Report No. BD544-36

Final Report

Investigation of Automated and Interactive Crack Measurement Systems

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Submitted to
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May 27, 2008

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1. Report No. BD544-36	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Investigation of Automated and Interactive Crack Measurement Systems		5. Report Date May 27, 2008
		6. Performing Organization Code CEE/FDOT/1014
7. Author(s) M.Gunaratne, S.Amarasiri and S. Nasseri		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil and Environmental Engineering College of Engineering University of South Florida, Tampa, FL 33620		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. BD-544-36
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee St. MS 30 Tallahassee, FL 32399		13. Type of Report and Period Covered Final report Aug. 2006 – May 2008
		14. Sponsoring Agency Code
15. Supplementary Notes Prepared in cooperation with the Federal Highway Administration		

16. Abstract

Currently adopted manual distress surveys involve a high degree of subjectivity, low production rates, and exposure to hazardous conditions. FDOT has acquired and validated a multi-functional survey vehicle (MPSV). However, when an automated crack distress survey operation is complete, FDOT must also use a reliable, accurate and speedy mechanism to analyze the distress information obtained from the survey. A number of automated and interactive crack measurement systems are available to assist pavement engineers to objectively evaluate pavement cracking from digital images of the pavement surface. Based on the findings of this research project the investigators found two such software packages which have the ability to function in conjunction with the imaging and inertial sub-systems of FDOT's MPSV and produce repeatable and speedy distress evaluations. Of the two software that were studied in detail, namely, the *Crackscope* Program and the *Workstation* Program, the latter is more compatible with the MPSV. From the results it is seen that the accuracy of evaluation of both programs was satisfactory only with respect to computer-based manual evaluation. However, the *Crackscope* program proves to be more precise (reliable) and efficient for analysis of Superpave pavements at the network level while the *Workstation* program would be a strong candidate for project-level evaluations.

17. Key Word	18. Distribution Statement
Crack Rating, Threshold sections, Manual rating, Digital Images, Pixel intensities, Wheel paths, Binarization.	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classification of this report	20. Security Classification of this page	21. No. of Pages	22. Price
Unclassified	Unclassified	106	

CONVERSION FACTORS

To convert	British	SI	multiply by
Acceleration	ft/s^2	m/s^2	3.048E-1
Area	ft^2	m^2	9.290E-2
Density	$slugs/ft^3$	kg/m^3	5.154E+2
Length	ft	m	3.048E-1
Pressure	lb/ft^2	N/m^2	4.788E+1
Velocity	ft/s	m/s	3.048E-1

Acknowledgments

The authors are indebted to Mr. Abdenour Nazef, Pavement Systems Evaluation Engineer, State of Florida Department of Transportation (FDOT), State Materials & Research Office, Gainesville, Florida, for his diligent project management efforts. In addition, the constant collaboration of Dr. Alex Mraz of Applied Research Associates, Gainesville, FL and Mr. Stacy Scott, Mr. Glenn Salvo and Mr. Kyle Kroodsma of FDOT State Materials & Research Office, Gainesville, Florida is greatly appreciated. Finally, the financial support provided by Dr. Bouzid Choubane, State Pavement Materials Engineer, FDOT, is gratefully acknowledged.

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EXECUTIVE SUMMARY

Periodic pavement distress evaluation is an essential component of a pavement management system (PMS). In this regard, the Florida Department of Transportation (FDOT) has been using windshield-based manual distress surveys performed by well trained inspectors. In the FDOT PMS, such manual distress surveys are currently adopted for both highway network-level and project-level pavement evaluations. Manual distress surveys could involve exposure to hazardous conditions and introduce some subjectivity into the rating procedure. Meanwhile, FDOT has also developed a multi-purpose survey vehicle (MPSV) for collection of pavement images at normal operating speeds combined with the ability of data geo-referencing. The MPSV has been proven to be an efficient, cost-effective, and safe method for collection of pavement distress data and other pavement data. However, on completion of each automated distress survey operation, FDOT must also use a reliable, accurate and speedy mechanism to analyze the distress information from the survey images.

Furthermore, the manual/windshield distress surveys do not provide the degree of quantification as well as the precision and accuracy required for project-level surveys. On the other hand, a number of automated and interactive crack measurement systems are available to assist pavement engineers and managers to objectively evaluate pavement cracking from digital images of the pavement surface. Most of the existing evaluation systems involve a software package incorporated in a workstation that enables the identification and quantification of cracks in a fully automated or interactive basis. Based on the preliminary findings the investigators considered two automated/interactive software packages which have the ability to function in conjunction with the imaging and inertial sub-systems of the MPSV and produce repeatable and speedy distress evaluations. They are (1) the *Crackscope* program and (2) the *Workstation* program. Of these the latter, developed by the manufacturer of the MPSV, is more compatible with the images collected by MPSV.

The crack evaluation study involved manual and image-based automated/interactive evaluation of cracks in one concrete pavement section and three Superpave pavement

sections selected from different FDOT administrative districts. The Superpave pavement sections were verified to be at crack thresholds corresponding to their ages. Crack thresholds were identified based on the review of historical record of crack ratings of the entire FDOT highway network. From the results of the comparisons between the manual crack evaluations and the corresponding automated/interactive evaluations based on the above two programs, it was seen that the evaluations of both programs are repeatable (precise) while the accuracy of evaluation is not very satisfactory. When the results from computer-based manual evaluation of the corresponding pavement images were considered, the accuracy of the fully-automated program (*Crackscope*) in particular improved significantly. Hence the investigators were able to attribute the inaccuracy in part to the uncertainty involved in the field manual evaluation conducted during night time. The *Crackscope* program proved to be more efficient for analysis of Superpave pavements. In order to obtain meaningful results in the case of concrete pavements, the *Crackscope* program must be modified to (1) incorporate the FDOT Rigid Pavement Condition evaluation methodology, and (2) automatically discard the results of evaluation of unrelated texture such as grooving and tinning. In addition to its compatibility with the MPSV images the other main advantage of the *Workstation* program is its applicability to concrete pavements. For extensive crack evaluation projects, the evaluation time required by the *Workstation* program would be significantly more than that for the *Crackscope* program. However, for less frequent and limited project-level evaluations such as warranty projects the *Workstation* program would be a strong candidate since the excess evaluation time would be offset by its adaptability to MPSV images and the slightly better accuracy.

CHAPTER 1

IDENTIFICATION OF AUTOMATED AND INTERACTIVE CRACK EVALUATION SOFTWARE

1.1 Need for Automated Crack Evaluation

Among the surface distresses which cause common failures of pavements, cracking is a major type. Prompt surface rehabilitation is required in order not to jeopardize road serviceability due to cracking. The distress identification manual (Miller and Bellinger, 2003) developed for the Long Term Pavement Performance Program (LTPP) has been widely used by many highway agencies to develop their specific distress classification guides for asphalt and rigid pavements.

At present, the Florida Department of Transportation (FDOT) uses the windshield-based manual surveys to conduct crack evaluations. Manual surveys generally do not provide the level of detail and quantification required for project level acceptance and warranty work. A multi-functional survey vehicle (MPSV) has been developed by the Florida Department of Transportation (FDOT) as a more efficient and safer alternative to manual crack evaluation (Mraz et al, 2005b). The FDOT MPSV collects and stores digital pavement images along with other information relevant to pavement performance. However, once the images of pavement sections are collected, they need to be analyzed in order to quantify the crack condition of each pavement section according to a pre-determined format.

On the other hand, a variety of automated and interactive crack measurement systems are available to assist pavement engineers and managers to objectively evaluate pavement cracking from digital images of pavement surfaces. In these systems, typically, a software package incorporated in a dedicated computer workstation enables the analysis and quantification of cracks in a fully automated (real-time basis) or partially automated (interactive) basis. Appropriate use of such systems can minimize the errors and subjectivity inherent in human judgment in affecting the quality of distress evaluation results. Above all, automated surveys eliminate the potential hazards associated with current manual surveys. An example of a traffic hazard caused by survey vehicle would be the need to reduce its speed to facilitate the manual evaluation in high-speed facilities.

1.2 Objective of Research Project

There were two primary objectives of this research. The first was to evaluate existing automated and interactive evaluation systems. The specific focus of this objective was to assess how well the systems perform in conjunction with the imaging and inertial sub-systems of the FDOT MPSV, with respect to precise and accurate identification of pavement cracking. The second objective was to investigate the calibration of the existing automated and interactive evaluation systems to allow them to detect designated thresholds of cracking in relation to pavement age and cumulative traffic.

1.3 Research Tasks

In order to facilitate the investigation process the following tasks were identified at its inception. Figure 1.1 illustrates the sequence of the specific steps followed during the implementation of the project.

