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16. Abstract			

This paper presents the image-processing algorithm customized for high-speed, real-time inspection of pavement cracking. In the algorithm, a pavement image is divided into grid cells of 8 x 8 pixels, and each cell is classified as a non-crack or crack cell using the grayscale information of the border pixels. Whether a crack cell can be regarded as a basic element (or seed) depends on its contrast to the neighboring cells. A number of crack seeds can be called a crack cluster if they fall on a linear string. A crack cluster corresponds to a dark strip in the original image that may or may not be a section of a real crack. Additional conditions to verify a crack cluster include the requirements in the contrast, width, and length of the strip. If verified crack clusters are oriented in similar directions, they will be joined to become one crack. Because many operations are performed on crack seeds rather than on the original image, crack detection can be executed simultaneously when the frame grabber is forming a new image, which permits a real-time, online pavement survey. The trial test results show good repeatability and accuracy when multiple surveys were conducted in different driving conditions.

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Automatic Inspection of Pavement Cracking Distress

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Disclaimers

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Patent Disclaimer: The University of Texas at Austin filed a U.S. patent on the "Automated Pavement Surface Distress Measurement System" on May 10, 2005.

Engineering Disclaimer

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Acknowledgments

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1. Introduction

Pavement surface distresses are common failures of pavement construction. Among these distresses, cracking is a major cause, jeopardizing road serviceability and requiring prompt surface rehabilitation. From the early 1970s, researchers started to use digital imaging technology to develop automated pavement surface distress inspection (APSDI) systems for pavement distress surveys [1,3,4]. An APSDI system may reduce disturbances to public traffic and road hazards to human inspectors during the survey. A true APSDI system needs to be able to detect thin cracking distress of 2 mm in width in various background textures while traveling at highway speeds. Given the complexity of pavement conditions and textures, implementing such a system remains challenging.

The commercially available APSDI systems differ in their image acquisition devices. These devices include area-scan, linescan, and time delay integration (TDI) linescan cameras. An area-scan camera grabs one frame of image at a time and must be mounted to have a clear and perpendicular view of a rectangle area of the pavement. This makes the system vulnerable to vehicle vibration because of the long extension of the mounting device. It is also difficult to provide uniform lighting to a large area under different weather conditions. The TDI technology integrates photo charges from multiple CCD line arrays. It is useful in high-speed image acquisition where the exposure time is limited or when the illumination is low. However, a TDI camera is sensitive to the optical alignment to the target. The camera has to be mounted perfectly perpendicular to the surface of pavement. Vehicle vibration causes more blurriness of image with a TDI camera, especially at a high speed. Recent development on CCD technology not only dramatically increases the camera's resolution and line scan rate, but also greatly enhances the sensitivity of CCD sensors. For example, the Dalsa Piranha2 2048 pixel linescan camera can grab 44,000 line images per second, and its sensitivity is high enough to get good quality images while moving 112 km/h (70 mph) without artificial lighting.

Another main characteristic that differentiates APSDI systems is the image processing technique used for the feature extraction. The processing speed is one of the main concerns when developing an effective image processing algorithm for real-time crack detection. If the image size is 2048 x 512 pixels covering a pavement area of 3.05 x 0.76 m^2 (10 x 2.5ft^2), and the vehicle speed is 112 km/h (70 mph), the computer has only 24.35 ms to acquire and process an image. This is why many existing systems use an offline approach to extract data from grabbed images. The offline processing, however, provides no real-time data on site, and it requires additional work and equipment for the post processing. A recent study conducted by the Naval Facilities Engineering Service Center concluded that an offline APSDI system and the manual survey provided consistent pavement condition index (PCI) measurements, and the costs of both surveys were at the same level [5]. Many offline image processing techniques such as digital filter, adaptive threshold, and expert system can be readily found in the literature [6,7,8]. In 1998, the CSIRO Manufacturing Science & Technology in Australia developed an automated pavement surface inspection system, RoadCrack, which can be operated at a vehicle speed up to 105 km/h while processing images in real time. The system uses four CCD cameras to grab

images of a 500 mm wide wheel path with a 1mm resolution. Although it was the first fully functional online APSDI system, RoadCrack guarantees only a minimum of 10 percent distance coverage.

