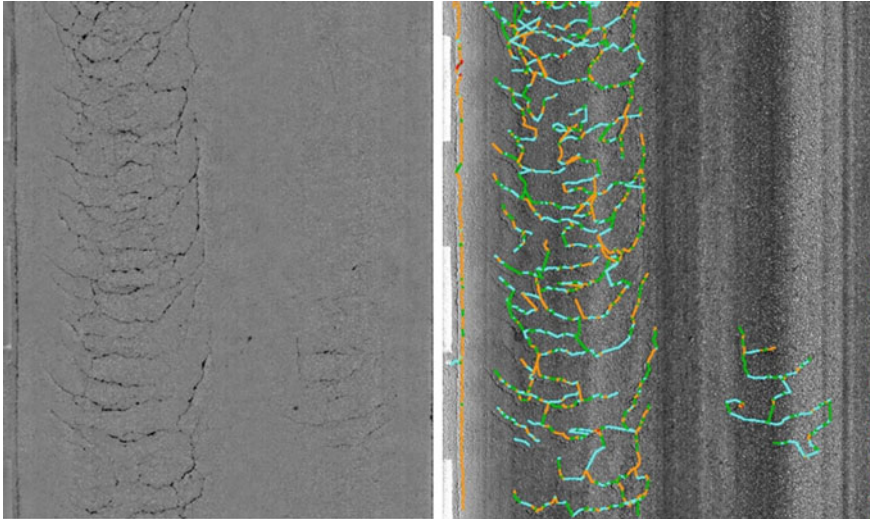


**Fig. 2** An LCMS-2 vehicle used in Singapore

The LCMS-2 sensor uses laser line projectors, high speed camera and advanced optic to acquire high resolution 3D profiles of the lane of a road [9]. This unique 3D vision technology allows for automatic pavement condition assessment of all types of asphalt and concrete surfaces. The LCMS-2 acquires both 3D and 2D image data of the road surface with 1 mm interval over a 4 m lane width in transverse direction and also 1 mm interval in the longitudinal direction at survey speeds up to 100 km/h [10].

The LCMS-2 system comes with a processing software, called RoadInspect, that automatically detects surface distresses. Figure 3 shows a grey-scale image on the left known as the range image which shows the distance from the sensors to the road surface corrected to the same reference level. The image on the right is a 3D image which shows pavement cracks visualized in color-coded overlays. The color coding is based on a user-defined range of crack width.

The colour coding overlay for the cracks used in this image and all subsequent 3D images is: Green (crack width < 3 mm), Orange (crack width 3-20 mm) and Red (crack width > 20 mm). The color-coded overlay produced by RoadInspect software shown in Fig. 3 is useful at micro-level but not suitable for network-level pavement management system. In order to categorize cracks in a meaningful manner for pavement management purpose, the crack data from the LCMS-2 needs to be organized and rated in such a way that is consistent with the pavement management functions.