Task 1 Consult vendors with applicable distress evaluation systems

Task 2 Develop performance curves for the FDOT State Highway System

Task 3 Select test pavement sections

Task 4 Perform manual crack evaluation

Task 5 Determine age-based distress thresholds

Task 6 Perform automated crack evaluation

Task 7 Evaluate distress evaluation software

Task 8 Make recommendations for implementation

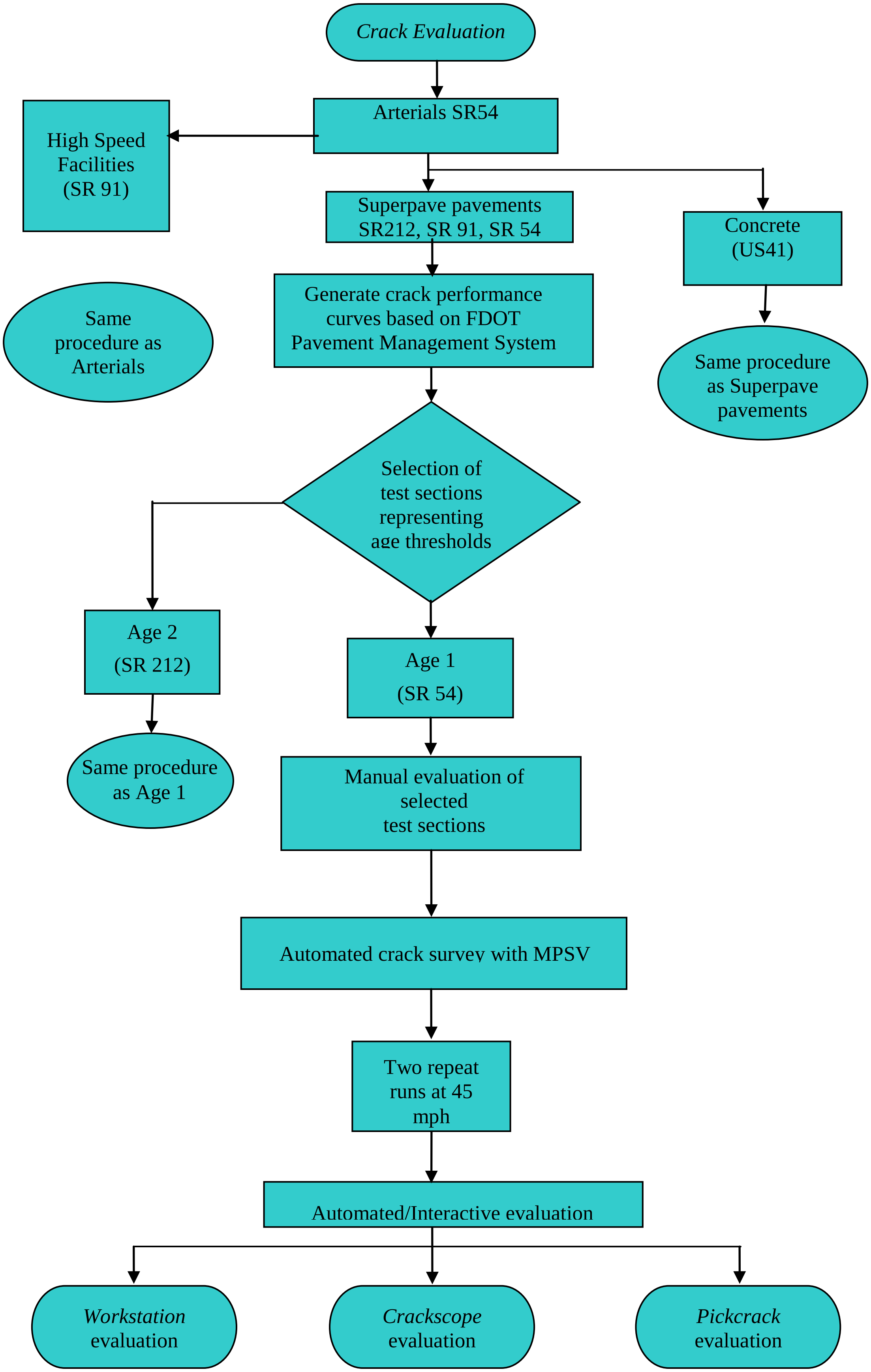

Figure 1.1 Flow chart summarizing the research methodology

1.4 Commercially Available Methods for Automatic Crack Detection

A significant effort has been made in the last two decades not only for objective and automated determination of crack types but also for the accurate estimation of extent and severity of the cracks. Researchers had started using digital imaging technology from the early 1970's to develop automated pavement surface distress inspection (APSDI) systems to aid pavement distress surveys and made them more and more efficient in the recent years. An ideal APSDI system needs to be able to detect cracks down to 3 mm in width (hairline cracks) in various background textures while traveling at highway speeds. Implementing such a system is a challenging task given the versatility of pavement conditions and textures.

Complex algorithms with high levels of computing power are required for most automated crack type determination and crack evaluation systems. Nonetheless, most automated crack type determination systems as well as evaluation systems have not provided accurate results acceptable to public highway agencies. Hence, currently there is no automated crack evaluation system that can be adopted as part of a national standard (Huang and Xu, 2006).

Commercially available APSDI systems include area-scan, line-scan, and time delay integration (TDI) line-scan cameras. An area-scan camera requires a mounting to have a clear and perpendicular view of a rectangle area of the pavement. Hence the system becomes vulnerable to the vehicle vibration due to the long extension of the mounting device. It is also difficult to provide uniform lighting to a large area under different weather and environmental lighting conditions. On the other hand, in line scan cameras, the TDI technology is useful in high-speed image acquisition where the exposure time is limited or when the illumination is low. The camera has to be mounted perfectly perpendicular to the surface of the pavement. Especially at high speeds, vehicle vibration causes more blurriness of an image with a TDI camera.

In real time crack detection, the processing speed is another main concern in developing an effective image processing algorithm. For example in the system developed by the

Texas Department of Transportation, an image with size 2048x512 pixels covering a pavement area of 10x2.5 ft^2 and vehicle speed of 70 mph, the computer is constrained to 24.35 ms to acquire and process an image. On the other hand, many offline image processing techniques such as digital filters, adaptive thresholds, and expert systems can be readily found in the literature (Huang and Xu, 2006).

Currently, there are many industries that use automated real-time pavement cracking detection systems to detect and classify cracks. At normal collection speeds, all crack types with different severities and extents must be detected by the ideal automated crack detection systems. However, automatic identification of cracks from asphalt pavement images remains a major challenge. For example, since there is no significant contrast between dark cracks and black pavement surfaces, it is difficult to differentiate them. In real time-processing it is important to use real-time thresholding. Thresholding is performed to identify the gray-scale intensity level (between 0 – 255 for an 8 bit image) that marks the differentiation between cracks and the pavement background. After identification of the appropriate intensity threshold, one can binarize images by using an intensity of 255 (white) for the background and 0 (black) for cracks. Hence, optimal binarizing of a pavement image certainly helps to identify the areas where there are cracks. To binarize images, two different thresholds or a single threshold may be used. In this chapter some of the real-time crack detection systems and the background information relating to their analysis methods are presented.

1.4.1 Method Developed by Lee (2005)

1.4.1.1 Summary of Method

A crack type index (CTI) was developed by Lee and Kim (2005) to identify the crack types as longitudinal, transverse, and alligator cracks using tiles. A tile is defined as a sub-image of a whole digital image and the CTI is based on the vertical and horizontal spatial distribution of these tiles rather than image pixels. To accurately determine the CTI threshold values for longitudinal, transverse, and alligator cracks, 150 pavement images were captured and analyzed. Furthermore, to validate against block cracks and multiple cracks the CTI method was combined with an existing index called the Unified Crack Index (UCI).

1.4.1.2 Development of UCI

In Lee (1992), the new concept of a Unified Crack Index (UCI) based on image tiles was proposed to quantify cracks and possibly overcome the difficulty of accurately determining the crack types. The tile-based UCI system was developed to overcome the main limitation of the smaller scale pixel-based system, which requires long processing time even on high performance computers. The UCI system measures the total amount of cracks based on sub-images. It is possible to measure crack quantities rapidly from the tile-based computation because it significantly reduces the computational complexity over pixel-based computation. Also, when there is a significant degree of noise in the pavement image, a pixel-based approach would produce unreliable results. In addition, since isolated crack pixels will be ignored as background noise, the tile-based UCI system would be relatively stable.

In implementing the UCI system, first, a median filtering technique is applied to reduce the noise in the pavement image. By using a regression equation developed as a function of the average brightness level of each tile, an optimal threshold value is determined. Then, each pixel is binarized by applying this threshold value to each tile. A tile is considered as a crack tile if the percentage of crack pixels in a tile is greater than a separately predefined threshold value. Finally, the UCI is calculated by dividing the number of crack tiles by the total number of tiles of the entire image.

1.4.1.3 Theory of CTI

In determining the CTI, first, the *vertical vector* is determined by recording the number of crack tiles identified in each column. Similarly the *horizontal vector* is determined by recording the number of crack tiles identified in each row. Each element of the vertical and horizontal vectors is defined as the summation of the number of vertical crack tiles in each column and horizontal ones in each row, respectively. The *total vertical difference* is computed by accumulating the absolute differences between two adjacent elements of the vertical vector and *the horizontal difference* is computed by accumulating the absolute differences between two adjacent elements of the horizontal vector. Finally the CTI is computed by subtracting the total horizontal difference from the total vertical difference. Hence, transverse cracking is indicated by a large negative number and conversely longitudinal cracking is indicated by a large positive number. However, the above technique will generate a less-precise CTI value if the background noise tiles are not removed from the original image.

1.4.1.4 Determination of CTI Threshold Values

To determine more precise CTI threshold values that would enable one to distinguish longitudinal, transverse and alligator cracking, 150 images of actual pavements were used without background noise (Lee and Kim, 2005). As explained above, the noise was removed by discarding isolated crack pixels. The tile sizes were varied from 4 to 6 inches of pavement surface coverage resulting in different CTI values for all images. The accuracy does not necessarily increase when the number of tiles is increased since the chance of the occurrence of false crack tiles could also increase.

Subsequently, specific threshold values were determined as follows:

Transverse cracking; CTI<-16 or -16<=CTI<=0, UCI<=8

Longitudinal cracking; 30<CTI or 0<CTI<=30, UCI<=12

Block cracking; -16<=CTI<=0, 8<UCI<36 or 0<=CTI<=30, 12<UCI<36

Alligator cracking; -16<=CTI<=0, 36<UCI or 0<=CTI<=30, 36<UCI

1.4.1.5 CTI Validation Against Multiple Cracking

When the CTI system was applied by Lee and Kim (2005) to an image with both longitudinal and transverse cracks, the image was classified as a longitudinal crack whereas another image with one transverse crack and one alligator crack was classified as an alligator crack. Images with longitudinal, transverse, and alligator cracks in most cases would be classified as alligator cracking. Hence one reported shortcoming of Lee and Kim (2005) method is the possibility of ambiguous crack type determinations in the presence of multiple crack types.