In 1999 we started a project to develop an APSDI system called "VCrack" for the Texas Department of Transportation (TxDOT). The VCrack system was designed to run at a vehicle speed ranging from 5 to 112 km/h (3 to 70 mph), to characterize cracking distress in real time, and to report the data via a local network to the database at a given distance interval. The data format was required to be compatible with both the Texas PMIS (pavement management information system) protocol and the AASHTO (American Association of State Highway Transportation Officials) protocol. The system also needed to cover the full width of pavement (3.05m) and 100 percent of the pavement in traveling distance. The system has been used by TxDOT for pavement inspections since 2003. This paper intends to report the image processing algorithm used in the VCrack system for crack detections.

2. System Configuration

Figure 2.1 shows a TxDOT's pavement inspection vehicle equipped with the VCrack system, which consists of a linescan CCD camera, a PCI frame grabber, and a PC computer. The linescan camera, mounted in a waterproof enclosure, is a Dalsa Piranha2 camera that has a linear array of 2048 pixels. When the camera covers 3.05 m in width, it has a ground resolution of 1.488 mm/pixel. The camera captures a line image one at a time and sends individual lines to the frame grabber through a high-speed Camlink interface. Once 512 lines, covering 0.76 mm (3 ft) in distance, are accumulated on the board, an image of 2048 x 512 pixels is transferred to the main memory of the computer. The cumulative lines per image can be set to a different number. The line scan rate of the camera is calculated based on the traveling speed and dynamically adjusted by the computer through Camlink's communication port. The rate must be synchronized with the vehicle speed to ensure that each line covers exactly the same distance on the pavement. The exposure time of the CCD array is also controlled for each scan through the communication port. The brightness of the current image can be used to calculate a reasonable exposure time for the next scan to avoid an over- or under-exposed image. It takes about 5 milliseconds to transfer this 8-bit grayscale image from the frame grabber to the system memory, leaving less than 20 ms for the image processing when the vehicle travels at the speed of 112 km/h. The VCrack can communicate to the other inspection modules on the vehicle through a local network. It supports multiple data clients during run time. It accepts external GPS and time data from other modules for the system synchronization.
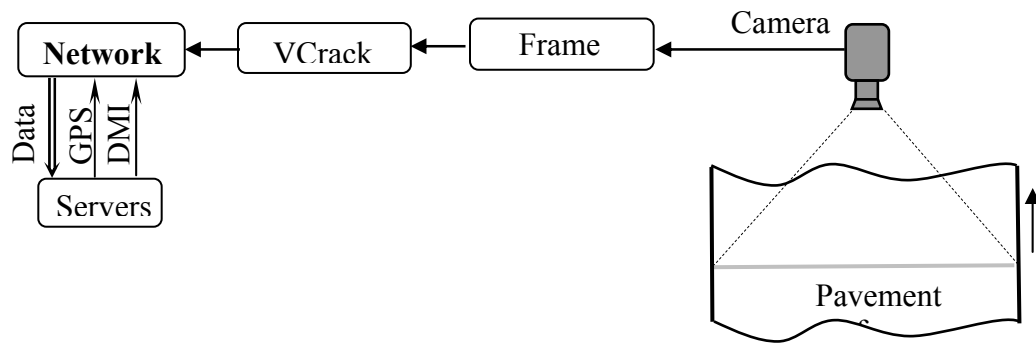

Figure 2.1   Image acquisition and processing modules

3. Grid Cell Analysis (GCA)

A primary clue for detecting cracks in a pavement image is that a crack is a thin strip of pixels whose intensities are appreciably darker than the surrounding background. In order to save time in crack tracing and classification, we attempt to divide an image into grid cells of 8 x 8 pixels and extract cracking information from small cells rather than the entire image. The cracking information from each cell (the length, width, and contrast of a dark object) includes its mean brightness and minimum brightness and the presence of a dark strip within the cell. A cell is then categorized as either a non-crack cell or a crack seed by comparing its features to the preset thresholds. Only crack cells will be used as potential seed that may form cracks in further processing.