**Fig. 3** LCMS-2 rating of cracking width (left) range image and (right) using color overlay

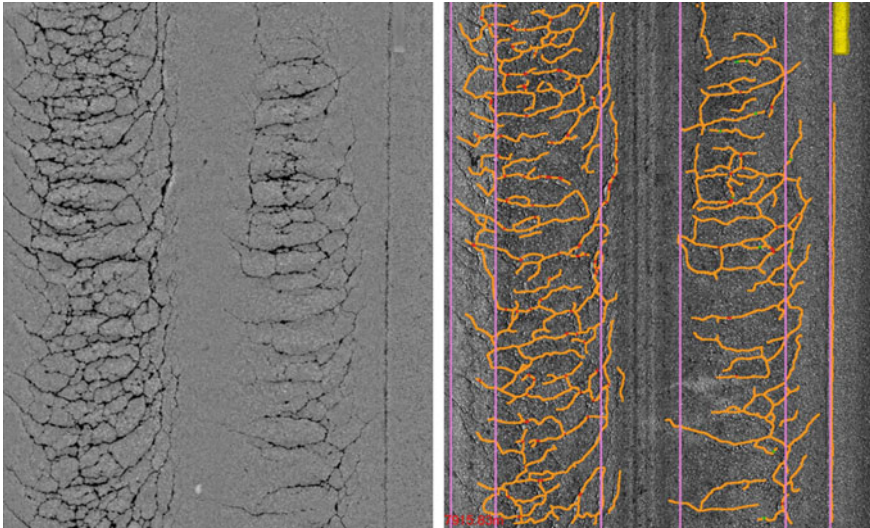
## 2.2 Classification of Crack Types

The first step in developing a crack rating system is to consider the types of cracks to be classified and rated. The PCI system classifies six types of cracks for asphalt pavement, namely alligator cracking, block cracking, edge cracking, joint reflection cracking, longitudinal and transverse cracking, and slippage cracking [6]. It was decided that the number of crack types shall be simplified considering factors such as the frequency of occurrence in Singapore roads and the main causal factor.

Proper classification of crack types is vital in the assessment works. To determine the types of cracks that most commonly occur in Singapore pavement condition, distress data of over 300 lane-km of asphalt pavements was collected and studied. The following observation can be summarized:

- (a) Three main classification of cracks can be observed: transverse cracks, longitudinal cracks, and alligator-type cracks.
- (b) The transverse cracks occur mainly as construction joints and the several different types of transition joints at bridges/flyovers.
- (c) Longitudinal cracks are mostly constructions joints/resurfacing of a lane occurring outside the wheelpath.
- (d) Alligator cracks and slippage cracks can be found mostly within the wheelpath.

Pavement surface distresses can be broadly regarded as either functional or structural related. Transverse and longitudinal cracks are in-principle functional distress types that are climate or environmental related, whereas alligator, block and slippage cracking are structural distress types caused by or associated with traffic loading.



**Fig. 4** Example of high severity structural cracking (slippage crack characterized by crescent shape) (left) range image and (right) using color overlay

Figure 4 is an example of high severity structural cracking consisting of slippage cracks characterized by its crescent shape.

### 2.3 Definition of Wheelpath

Transverse and longitudinal cracks are generally defined based on their angle and orientation. However, some longitudinal cracks can be load-induced or structurally-related cracks.

To make a distinction between structural cracks and longitudinal cracks (defined as functional distress), reference can be made to whether the cracks occur within the wheelpath or outside the wheelpath. AASHTO R 85-18 [11] defines five zones across the lane width based on the crack location (see Fig. 5). Zones 1 and 5 are located outside the wheelpaths, zones 2 and 4 are the wheelpaths and zone 3 is in between the wheelpaths. The width of zones 1 and 5 can be varied according to the width of a lane and local requirements. The centre zone width is 750 mm and both wheelpaths (zones 2 and 4) are 1000 mm.

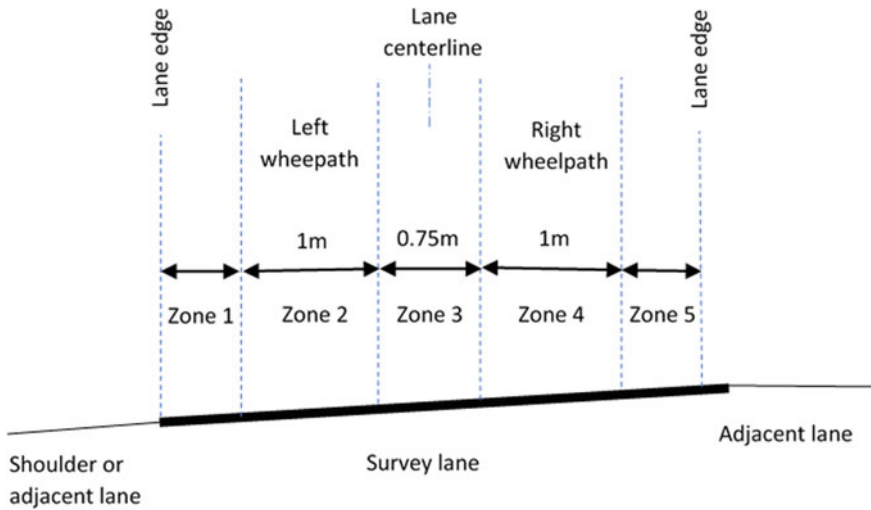


Fig. 5 Definition of wheelpath on Singapore roads based on AASHTO R 85-18 [11]