1.4.2 Method Developed by Xu (2006)

1.4.2.1 Summary of Method

In 1999, a project was initiated by Huang and Xu (2006) to develop an APSDI system called "*VCrack*" for the Texas Department of Transportation. The system was designed to run at vehicle speeds from 3 to 70 mph and characterize cracking in real time. The format of data was required to be compatible with both the Texas pavement management information system protocol and the American Association of State Highway Transportation Officials (AASHTO, 2001).

An image processing algorithm customized for high-speed, real-time inspection of pavement cracking was presented by Huang and Xu (2006). A pavement image is divided into grid cells of 8x8 pixels, and each grid cell is classified as a non-crack or crack cell using the grayscale information of the pixels bordering it. Whether a crack cell can be regarded as a basic element (or seed) depends on its contrast with the neighboring cells. If they fall on a linear string, a number of crack seeds can be called a *crack cluster*. A crack cluster is a dark strip in the original image that may or may not be a part of a real crack. Additional conditions to verify a crack cluster are the contrast, width, and length of the strip. If verified crack clusters are oriented in directions within a specified tolerance, they are joined to form one crack. Since many operations are performed on the crack seeds instead of on the original image, crack detection can be executed simultaneously when the *frame grabber* is forming a new image, permitting real-time, online pavement surveys.

1.4.2.2 System Configuration

The *VCrack* system consists of a line-scan CCD camera, a PCI frame grabber, and a PC computer. When the camera covers 10 ft in width, the images provide ground resolution of 1.488 mm/pixel. Once 512 lines covering 3 ft in distance are accumulated, an image of 2048x512 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 is calculated based on the traveling speed and can be dynamically adjusted. The rate must be synchronized with the vehicle speed to ensure that each line covers exactly the same distance on the pavement.

The brightness of the current image is used to calculate a reasonable exposure time for the next scan to avoid an over-exposed or under-exposed image. When the vehicle travels at 70 mph, it takes about 5 ms to transfer the 8-bit grayscale image from the frame grabber to the system memory, and leaves less than 20 ms for image processing.

Pavement images are captured and saved over a long distance and the crack maps are generated by the *VCrack* system. Full size images of 1 km pavement or compressed images of 16 km pavement are continuously recorded. For scanned pavements, both summary data and distributed data are provided and continuous crack maps are stored.

1.4.2.3. Grid Cell Analysis

An image is divided into grid cells of 8x8 pixels and cracking information of small cells are extracted instead of the entire image. The cracking information from each cell includes its mean brightness and minimum brightness, and presence of a dark strip within the cell. By comparing a cell's features to the preset thresholds, a cell is categorized as either a non-crack cell or a crack seed. In further processing, only crack cells are used as potential seeds that may form cracks.

In the brightness profile of the border pixels, if there are two sharp valleys in brightness, they indicate the crossing points of a crack on the border. The center of these two valley pixels can be selected as a crack seed, and its grayscale can be replaced by one of its immediate neighbors that have the minimum grayscale value. For subsequent crack verification, the minimum grayscale and the coordinates of the center in the original image are recorded. This information is useful for checking the orientation, length, width, and contrast of the crack. The border intensity profile does not show any apparent valley when a cell does not contain a crack. The cell is marked with a non-crack flag at the pixels that has the minimum grayscale in the cell. The cell may have an edge crack if the border grayscale profile shows only one significant valley. Whether this cell is part of a crack depends on the intensities of its neighbor cells. The cell map of a pavement image is created by setting the grayscales of the 8x8 pixels of each grid cell to the selected minimum value. A scaled-down image that is used for further verification of cracks is formed by reducing each cell to one pixel and marking potential crack seeds.

1.4.2.4 Crack Seed Verification

A crack is a fissure on a pavement surface with a high length-to-width ratio and a significant contrast to its neighboring area. All cracked cells are marked as potential crack seeds. Whether a crack seed is part of a crack is verified by analyzing the contrast in intensities between a crack seed and its neighbor. Also the crack seed must have at least one dark neighbor to be considered a crack portion. As shown in Figure 1.2, a set of templates containing six pixels is designed to determine the contrast of a crack seed. The black pixel represents the 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.

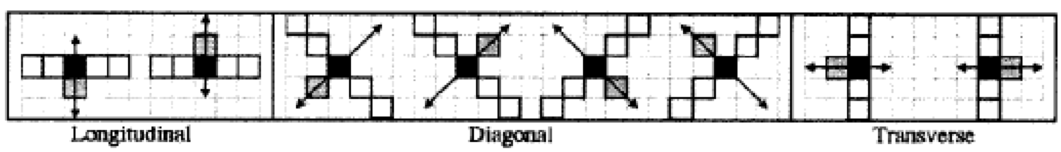

Figure 1.2 Templates for crack seed verification

The contrast C_c of the seed is defined as,

$$C_c = \frac{2\bar{V} - V_b - V_g}{\bar{V}} \qquad (1.1)$$

Where $\bar{V}$ is the average value of all six cells in the template, and V_b and V_g are the values of the black and gray cells in the template, respectively. The crack seed is validated if the contrast passes a preset threshold. Otherwise, the computer is made to repeat the process with another template. The seed will be discarded if none of the eight templates yields a satisfactory contrast. If the C_c values from multiple templates exceed the preset threshold, the one that gives the maximum is selected. From the template, a seed can also be determined as a longitudinal, transverse, or diagonal seed. A longitudinal crack has only longitudinal and diagonal seeds, and a transverse crack has only transverse and diagonal seeds.

1.4.2.5 Crack Cluster Connection

Individual seeds are connected into seed clusters by starting from one seed, and adding adjacent seeds one at a time until all seeds are exhausted. To verify whether a crack cluster corresponds to a real crack, features of the crack path in the original image are examined. The contrast of the pixels on the path to the neighboring pixels on both sides should not exceed the preset threshold, to avoid light marks of skid or paint. The width and the width variation of the strip should not go beyond the pre-determined limits to omit shadows, pavement joints, and other non-crack objects. Also the path must have a certain length to be separated from short segments that may be simply caused by pavement noise or unwanted features. The clusters that are in the vicinity and have similar orientations can be traced to produce a long crack. The direction of a traced crack is determined based on its starting and ending coordinates.

1.4.2.6 Validation Tests

To test the repeatability of the *VCrack* system, the same asphalt pavement has been scanned multiple times by the vehicle. The results have shown some difference in the outputs since it has been difficult to reproduce the driving path of the vehicle in different runs. Difference in lighting conditions (sunny and cloudy) and the vehicle speed may have also contributed at a lower degree to the variations of multiple scans. Since *VCrack* just uses natural lighting for image capturing at the reporting time, weather conditions could in fact affect the image quality and hence the output data. The correlation analysis has suggested that the system can provide fairly consistent measurements under different lighting conditions. A cloudy day provides an ideal lighting condition since it had sufficient natural lighting for image capturing, but does not cause any shadow in the images. On a sunny day, errors may be caused by shadows due to sunlight being partially obstructed by the vehicle. To ensure reliable and consistent performance, a linear lighting device was developed for the *VCrack* system to provide uniform lighting conditions.

The reproducibility of the system on multiple *VCrack* systems installed on different vehicles has also been tested by comparing the data that was generated. The test has been performed using AASHTO (2001) protocol on a concrete pavement. The results for the two vehicles showed that there were highly consistent counts for transverse cracks.

1.4.3 Method Developed by Wang (2002)

1.4.3.1 Summary of the Method

Wang (2002) has developed a real time image processing software called Automated Distress Analyzer (ADA) that analyzes pavement images. The software is separated into two parts. One part of the software analyzes cracks such as longitudinal, transverse, block and alligator cracking. The other software analyzes distresses such as rutting and roughness. The images of the pavement surface are obtained by using two simultaneous cameras, each with a resolution of 1300 x 1024. Then the two images are interlaced to combine them to form a single image. The real time distress data is produced using the computing facilities on board the data vehicle (Figure 1.3) and multimedia databases are generated. The speed of collection and analysis of data is above 60 mph. The three protocols used to analyze multi-pass data sets of pavement images from a roadway section are, (1) the AASHTO interim distress protocol (AASHTO, 2001), (2) the World Bank's Universal Cracking Indicator (CI) (Peterson and Uddin, 1994), and the (3) Texas Department of Transportation's (TxDOT) method (TxDOT manual, 1999).

Figure 1.3 Dual camera subsystem Wang (2000)

1.4.3.2 System Features and Performances of Automated Device

The vehicle (Figure 1.3) is based on a full-digital design and the operating software environment is based on 32-bit technology. The vehicle's subsystem for pavement surface image collection has a frame-based digital camera and four strobe lights for illumination. They are extended from the back of the vehicle for data collection. The configuration diagram of this system is depicted in Figure 1.4. To obtain high-quality images at high shutter speed, the firing of the strobes and the shutter opening of the camera are synchronized. A dual-CPU computer is used for GPS data acquisition, DMI data, and images from the digital camera at 12 frames/s. The image processing system for cracks is called the distress analyzer. For real time distress analyzer, these data sets are moved to a multi-CPU computer.