Figure 3.1(a) shows three different grid cells. The top one contains crack pixels (dark), the middle one does not have crack pixels, and the bottom one has crack pixels on its border. The average grayscale of the border pixels, indicated by white circles in Figure 3.1(b) can be used as an overall brightness of the cell. Figure 3.1(c) shows the brightness profiles of the border pixels of the three cells. In the top profile, the brightness shows two sharp valleys, indicating the crossing points of a crack on the border. The center of these two valley pixels can be selected as crack seed, and its grayscale can be replaced by one of its immediate neighbors that have the minimum grayscale value. This minimum grayscale and the coordinates of the center in the original image are recorded for later crack verification. This information is useful for checking the orientation, length, width, and contrast of the crack. When a cell does not contain a crack, its border profile (middle) shows no apparent valley. This cell will be marked with a non-crack flag at the pixel that has the minimum grayscale in the cell. If the border grayscale profile shows only one significant valley (bottom), the cell may have an edge crack. The darkest pixel on the border is selected as a crack seed. Whether this cell is part of a crack depends on the characteristics of its neighbor cells.
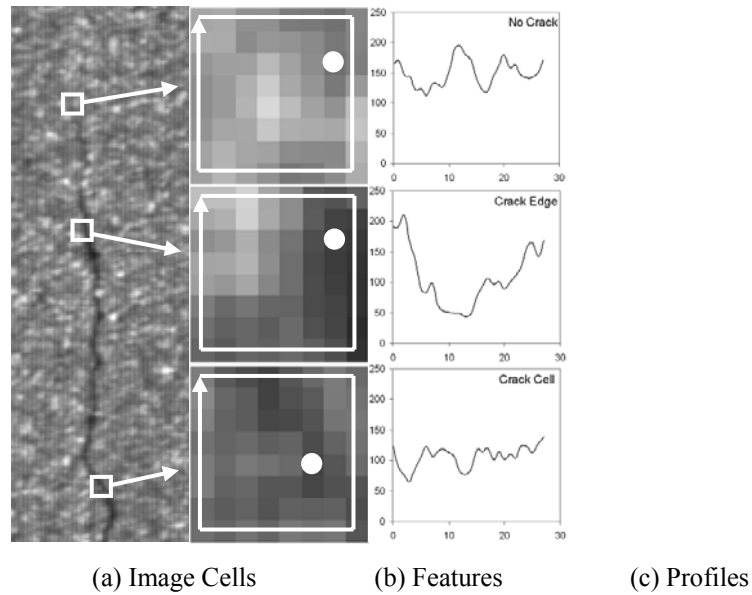
(a) Image Cells   (b) Features   (c) Profiles