### 3 Rating Procedure

#### 3.1 Sample Unit

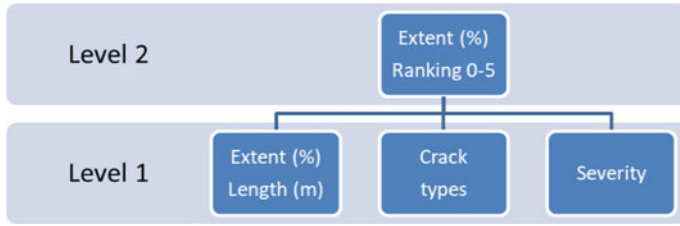
A pavement is rated based on a unit area referred to as sample unit. Sample unit can be defined based on a length or an area that is logical and consistent with the PMS functions. In Singapore's context, a sample unit for crack rating is defined as every 10 m length of a road in order to be consistent with the data interval used in the PMS.

#### 3.2 Rating Process

Two levels of crack rating are proposed, from general to detailed information, to serve different purposes of the local transport authority (see Fig. 6).

Level 2 crack rating is a macro-indicator of general/overall cracking extent on a pavement section. This is a management-level index which gives a quick overview of the general crack health of the road network.

Level 1 crack rating contains detailed crack information including cracking extent, crack types and severity. This is an operational-level index which can be used for decision-making when it comes to repair action, scheduling and allocation of budget.



**Fig. 6** Two levels of crack rating indicator and the components of crack data within each level

**Table 1** 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

### 3.3 Level 2 Crack Rating

Level 2 crack rating is calculated as the total crack areas over 40 m<sup>2</sup> (4 m width × 10 m length) of the pavement unit section, and regardless of crack types, extent and severity. Based on the extent (%) of all cracks on a pavement section, the equivalent rating in a five-scale (0–5) is proposed as shown in Table 1. At crack ranking = 0, the pavement section is in excellent condition, whereas ranking = 5 means the pavement section is in very bad condition.

### 3.4 Level 1 Crack Rating

The rating process is shown in a flowchart in Fig. 7. In summary, the rating process can be organized into the following steps:

- Step 1: Determine whether it is functional or structural crack based on the location of the crack.
- Step 2: For functional crack, determine whether it is transverse or longitudinal crack based on orientation.
- Step 3: Determine severity level according to the type of crack.
- Step 4: Compute extent of the crack for each severity level.



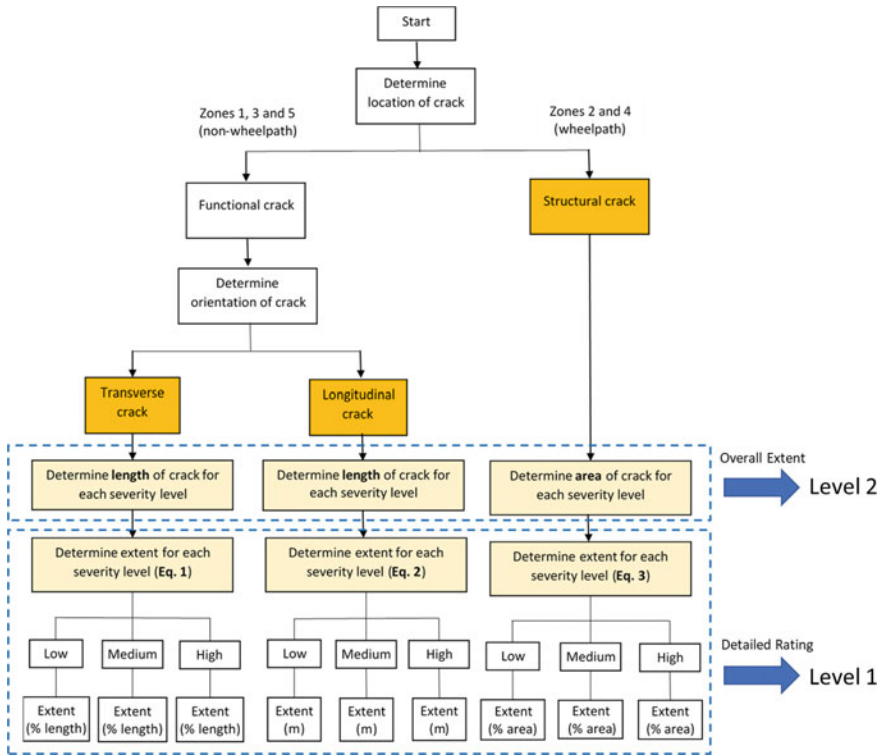


Fig. 7 Flowchart of crack rating process

### 3.4.1 Severity and Extent

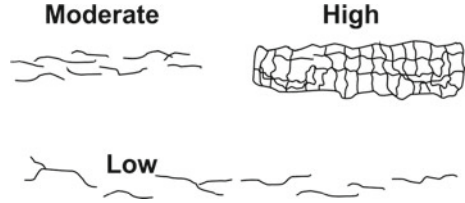
The outcome of the rating process should provide the following vital information for the road agency:

- (a) Type of crack (transverse, longitudinal, or structural)
- (b) Severity level
- (c) Extent.

Severity level refers to how far the cracking has progressed and is often directly related to the crack width, whereas extent is the amount of road surface area which is affected. Severity is categorized into three levels: low, medium and high.

The severity for linear cracks such as transverse and longitudinal cracks is defined by the crack width and categorized into low, medium, or high severity level. The range of crack width for the categories differs from country to country depending on local specifications and requirements. The following severity levels for transverse and longitudinal cracks is proposed for Singapore and this can be further refined as more data is available:

**Fig. 8** Illustration of severity level for structural cracks



*Severity Level for Transverse and Longitudinal Cracks*

- Low: average crack width  $\leq 3$  mm
- Medium:  $3\text{mm} < \text{average crack width} \leq 20$  mm
- High: average crack width  $> 20$  mm.

Severity level for structural cracking is more complicated as it consists of multiple interconnecting cracks. The following description is used to define structural cracks and this is shown graphically in Fig. 8.

*Severity Level for Structural Cracks*

- Low: area of cracks sealed or unsealed with no or a few interconnections
- Medium: area of interconnected lightly spalled cracks
- High: area of interconnected medium to highly spalled cracks with a well-defined pattern. Some of the pieces may rock under traffic resulting in potholes.

The extent of a crack, except for transverse crack, is the percentage of surface area or length that is affected by the crack. The extent for linear cracks (transverse and longitudinal) is computed using length while the extent for area cracks (structural) is computed using area.

For transverse crack, the extent is not computed into percentage because there is no definable limit to the number of transverse cracks that may occur within a sample unit. The equation for transverse crack is shown in Eq. (1).

$$E_{u,s}^T = \sum_i^n T(\text{length})_{s,i} \tag{1}$$

where

- $E^T$  is the extent for transverse crack (expressed in meter) for sample unit  $u$  and severity level  $s$ .
- $T(\text{length})_{s,i}$  is the length of the  $i$ -th transverse crack with severity  $s$ .
- $n$  is the total number of transverse cracks with severity  $s$ .

For longitudinal crack, the extent is computed as a percentage of longitudinal crack length to the total length of zones 1, 3 and 5 within a sample unit, as shown by Eq. (2).

$$E_{u,s}^L = \frac{\sum_i^n L(\text{length})_{s,i}}{l_1 + l_3 + l_5} \times 100\% \quad (2)$$

where

$E^L$  is the extent for longitudinal crack (expressed in percentage) for sample unit  $u$  and severity level  $s$ .

$L(\text{length})_{s,i}$  is the length of the  $i$ -th longitudinal crack with severity  $s$ .

$n$  is the total number of longitudinal cracks with severity  $s$ .

$l_1 + l_3 + l_5$  is the sum of the length of the three functional non-wheelpath zones (zones 1, 3, and 5) within a sample unit. This shall be equal to  $10 \text{ m} + 10 \text{ m} + 10 \text{ m} = 30 \text{ m}$ .

For structural crack, the extent is computed as a percentage of total structural crack area to the total area of zones 2 and 4 within a sample unit, as shown by Eq. (3).

$$E_{u,s}^S = \frac{\sum_i^n S(\text{area})_{s,i}}{a_2 + a_4} \times 100\% \quad (3)$$

where

$E^S$  is the extent for structural crack (expressed in percentage) for sample unit  $u$  and severity level  $s$ .

$S(\text{area})_{s,i}$  is the area of the  $i$ -th structural crack with severity  $s$ .