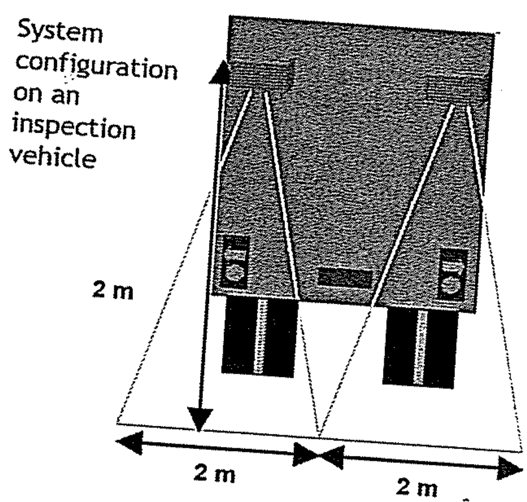

Figure 1.4 System configuration of an inspection vehicle

The first step is to distinguish cracks from other non-distress noises using the characteristics of distresses. Then the cracks are connected and vectorized, and a distress database related to location, orientation, and size of each crack is established. Using this geometric information, the cracks can be classified by using any predefined distress categorization protocol such as the AASHTO Interim Distress Protocol (AASHTO 2001), the World Bank's CI method (Peterson and Uddin, 1994), and the TxDOT's method (TxDOT, 1999).

CI is the simplest form of index since it represents each section with only one number. CI is proportional to the number of cracks as well as their severity. For each section, the TxDOT indices provide a number each for longitudinal crack length, transverse crack count, alligator crack percentage, and block crack percentage. The details of crack types and their severities can be obtained by the AASHTO protocol (2001) and the TxDOT method. If the cracking details are not important, then CI can be used to simply express the general distress condition of the pavement. The problematic spots on the pavement section and the corresponding severity levels can be found by using any of the three methods. Although there are technical differences among the three methods, the results from the automated system have been comparable and reflect the condition of the pavement.

1.4.4 Method Developed by International Cybernetics Corporation (ICC)

The International Cybernetics Corporation (ICC), Largo, FL has developed an interactive crack detection software that incorporates semi-automated crack detection algorithms. When the images are loaded onto this software, the type of pavement surface as well as the types of distresses must be specified. When a crack is observed in the image, the user must first select the type and severity of crack manually. Once the type and severity are specified, the length of the crack is specified by dragging the mouse along that crack. Then the software computes the extent of the crack based on the movement of the mouse. Since this involves both manual and automatic maneuvers, this method is obviously an interactive method. Figure 1.5 shows how the crack descriptions are selected and the extent of the crack is recorded on the computer typically.

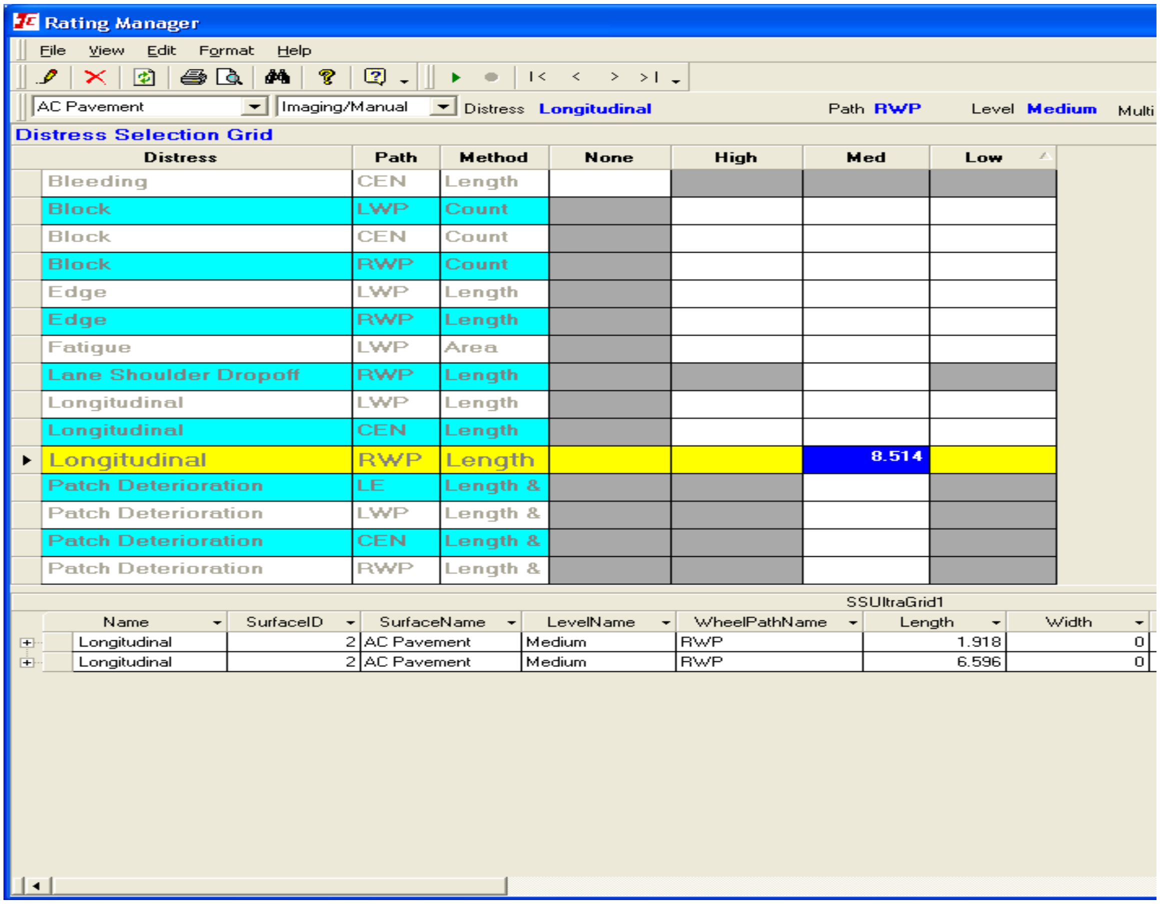

Figure 1.5 Crack detection using ICC workstation software

CEN: Center line of the lane

LWP: Left Wheel Path

RWP: Right Wheel Path

1.5 Consultation of Vendors with Applicable Distress Evaluation Systems

Once digital images of a pavement section are collected, it is necessary to find a suitable software program that would analyze these images and identify the extent and severity of cracks accurately. There are many vendors in North America who own such proprietary crack evaluation software based on the automated crack evaluation methodologies presented in Section 1.4. Six companies were contacted to obtain the relevant information. The first task was to consult vendors with applicable crack evaluation systems which would be able to analyze the pavement images captured by FDOT MPSV. The following vendors were contacted;

1. Infrastructure Management Services (IMS)
2. Roadware Group Inc.
3. Pathway Services
4. CGH Pavement Inc.
5. Dr. Kelvin Wang
6. TxDOT (Dr. B.G. Xu)
7. International Cybernetics Corporation (ICC)

In addition, extensive discussions were held with the International Cybernetics Corporation (ICC), Largo, Florida, which assembled the FDOT MPSV and acts as an agent for Xu (2005) and Lee (2005) software. The relevant information collected from the vendors is summarized in Table 1.1. As seen in Table 1.1, most of the vendors do not possess fully automated crack evaluation systems. Generally, it was reported that most systems cannot be operated on a fully automated basis because some of the artificial pavement features which are unrelated to cracks are often interpreted as cracks by automated evaluation systems. Hence, when most evaluation systems identify a portion of an image as cracks, it is necessary to manually verify whether it is really a crack, rendering the evaluation process to be at least partly interactive.

One noticeable fact in Table 1.1 is that most of the above vendors use their own pavement imaging systems to capture the images prior to analyzing them. Consequently, all the contacted vendors requested pavement images captured by the MPSV be sent to them ascertain their evaluation systems' compatibility with FDOT MPSV images. The computer memory requirements for any of the above evaluation software would not be excessive if the MPSV images are in a format compatible with that software. The computer memory requirement would also depend on the number of images to be stored and their individual sizes.

Table 1.1(a) Preliminary information obtained on vendor software (IMS, Roadware, Pathway)

Software Vendor/ e-mail Software Characteristics	**IMS** ssmith@ims-rst.com	**Roadware** Paul Harbin pharbin@roadware.com	**Pathway** Scott Mathison smathison@pathwayservices.com
1. Computer requirements a. Memory b. Resolution c. Speed	a. Depends on the number of images. b. Computer should have a good monitor and resolution	a. Typically, 250 GB hard drive for the latest commercially available computer. c. Typically 4 GB memory	a. Memory requirement not significant (300/500 MB). Depends on the size of the images
2. Capabilities of the company's software	A grid analysis is done to count cracks (Alligator, Unified, SHRP distresses) Checks whether a pixel is black or gray, if black, it is considered as a crack	Both automatic and manual evaluation of cracks	Enhances distress images. Evaluates extent and severity. Enhancement is part of the procedure.
3. Limitations of the company's software	Not fully automated, therefore verification with manual results is needed. Severity not predicted well, although extent and type are predicted Some non cracks are interpreted as cracks. Hence results have to be manually verified. Ex. Cannot differentiate D-cracking and corner break cracking USF cannot modify the source code	Some cracks get missed. Some cracks are incorrectly identified.	Not fully automated. 90% manual. Rating is manual. Measuring, type etc are automated.
4. Resolution of crack evaluation	If manually intervened reasonable results obtained	1mm/2mm/3mm Manually Verified	1/8" discernible Manually Verified
5. Evaluation of images captured by FDOT MPSV	Possible. Samples have been sent for verification	Usually analyze their own images. Samples have been sent for verification	Samples have been sent for verification. Applications used to analyze distresses are specifically designed to operate with Pathway Services collection equipment.
6. Time taken to provide results, once images are given	Long time, due to many accumulated jobs	Can decide only after viewing the samples	Can decide only after viewing the samples
7. Train graduate students to run demonstration software	Possible, but requires a lot of training. IMS does not own the software they have license to use it.	No. Demonstration software is not available.	Yes
8. Results based on AASHTO protocol	Yes	Yes	Yes

Table 1.1(a) (Contd.) Preliminary information on vendor software (IMS, Roadware, Pathway)

Software Vendor/ e-mail Software Characteristics	**IMS** ssmith@ims-rst.com	- **Roadware** Paul Harbin pharbin@roadware.com	**Pathway** Scott Mathison smathison@pathwayservices.com
9. Availability of manuals	The owners do not allow any manuals to be distributed.	Sales and marketing department has to be contacted	Yes
10. Background computer software needed to support the evaluation software	Like with any new software.	Windows would be adequate	Like with any new software.
11. Superiority of the company's software	Comparable to other's software, but it would be more effective if used for their own images, software. Drainage patching can be detected. Data is collected and checked with other conditions	The results are good.	Most widely used in USA. However, it is designed for use with their own equipment.