Figure 3.1   Cell characteristics in a pavement image

The cell map of a pavement image can be created by setting the grayscales of the 8 x 8 pixels of each grid cell to the selected minimum value (Figure 3.2). Furthermore, each cell can be reduced to one pixel to form a scaled-down image in which potential crack seeds are marked. The scaled-down image of crack seeds is the one to be used for further verifications of cracks.
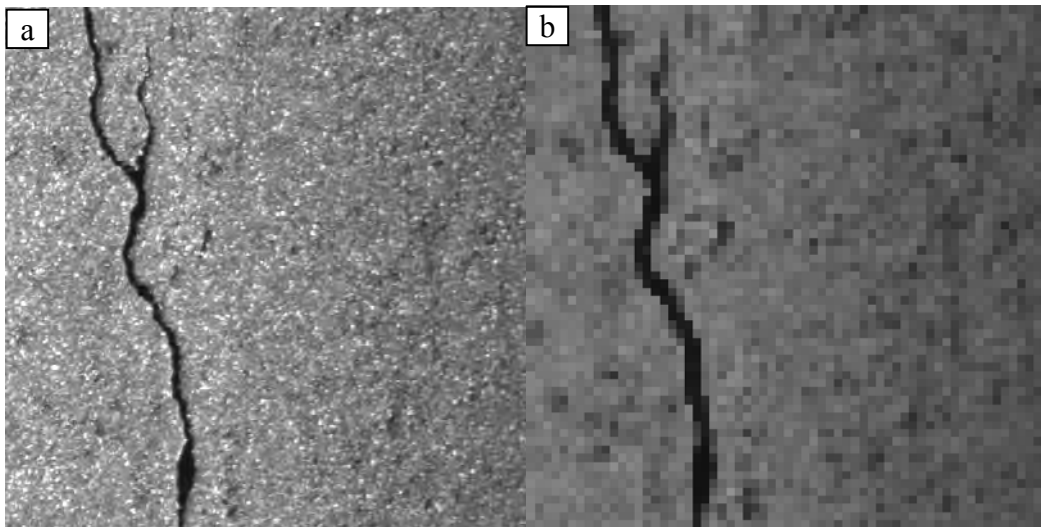

Figure 3.2   Pavement image (a) and cell map (b)

4. Crack Seed Verification

A crack is a fissure on a pavement surface with a high length to width ratio and significant contrast to its neighboring area. Analyzing the contrast between a crack seed and its neighbor is the main cue for verifying if the crack seed is indeed a part of a crack. In addition, the crack seed must have at least one dark neighbor to be considered a crack portion, not an isolated pixel. A set of templates is designed to calculate the contrast of a crack seed (Figure 4.1). Each template contains six pixels. The black pixel represents a crack seed to be evaluated; the gray pixel represents the direction in which the contrast is calculated, and the four white pixels are the neighbors of the seed. The contrast C_c of the seed is defined by as follows:

$$C_c = \frac{2 \times \overline{V} - V_b - V_g}{\overline{V}},$$

where $\overline{V}$ is the average value of all the six cells, and V_b and V_g are the values of the black and gray cells, respectively. If the contrast passes the threshold, the crack seed is validated. Otherwise, the computer continues to try with another template. If none of the six templates yields a satisfactory contrast, the seed will be discarded. If the C_cs from multiple templates exceed the threshold, the one that gives the maximum C_c will be selected. From the template, a seed can also be determined as a longitudinal, transverse, or diagonal seed. This directional information is useful for avoiding false connections in the crack-tracing process. A longitudinal crack may consist of only longitudinal and diagonal seeds, while a transverse crack should have only transverse and diagonal seeds.
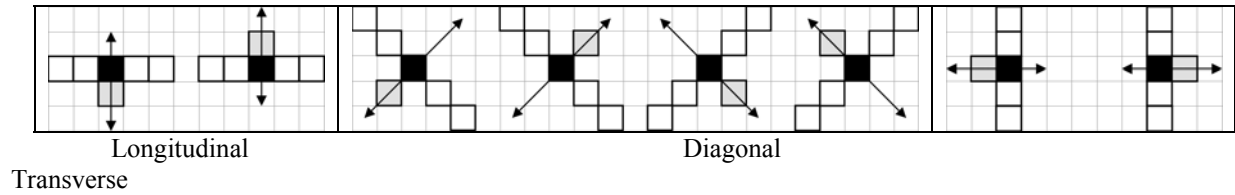