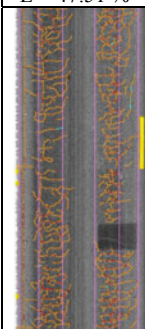
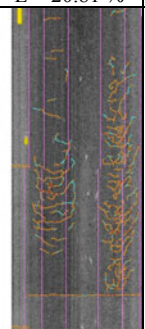
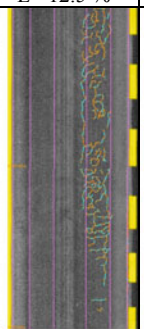
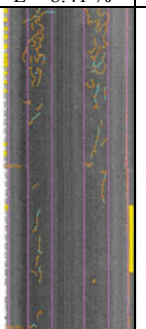
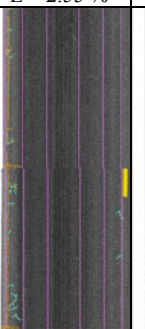
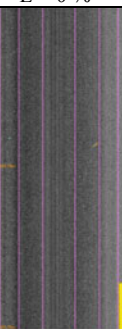
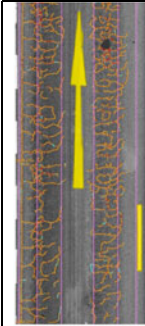
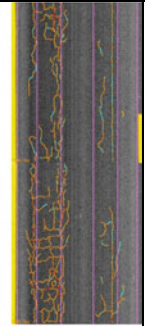
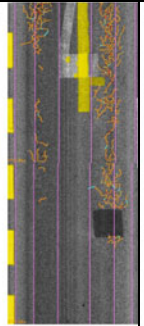

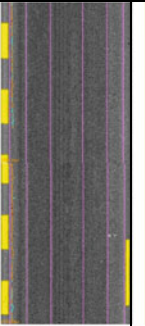
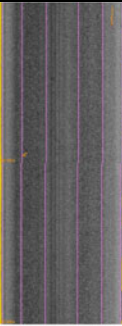
$n$  is the total number of structural cracks with severity  $s$ .

$a_2 + a_4$  is the sum of the area of the two wheelpath zones 2 and 4 within a sample unit. This shall be equal to  $10 \text{ m}^2 + 10 \text{ m}^2 = 20 \text{ m}^2$ .

## 4 Result and Discussion

For validation purpose, the proposed automated cracking rating was applied to every 10 m of LCMS-2 data collected in Singapore expressway network. After data collection, crack information was analysed, classified and quantified according to the flowchart in Fig. 7. Table 2 shows samples of validation carried out for the overall extent and level 2 crack ranking, ranging from 0 to 5, on the Kranji Expressway. Medium and high severity structural cracks were seen clearly on pavement surfaces with ranking 3, 4 and 5. High severity cracks were observed on both wheelpaths of crack rating 5 along 10 m segments. The calculated crack extent ( $E$  in %) and the appearance of cracking along 10 m length of pavement unit section from RoadInspect output are quite similar. The simplified 5-scale level 2 crack rating can express pavement crack condition in a relatively linear relationship. Maintenance and rehabilitation activities should be planned immediately for those segments with level 2 crack rating from 3 to 5.

**Table 2** Validation samples of overall extent (E%) and Level 2 crack ranking on Kranji Expressway

Ranking: 5	Ranking: 4	Ranking: 3	Ranking: 2	Ranking: 1	Ranking: 0
E = 47.51 %	E = 20.81 %	E = 12.5 %	E = 8.41 %	E = 2.55 %	E = 0 %
					
E = 44.26 %	E = 18.88 %	E = 14.35 %	E = 9.21 %	E = 2.10 %	E = 0 %
					

From level 2, cracks are broken down into structural, longitudinal and transverse cracks with three severity levels for each crack type. Table 3 lists the examples of both crack rating levels which are proposed for LTA PMS. Level 2 crack index can be used as macro-level indicator to quickly tell the cracking extent of a pavement segment. It should be noted that the severity or “seriousness” of a crack may not be equal to the “extent”. The crack severity can be different even within the same cracking index (e.g. index 1, 2, 3, 4 or 5) due to direction and various connectivity levels. For example, a section with ranking = 1, where cracking extent ranges from 0 to 5%, may contain transverse or longitudinal cracks at high severity that requires a specific crack sealing/filling preventive maintenance. Therefore, the simplified crack index at level 2 can provide an overview of the cracking condition. Further investigation into level 1 is always recommended for detailed consideration of suitable maintenance treatments.