Table 1.1(b) Preliminary information on vendor software (CGH, Dynatest, TxDOT)

Software Vendor/ e-mail Software Characteristics	**CGH Pavement** (Gaylord Cumberledge) gcumberledge@ara.com	**Dynatest** Dr. K. Wang kcw@uark.edu	**TxDOT** Dr. B.G.Xu bxu@mail.utexas.edu
1. Computer requirements a. Memory b. Resolution c. Speed	a. High-in computer. Removable hard drive. Capacity not a problem.	a. A good PC	c. Any PC with at least 2GHz CPU and 1GB ram
2. Capabilities of the company's software	Can view all the distresses. ICC software is used to manually rate cracks by observing the images. Record on databases manually.	The software is capable of finding and identifying cracks, and classifying the cracks into four categories: longitudinal, transverse, block and alligator.	Detects cracks and classifies them in PMIS (Pavement Management Information System) and AASHTO protocols.
3. Limitations of the company's software	No image enhancement. No clearing of shadows. Do not have an automated/interactive software package.	LRIS system is an image acquisition system. Images from LRIS are not affected by sunlight and works at day or night without any shadow problems. If images were obtained from regular lighting, shadow problem can be in the images, which somewhat affects processing results	Less reliable in detecting fine cracks, block cracks spalled cracks. Progress is still made on these areas.
4. Accuracy of crack evaluation	Very accurate in identification. Severity assessment is not accurate – a lot of room for errors.	1-mm	The resolution of the image is 1.5mm/pixel. There is no absolute accurate data.
5. Evaluation of images captured by FDOT MPSV	Samples have been sent for verification.	Customization work is needed to get ADA to analyze images from other acquisition systems. Samples have been sent for verification.	FDOT MPSV images have been tested. Results available.
6. Time taken to provide results, once images are given	Approximately 250-300 images/hr for manual evaluation. Typically 20ft x 14.5ft sections	Two weeks if the image number is only a few hundred. It has to be a contract arrangement.	Real time processing is possible up to a vehicle speed of 70 mph. Post processing can be done at a rate of 3 to 5 images per minute.
7. Train graduate students to run demonstration software	Yes	Demo software is not given out unless there is contract arrangement.	Yes
8. Results based on AASHTO protocol	AASHTO	Yes, the *ReportWriter* software summarizes results from ADA and produces results based on AASHTO protocol and other protocols.	Yes. Density data but not width data are based on AASHTO protocol.

Table 1.1(b) (Contd.) Preliminary information on vendor software (CGH, Dynatest, TxDOT)

Software Vendor/ e-mail / Software Characteristics	**CGH Pavement** (Gaylord Cumberledge) gcumberledge@ara.com	**Dynatest** Dr. K. Wang kcw@uark.edu	**TxDOT** Dr. B.G.Xu bxu@mail.utexas.edu
9. Availability of manuals	AASHTO, SHRP manual	Yes, only available under contract.	Not currently available, but can be provided
10. Required background computer software from the users' end	ICC software.	A good Windows XP based computers with MS Office installed.	No software necessary. ICC will provide all the necessary software.
11. Superiority of the company's software	Depends on the personnel analyzing the images.	ADA works in real-time at 60MPH when images are acquired at the same speed. The images from LRIS are 1-mm resolution. ADA is able to achieve 1-mm resolution.	Have very comprehensive features such as real time processing capabilities.

Most of the above vendors were willing to issue manuals describing the evaluation procedure. However, some vendors that use software owned by other sources obviously did not have the rights to issue the manuals. In addition, the source codes could not be modified by the users. The Principal Investigator also contacted the vendors to obtain additional information regarding the software and solicit their participation in the software testing program. On receiving the sample images collected by the MPSV, the owners of *Workstation* program (ICC), *Crackscope* program (Xu) and *PickCrack* program (Lee) verified the compatibility of their systems with the MPSV images and modified their software to be able to analyze the FDOT MPSV images in batch mode. Hence the investigators decided to pursue the evaluation of the above three programs as candidates for automated crack evaluation software required for this research project.

CHAPTER 2

IDENTIFICATION OF CRACK THRESHOLD SECTIONS

To determine the suitability of the candidate automated/interactive crack evaluation software identified in Chapter 1, the investigators decided to conduct a testing program on a number selected pavement sections where manual crack evaluations, considered as the ground truth, would be compared with the automated/interactive crack evaluations. It was also decided that the test pavement sections should be ones that were currently at threshold crack levels corresponding to different ages. Task 2 of the project involved the plotting of crack performance curves for the entire FDOT highway network which would lead to the selection of a set of pavement test sections for the above purpose. The criterion that was used to select threshold pavement sections is explained in detail in the ensuing section.

2.1 Development of Performance Curves for FDOT State Highway System

The pavement crack rating (CR) is a rating assigned subjectively on a scale of 0 to 10, where 0 indicates a very poor crack condition and 10 indicates an excellent condition on a given pavement. The historic CR data on any pavement section can be obtained from the FDOT Pavement Management (PM) database.

As described in the proposal for the current research project (Gunaratne, 2005), using the FDOT PMS database, the crack rating (CR) vs. age curves were plotted for each pavement section to obtain the performance curves similar to Figure 2.1. When CR Vs Age trends are plotted for a given pavement family consisting of a set of pavement sections with similar design, construction, traffic volume, geographical location, and life cycle, trends such as that shown in Figure 2.1 can be obtained. Such plots would display a band of CRs which encompasses the majority of pavement sections in that family with a few scattered sections lying outside the band. If one considers a designated set of ages (i.e.1, 5 and 10 years), the lower boundary of the above band at these ages can be considered as the threshold crack rating (CR) corresponding to these ages. Then, those pavement sections which *currently* exist at the threshold crack conditions would be selected for the testing program that involves manual Vs automated crack evaluation comparison.

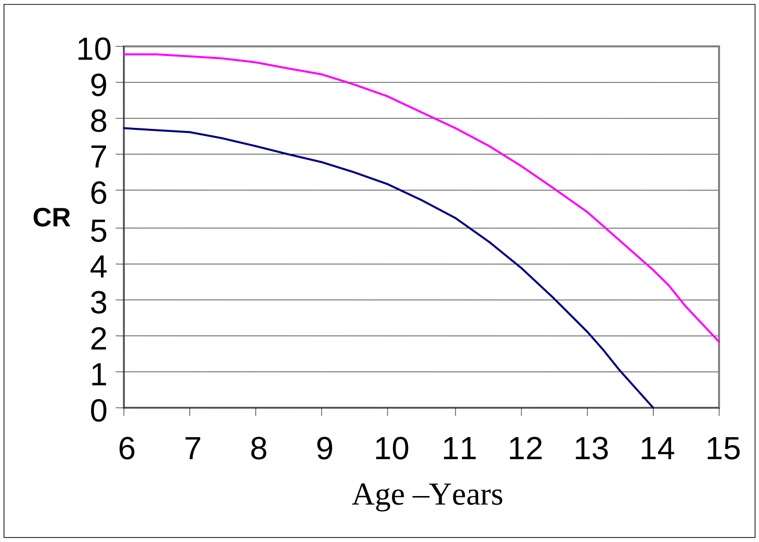

Figure 2.1 Sample plot showing the variation of CR range with age within one construction cycle for a family of pavements

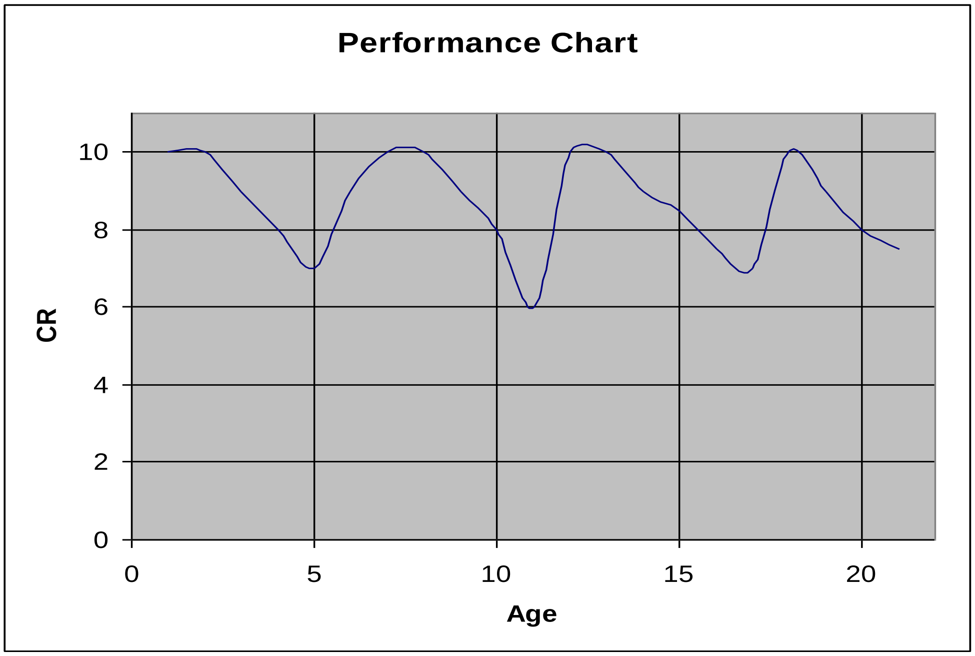

Figure 2.2 Sample plot showing the cyclic variation of CR for a single pavement section

The construction cycle of a pavement indicates the number of overlays that have been placed on the original pavement. In order to distinguish and display the cyclic behavior of CR, i.e. the variation from one construction cycle to the next, the trend shown in Figure 2.2 has been developed. The CR of a given pavement section generally deteriorates with time and at the time it is overlaid an instantaneous significant improvement in CR could be expected as shown in Fig 2.2. Furthermore, from plots such as that in Figure 2.2, the number of construction cycles that the pavement has undergone can also be determined. An example CR Vs age plot for a group of pavements in FDOT District 3 with a traffic level of D and surface layer type FC5 is shown in Figure 2.3. Each individual plot in Figure 2.3 represents a specific pavement section in that group. Finally, a sample of all such plots obtained for the entire FDOT controlled highway network is given in Appendix A.