Longitudinal   Diagonal

Transverse

Figure 4.1   Templates for crack seed verification

5. Crack Cluster Connection

The white dots in Figure 5.1(a) present all verified seeds of the image in Figure 3.1(a). Compared to the original image, the volume of data has been dramatically reduced. The next step is to connect individual seeds into seed clusters. Starting from one seed, a crack cluster grows by accepting adjacent seeds one at a time until no close seed can be taken. The size of crack clusters varies in the image. The information, such as the weight or the number of seeds in the cluster, the GCA parameters of each seed, the direction, and the starting and ending seeds, should be stored for each cluster. Figure 5.1(b) shows the crack clusters of Figure 5.1(a).
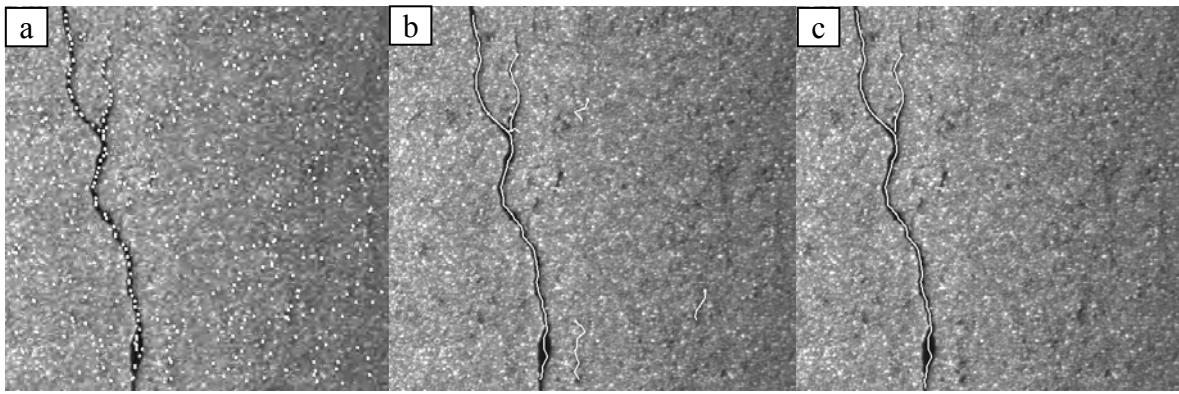

Figure 5.1   Tracing cracks from the seeds, verified seeds (a), seed clusters (b) and traced cracks (c)

A crack cluster can be used to draw a path in the corresponding pavement image. A valid crack cluster must have a clear, dark, and narrow strip along the path. To verify whether a crack cluster corresponds to a real crack, we need to examine three features of the crack path in the original image. First, the contrast of the pixels on the path to the neighbor pixels on both sides should not exceed a threshold to avoid light marks of skid or paint. Second, the width and the width variation of the strip should not go beyond the given limits to omit shadows, pavement joints, and other non-crack objects. Finally, the path must have a certain length to be separated from short segments that may be caused simply by pavement noise or unwanted features. After crack clusters are verified and short clusters are deleted, the clusters that are in the vicinity and have similar orientations can be traced to become a long crack (Figure 5.1[c]). The direction of a traced crack is calculated based on its starting and ending coordinates, and therefore the crack can be classified as longitudinal or transverse.