**Table 3** Data format incorporating both levels of crack rating

Road Code	Section	Str-Low	Str-Mid	Str-High	Long-Low	Long-Mid	Long-High	Tran-Low	Tran-Mid	Tran-High	Overall Extent	Ranking
BUE01Q	020	0.00	0.00	90.57	0.00	18.30	0.00	0.00	0.00	0.00	46.66	5
BUE01Q	020	9.50	0.00	75.00	0.00	12.90	0.00	0.00	0.00	0.00	43.22	5
BUE01Q	020	0.00	24.70	50.00	0.00	0.00	0.00	0.00	0.00	0.00	37.35	5
BUE01Q	020	14.01	0.00	49.59	0.00	0.00	0.00	0.00	0.00	0.00	31.80	5
BUE01Q	020	0.00	10.58	49.63	0.00	0.00	0.00	0.00	0.00	0.00	30.11	5
BUE01Q	030	28.49	0.00	0.00	0.00	30.90	0.00	0.00	5.35	0.00	17.90	4
BUE01Q	020	5.41	0.00	14.90	0.00	0.00	0.00	0.87	1.05	0.00	10.63	3
BUE01Q	020	16.77	0.00	0.00	0.00	0.00	0.00	0.00	3.11	0.00	9.16	2

*Note* Str-Low, Str-Mid and Str-High: Structural crack at low, medium, and high severity. Long-Low, Long-Mid and Long-High: Longitudinal crack at low, medium, and high severity. Tran-Low, Tran-Mid and Tran-High: Transverse crack at low, medium, and high severity

## 5 Conclusion

The emergence of automatic data collection method for cracking requires reconsideration of pavement condition evaluation which was built conventionally on visual inspection and manual survey [12]. The usage of 3D imaging sensor in LCMS-2 in Singapore has resulted in higher data collection efficiency and the opportunity to utilise crack data as part of LTA PMS.

This study has initially developed an automatic pavement crack rating for network-level pavement management system by incorporating two levels of crack rating for different usage purposes. Crack rating should start from general ranking—Level 2 to detailed rating—Level 1 as recommended in recent practices [7]. The proposed crack rating scales are simple enough to be analyzed in combination with pavement structural, roughness, and rut depth data for final decision making on pavement maintenance at network level. Validation of the data sampled from two expressways have shown promising results. Further study is on-going to validate and improve proposed methodology based on larger datasets.

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## References

1. AASHTO (2012) Pavement management guide, 2nd edn. American Association of State Highway and Transportation Officials
2. Nguyen T, Lechner B, Wong YD (2019) Response-based methods to measure road surface irregularity: a state-of-the-art review. *Eur Transp Res Rev* 11(1):1–18
3. Haas R, Hudson WR (2015) Pavement asset management. Wiley
4. Nguyen T, Lechner B, Wong YD, Tan JY (2021) Bus ride index—a refined approach to evaluating road surface irregularities. *Road Mater Pavement Des* 22(2):423–443
5. NCHRP Synthesis 531 (2019) Automated pavement condition surveys—a synthesis of highway practice
6. ASTM D6433-18 (2018) Standard practice for road and parking lots pavement condition index surveys (PCI)
7. National Academies of Sciences, Engineering, and Medicine (2020) Standard definitions for common types of pavement cracking. The National Academies Press, Washington, DC. <https://doi.org/10.17226/25928>
8. Henning T, Mia M Did we get what we wanted?—Getting rid of manual condition surveys, Pavemetrics Systems Inc. website <http://www.pavemetrics.com>
9. Laurent J, Hébert J, Talbot M Automated detection of sealed cracks using 2D and 3D road surface data, Pavemetrics Systems Inc. Website <http://www.pavemetrics.com>
10. Drenth K, Tan JY, Drenth M, Kit OJ (2020) LCMS-2 measurements of the quality of road markings. In: Proceedings of the 9th International conference on maintenance and rehabilitation of pavements—Mairepav9. Springer, Cham, pp 943–952

11. AASHTO R 85-18 (2018) Standard practice for quantifying cracks in asphalt pavement surfaces from collected pavement images utilizing automated methods
12. FHWA Distress identification manual for the long-term pavement performance program (FHWA-HRT-13-092). Revised May 2014