Data such as the roadway identification, section length, overlay type, and cumulative ESALs were also acquired from the FDOT PM database. The cumulative ESAL is an appropriate parameter to represent the traffic level since it indicates the cumulative damage that has been caused by truck traffic.When the ESAL countis higher the pavement deterioration rate would be faster. Hence the CR Vs age plots were further regrouped considering five (5) ESAL (traffic) groups. Appendix A shows sample plots belonging to two (2) of these ESAL (traffic) levels (C and D).

Since 1996, FDOT has been using mostly fine and dense graded Superpave (SP) mixes for road construction. Therefore, it was decided to limit the performance curves to those SP pavement sections with different traffic levels, which are currently performing at the threshold levels. Appendix A shows one such representative performance curve each for all seven districts in Florida with medium to high traffic levels (traffic levels C and D). It should be noted that after the introduction of Superpave mixes the surface types werealso changed from FC2 or FC3 to FC5 or FC6 for better drainage and protection of the structural layer.

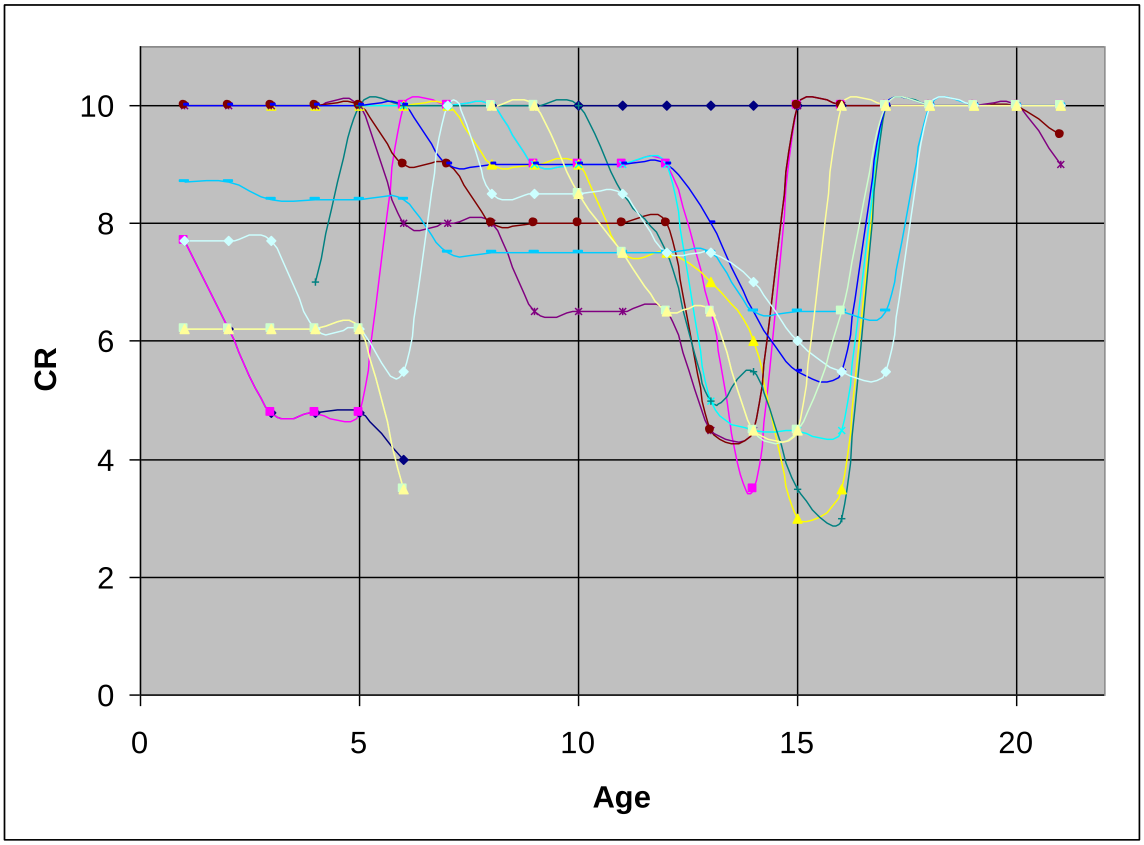

Figure 2.3 Crack rating curves for District 3 Superpave sections (FC5 traffic level D)

2.1.1 Development of Superpave Performance Curves

The FDOT highway network's PM database with respect to each district was searched to locate pavement sections that were made of SP with surface types of FC5 and FC6. Crack rating histories of all SP sections within each district were plotted according to the surface type (FC5 or FC6) on one individual plot. Figure 2.4 shows such a plot of Crack rating Vs Age for District 1. It was also noted that most of the sections within that district have been overlaid with a Superpave mix in recent years (mostly 4-5 years ago). For consistency the CR curves were plotted only for the last ten years during which the Superpave mix has been introduced. However, the analysis is performed to cover only the design life of each pavement. Further analysis of the CR plots will be presented in detail in the following sections.

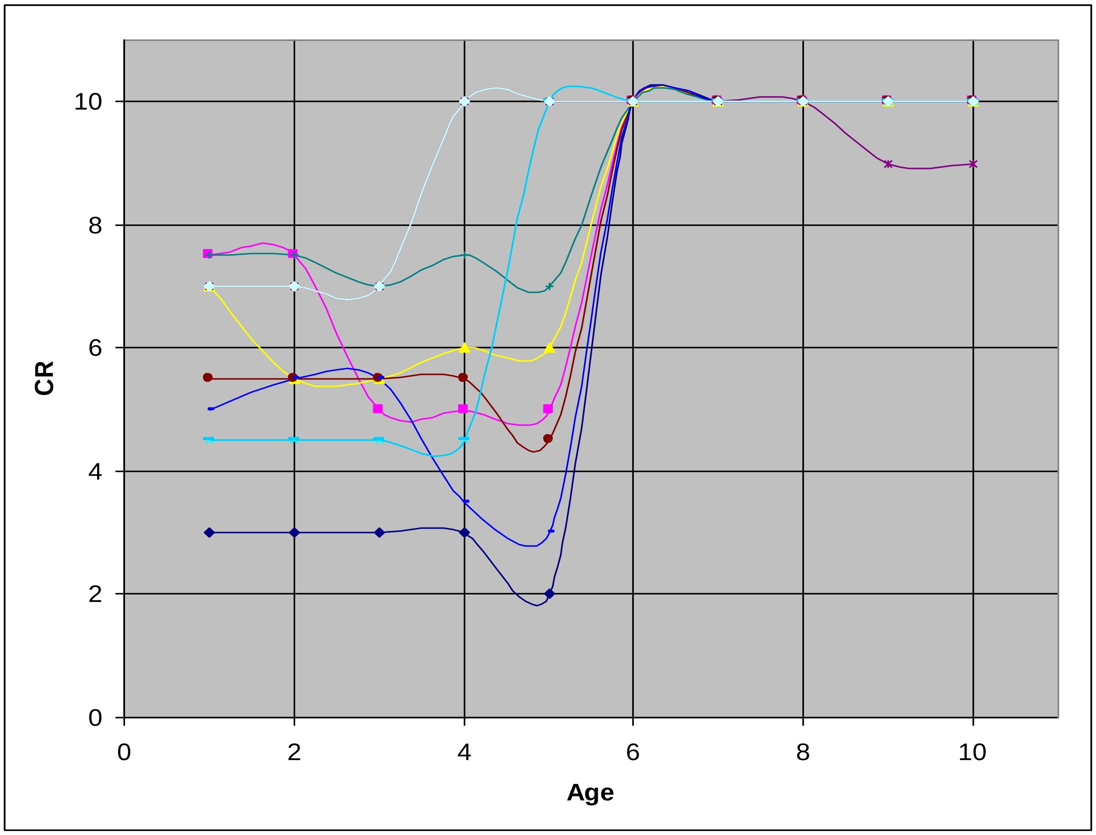

Figure 2.4 Crack rating curves for District 1 Superpave sections (FC5 traffic levels C and D)

2.2 Selection of Threshold CR Values

Since the Superpave sections are only about twelve years old, the CR threshold values were established at ages of 3,5,7, and 10 (Figure 2.5). Since there are not many sections aged enough to obtain the 10 year crack threshold value, the trend of CR threshold values at ages 5 and 7 was extended to obtain a value for the age 10 as shown by the dashed line in Figure 2.5. This is a rational approach since the pavements gradually deteriorate as they age, making it reasonable to predict the deterioration trend. Not all the sections within a district are overlaid at the same time. Thus it is critical to establish a general method to analyze them within a constant time frame (ex. 10 years). In order to accomplish this effort, plots such as Figure 2.5 were developed from the CR performance curves (Figure 2.4). This exercise would facilitate the consideration of groups of pavements in a given district with similar surface types at specific stages of their design lives. This consideration also enabled the researchers to compare the behaviors of similar pavement sections at the same stage of their design life. As stated in Section 2.1, the crack threshold value is the CR which corresponds to the lowest crack rating value of the designated curve band (Figure 2.1) at the specific age (ex. 3, 5 or 7 years).