6. Validation Tests

To facilitate the validation tests, the VCrack system also provides the functions for capturing and saving pavement images over a long distance and the functions for visual feedback (crack maps) of the detection results. It continuously records the full size images of 1 km (0.62 mile) pavement or the compressed images of 16 km (10 miles) pavement. The VCrack measurements are compared with those obtained from the on-screen visual examinations of the same images. Figure 6 shows a 10-meter pavement section with its crack map output from the VCrack. The cracks in the crack maps are simplified drawings of verified crack clusters, which do not intend to reflect the fine details of cracks, but rather to reflect their locations and orientations. Continuous crack maps are stored along with interval cracks, providing both summary data and distributed data for scanned pavements.
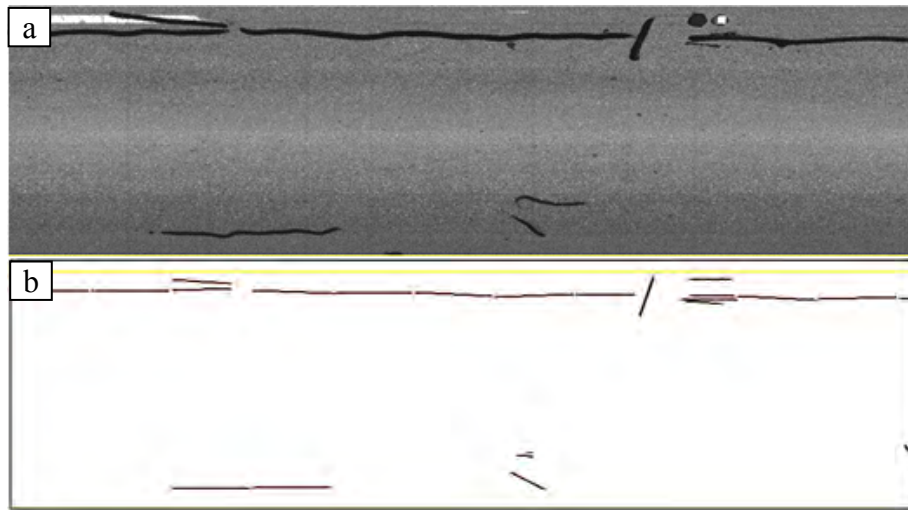

Figure 6.1   A 10-meter pavement image (a) and its crack map (b)

The accuracy of the VCrack was evaluated by comparing the results of the on-screen visual assessment of 100 pavement images chosen from pavement sections representing various cracking situations. The correlations (R^2) between the two evaluation methods are 0.91 for longitudinal cracking and 0.96 for transverse cracking.

The repeatability test of the VCrack was performed by scanning the same pavement (asphalt) section multiple times. The survey data were recorded at intervals of 30.5 m (100 ft). The correlations of the cracking data of any two scans were used to examine the consistency or repeatability of multiple tests. Figure 6.1 shows the alligator cracking data of the three scans (R1, R2, and R3) on a 4.8 km (3 mi) pavement at a constant speed of 72 km/h (45 mph). The correlation coefficients of any two of these three scans are above 0.95. Similar results were achieved on many other pavements. Because maintaining the same driving path of the vehicle in

different runs is difficult, it is logical to see the difference in the outputs as shown in Figure 6.2. Other factors that may contribute to the variations of multiple scans are the differences in the lighting conditions and vehicle speed.
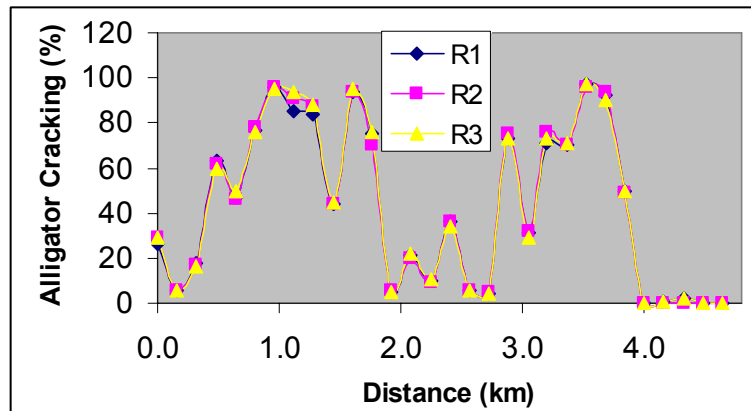

Figure 6.2   Repeatability test with multiple scans

Weather conditions can affect the image quality and hence the output data because the VCrack only uses natural lighting for image capturing at the reporting time. Figure 6.3 shows the longitudinal cracking of an asphalt pavement measured in different lighting conditions (sunny and cloudy). The correlation analysis of these scans suggested that the VCrack can provide fairly consistent measurements under different lighting conditions. The cloudy day had sufficient natural lighting for image capturing but did not cause any shadow in the images. Therefore, it provided an ideal lighting condition for the VCrack. On a sunny day, the sunlight might be partially obstructed by the vehicle, causing errors in capturing images of the cracks under the shadow. A device capable of providing constant lighting conditions is essential for an automated pavement cracking inspection system in order to ensure reliable and consistent performance. A linear lighting device is being developed for the VCrack system. Besides the lighting variations on those days, the difference in driving path and speed may be another main factor contributing to lower correlations.
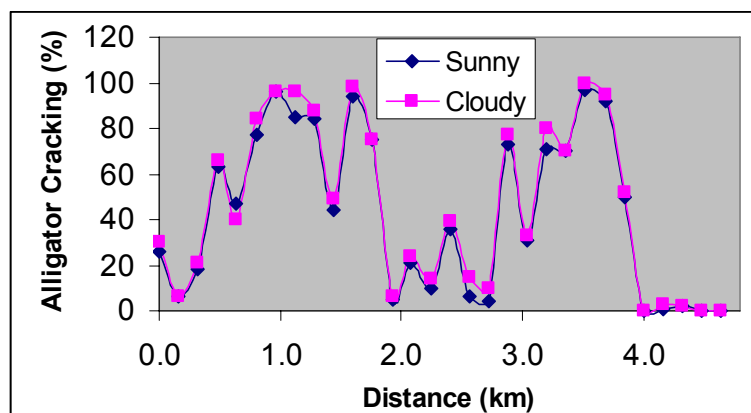

Figure 6.3   Repeatability test under different weather conditions

The reproducibility of the VCrack was also tested by comparing the data generated by multiple units installed on different vehicles (V1 and V2). This test was performed on concrete pavement, and the two vehicles output highly consistent counts for transverse cracks (Figure 6.4). Table 6.1 provides further information about the correlations of the multiple scans (R1, R2, and R3) of the two vehicles on the same pavement. Both vehicles have similar levels of correlations for their multiple scans.
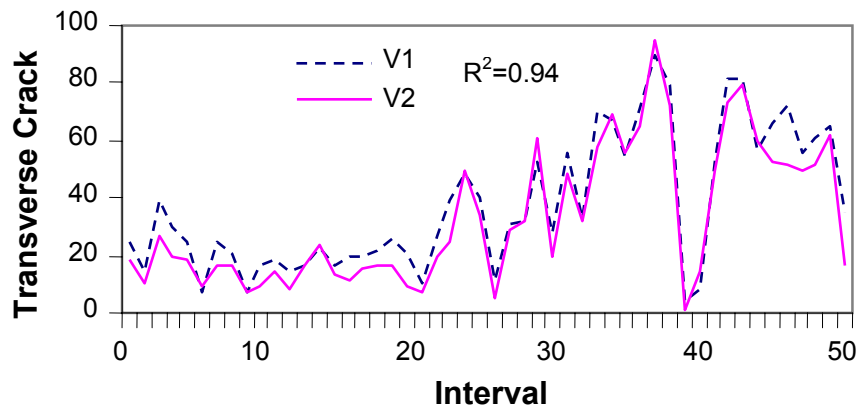