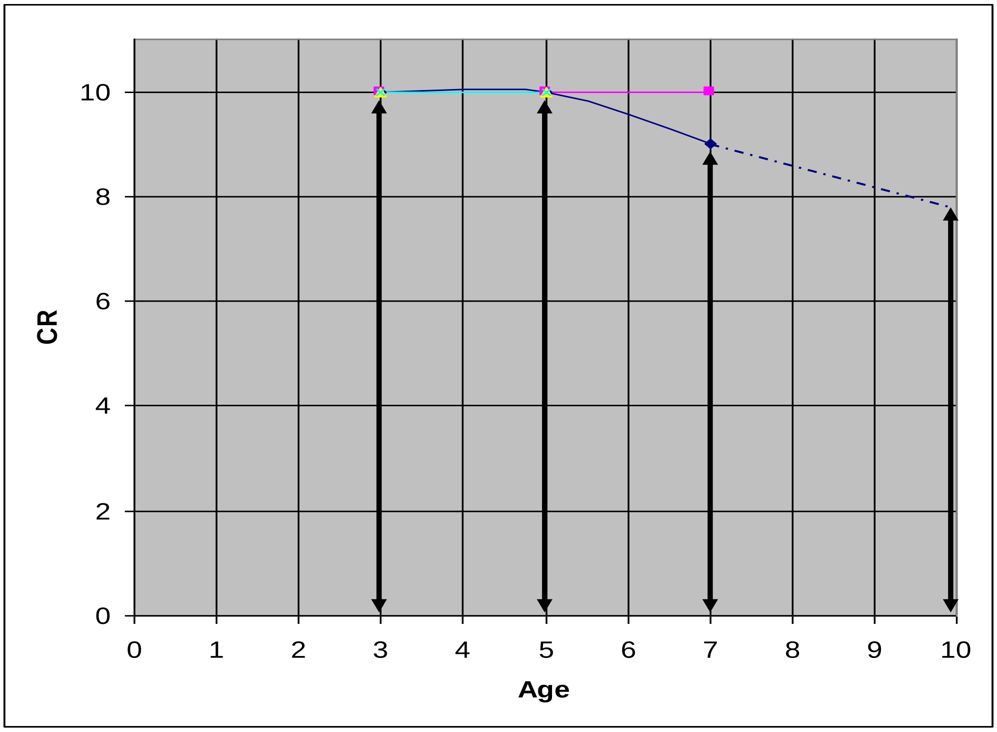

Figure 2.5 Crack thresholds based on minimum CR for District 1 Superpave sections (FC5, traffic levels C and D)

2.3 Selection of Superpave Threshold Sections

After determining the threshold CR values (Figure 2.5), pavement sections with CR values that were currently at the corresponding thresholds or just below them, were selected. These sections were then earmarked for crack evaluation using manual and automated means.

2.4 Verification of Selected Sections

After the selection of the threshold sections based on the FDOT PMS database, the corresponding video-logs on the FDOT intranet were used to verify the crack condition of the selected sections. This facility was made available to the investigators by Mr. Bijan Behzadi, P.E. of the FDOT District 7 office in Tampa, FL. Overall, the corresponding video-logs verified three of the selected SP sections to be significantly cracked and visibly at the threshold conditions corresponding to their current ages. They were SR54 (Pasco County, Tampa), SR 212 (Jacksonville), and SR91 (Florida Turnpike, West Palm Beach).

CHAPTER 3

MANUAL CRACK EVALUATION ON SELECTED TEST SECTIONS

3.1 Manual Survey of Concrete Pavement Sections

3.1.1 US 41 Econocrete Project

USF investigators and FDOT Project Management Team decided to utilize the FDOT's MPSV pavement images collected from a recent crack evaluation of an Econocrete section on US 41 in Charlotte County, FL to investigate the accuracy of existing crack evaluation software. A detailed manual survey was conducted on sample sections of US 41, in addition to the Superpave (SP) sections selected in the effort described in Chapter 2.

3.1.1.1 Criteria for Determination of the Sample Size

If one were to select a statistically adequate sample to represent the entire Econocrete project, statistical data on the variation of the crack condition along US 41 would be needed. Then the number of lots to be sampled within a section can be calculated by using the following equation:

$$N_{lot} = \left[\frac{s.t_{(\alpha/2)}}{\Delta} \right]^2 \qquad (3.1)$$

Where,

N_{lot} = number of lots to be sampled

s = the standard deviation of crack ratings (CR) of lots

(1-α) = the confidence level (greater than 85%)

t = the t-distribution variate corresponding to a probability of α/2 (Table 4.1)

Δ= the allowable tolerance between the measured values and actual CR values (0.1μ)

μ = the mean crack rating

The minimum number of samples per section required by AASHTO would be 4.

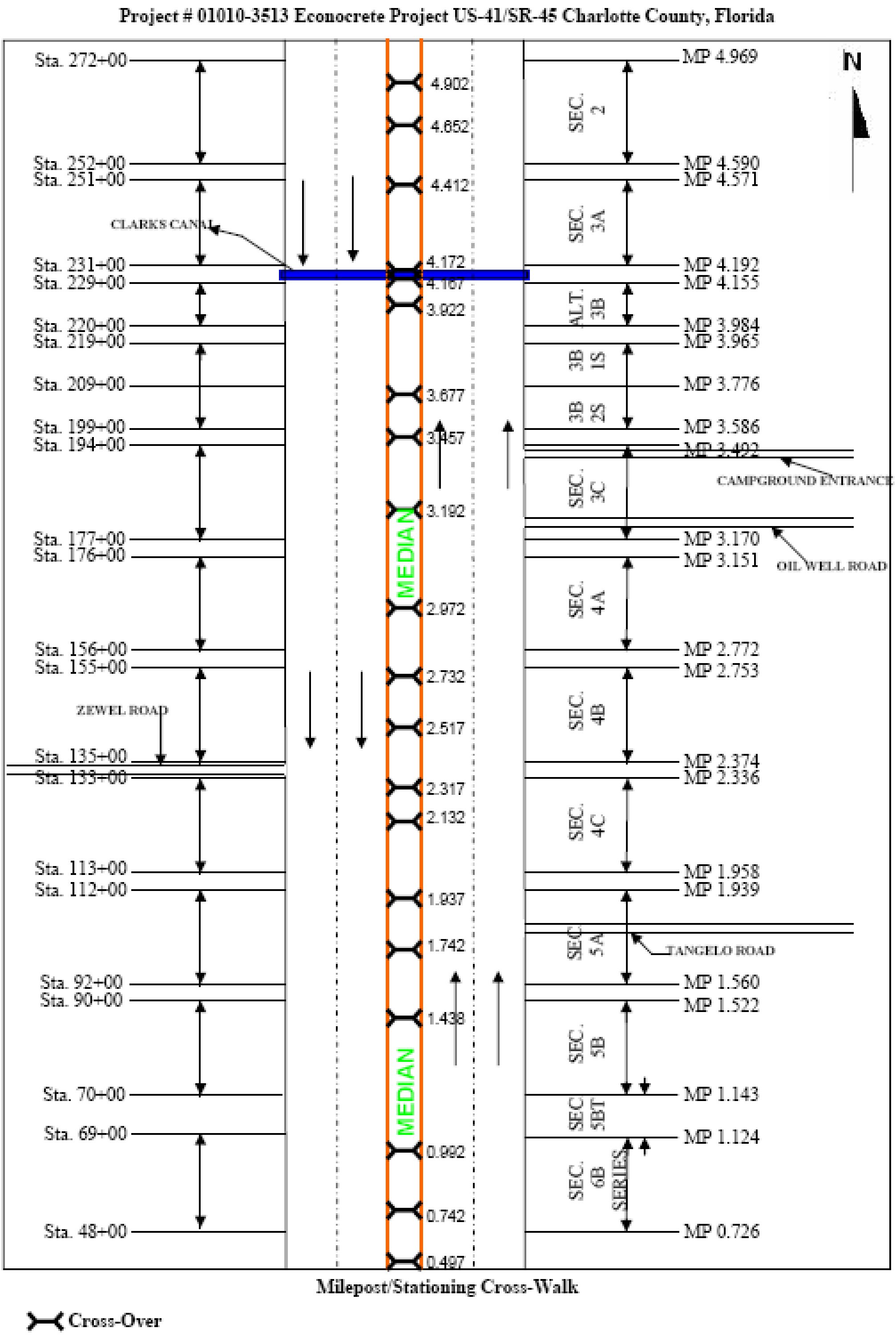

Figure 3.1 Configuration of SR 45/US 41 Econocrete section

3.1.1.2 Manual Crack Evaluation on Econocrete sections

A preliminary crack survey was conducted on the selected sections in July 2007 to evaluate the statistical variation in the crack condition throughout the entire section. During this preliminary survey the investigators found that it was practically possible to sample the entire project length within a relatively short time. Hence it was decided to rate all the pavement sections within the Econocrete project limits shown in Figure 3.1. The results of the comprehensive manual crack evaluation are illustrated in Tables 3.1 and 3.2.