Figure 6.4   Reproducibility of multiple units

Table 6.1   Correlations (R^2) of Multiple Scans of Multiple Vehicles

	V1	V2
R1 ~ R2	0.88	0.96
R1 ~ R3	0.96	0.96
R2 ~ R3	0.91	0.97

The same concrete pavement was tested in the AASHTO protocol, in which a pavement is longitudinally divided into four paths, left wheel path (LWP), right wheel path (RWP), between wheel path (BWP) and outside wheel path (OWP), and the linear density of cracks in each path is calculated. The high repeatability of the VCrack is also evidenced by the AASHTO data presented in Figure 6.5 and Table 6.2. The cracking data in Figure 6.5 are the percentiles of the cracks in each interval within the left wheel path. Three different scans on LWP show the consistent trend of cracking. The correlations of the AASHTO data in all the paths are presented in Table 6.2.
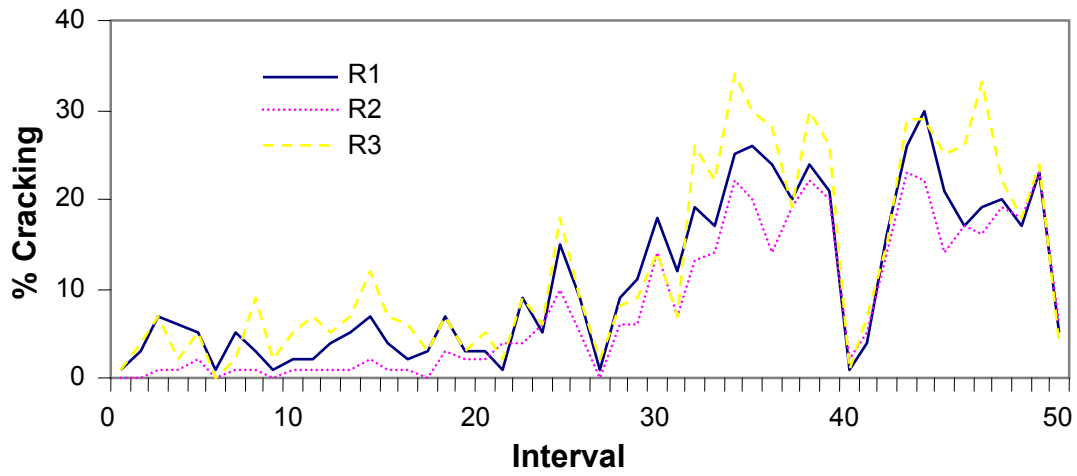
Figure 6.5   Repeatability test of AASHTO data in LWP

Table 6.2   Correlations (R^2) of Multiple Scans in AASHTO Data

	LWP	RWP	BWP	OWP
R1 ~ R2	0.96	0.91	0.93	0.97
R1 ~ R3	0.95	0.83	0.92	0.94
R2 ~ R3	0.92	0.82	0.92	0.93

7. Summary

This paper introduced a customized image-processing algorithm for high-speed, real-time inspection of pavement cracking. The algorithm consists of three main steps. The first step is called the "grid cell" analysis (GCA). The GCA method divides a pavement image into grid cells of 8 x 8 pixels and classifies each cell into a non-crack or crack cell by using the grayscale information of the border pixels. A scaled down image, whose size is only 1/64 of the original image, is formed using a pixel selected from each cell to represent the cell. In the scaled-down image, the pixels that are chosen crack cells are regarded as crack seeds. The second step is to verify the crack seeds by using the contrast of a crack seed compared to its neighbors. This step can remove many seeds that result from pavement noise. The verified crack seeds may form a crack cluster if they fall on a linear string. The third step is to verify and connect crack clusters to form cracks for final measurements including crack count, lengths, and orientations. A crack cluster corresponds to a dark strip in the original pavement image that may or may not be a section of a real crack. Additional conditions to verify a crack cluster include requirements in the contrast, width, and length of the strip. If verified crack clusters are oriented in similar directions, they can be joined to become one crack.

This algorithm permits the detection of cracks in one image to be done in less than 25 ms, which is the maximum time needed for the frame grabber to accumulate line images from the linescan camera to form a new frame image. Therefore, the VCrack system is able to perform real-time, highway speed, 100 percent coverage inspections on pavement cracking distress. The repeatability tests also show that the VCrack can provide consistent results in repeated runs and in different driving conditions.

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