3.2 Manual Survey of Asphalt Pavement Threshold Sections

In preparation for the manual survey of pavement sections, first the investigators reviewed the AASHTO (2001) crack evaluation guidelines. According to AASHTO (2001) guidelines for quantifying cracks in an asphalt pavement section, the manual survey must be performed on a statistically adequate sample of lots, which represents the condition of that entire test section. Generally, it is recommended to assess the crack condition of a section to be within an interval around its mean crack condition. The above interval is specified by a confidence level exceeding 85%. As stated in Section 3.1.1.1, it is also recommended to survey at least four lots in each test section. Also, it is emphasized that the sample lots must be distributed throughout the section, and should not be more than 30% of the section to be surveyed. The survey strip is defined as the area where the measurements and data collection must occur. This can be seen clearly in Figure 3.2.

Table 3.1 Detailed manual crack survey data for US 41 sections 3B2S, 3C, 4A and 4B

(The numbers in the table indicate the number of cracks in each slab
L- Low severity, M – Medium Severity and H – High severity)

SECTION	Station	Slab #	Transverse Cracking			Corner Cracking			Longitudinal Cracking		
3B2S			L	M	H	L	M	H	L	M	H
	195+22	1			1						
	205+35	2									1
	205+20	3						1			
	205+05	4			3						
	TOTAL		0	0	4	0	0	1	0	0	1
3C	180+60	1			1			1			
	180+75	2						1			
	TOTAL		0	0	1	0	0	2	0	0	0
4A	159+00	1								1	
	165+00	2								1	
	170+45	3								1	
	174+60	4								1	
	174+75	5								1	
	174+90	6								1	
	TOTAL		0	0	0	0	0	0	0	6	0
4B	144+25	1								1	
	TOTAL		0	0	0	0	0	0	0	1	0

Table 3.2 Detailed manual crack survey data for US 41 sections 4C, 5A, 5B and 6B

(The numbers in the table indicate the number of cracks in each slab
L- Low severity, M – Medium Severity and H – High severity)

SECTION	Station	Slab #	Transverse Cracking			Corner Cracking			Longitudinal Cracking		
4C			L	M	H	L	M	H	L	M	H
	113+25	1							2	2	
	113+45	2								1	
	116+35	3							2	2	
	120+70	4							1	2	
	121+60	5							2		
	122+35	6							2	7	
	123+70	7								1	
	124+45	8							1		
	124+60	9							1		
	126+15	10								1	
	127+45	11		1							
	128+20	12		1						1	
	128+35	13	1							1	
	128+50	14	1							1	
	128+65	15									1
	128+80	16								1	
	131+20	17					1				
	TOTAL		2	2	0	0	1	0	11	20	1
5A	Station	Slab #	L	M	H	L	M	H	L	M	H
	-	1	-	-	-	-	-	-	-	-	-
5B	Station	Slab #	L	M	H	L	M	H	L	M	H
	70+22	1			1						
	80+10	2		1							
	82+40	3		1							
	TOTAL		0	2	1	0	0	0	0	0	0
6B	Station	Slab #	L	M	H	L	M	H	L	M	H
	66+36	1		5							
	TOTAL		0	5	0	0	0	0	0	0	0

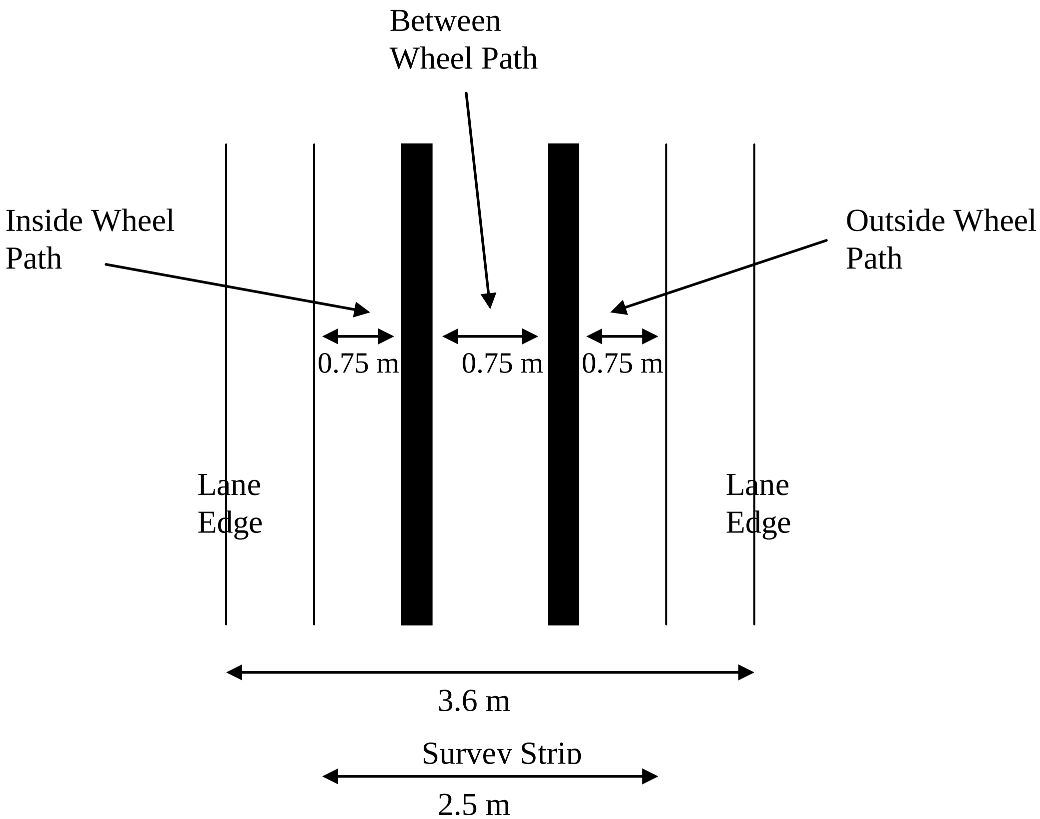

Figure 3.2 Cross section of survey lane

The survey data has to be stored in the format provided in Table 3.3 before subsequent analysis. Table C1 (in Appendix C) illustrates all the crack types found in asphalt pavements. Meanwhile, Figure C1 (in Appendix C) shows the template designed and constructed by the USF researchers to perform the manual crack survey according to the AASHTO (2001) format.

Table 3.3 Sample survey datasheet

Severity Level	Outside Wheelpath (m/m^2)	Inside Wheelpath (m/m^2)	Between Wheelpath (m/m^2)	Optional Areas and Distresses		
				Edge Cracking	Joints	Transverse Cracking
1				User Defined	User Defined	User Defined
2				User Defined	User Defined	User Defined
3				User Defined	User Defined	User Defined

3.2.1 Manual Crack Survey on SR-54

A sketch of SR-54 test section is also shown in Figure C1 (Appendix C). The manual crack evaluations data for SR-54 are summarized in Table 3.4 while samples of detailed results are provided in Tables C2-C4 in Appendix C.

3.2.2 Manual Crack Survey on SR-212

The manual crack evaluations data for SR-212 are summarized in Table 3.5.

Table 3.4 Manual crack survey results on SR-54

SECTION	Severity Level	Outside Wheelpath (m/m^2)	Inside Wheelpath (m/m^2)	Between Wheelpath (m/m^2)
Shelby Lane	1	0.0010	0.0021	0.0081
	2	0.0390	0.0064	0
	3	0.6206	0.9097	0.0142
Woodbine	1	0.0189	0	0
	2	0.2753	0.03822	0.0078
	3	0.7591	0.6462	0.0062
Wildpine	1	0	0.0067	0
	2	0.0129	0.3811	0.0045
	3	0.0097	0.2401	0

1 – Low severity, 2 – Medium severity and 3 – High severity

3.3 Crack Mapping on Florida Turnpike (SR 91)

On completion of the manual surveys on SR54 in Tampa, FL and SR212 in Jacksonville, FL the results were compared to the corresponding results obtained from automated/interactive evaluations using *Crackscope* and *Workstation* software. Since the manual survey format is based on AASHTO (2001) and not all the crack detection software could provide the results in the above format, crack maps were created as an alternative comparison base. In addition, this research project specifically involves selection of appropriate software to be used for project-level evaluations. For project-level evaluations, which are limited to a few lane miles, comparison of manual crack evaluations and automated evaluations can in fact be performed based on crack maps. Hence, for the purpose of this project, the LTPP crack mapping format used for FDOT's warranty projects was chosen for the manual survey. The LTPP crack mapping format is clearly outlined in the Distress Identification Manual for the Long Term Pavement Performance Program (1993). A third Superpave section that satisfied the crack threshold criteria was selected for crack mapping. This section was located between mileposts 103-104 along the southbound travel lane of Florida Turnpike (SR91) in West Palm Beach, FL. Crack mapping was performed under lane closure on the night of 19th of February 2008. During this exercise, the investigators were able to map the cracks in the inside and outside wheelpath areas based on the extent (length) and severity (Appendix D. The results of the crack mapping are seen in Appendix D.

Table 3.5 Manual crack survey results on SR-212

SECTION	Severity Level	Outside Wheelpath (m/m^2)	Inside Wheelpath (m/m^2)	Between Wheelpath (m/m^2)
Hodges	1	0	0.0373	0
	2	0.0011	0.0177	0
	3	0.2707	0.1880	0
Washburn	1	0	0	0
	2	0	0.0028	0
	3	0.2488	0.0712	0.0118
Aldridge	1	0	0.0038	0
	2	0.0012	0	0
	3	0.0415	0.0411	0

1 – Low severity, 2 – Medium severity and 3 – High severity

CHAPTER 4

AUTOMATED CRACK EVALUATION IN TEST SECTIONS

4.1 Automated Crack Classification Protocols

4.1.1 AASHTO Protocol

The AASHTO Interim Distress Protocol (2001) is designed primarily for automated equipment and covers the procedures for quantifying cracking in asphalt pavement surfaces in both wheelpath and non-wheelpath areas. A crack is defined as a discontinuity in the pavement surface with minimum dimensions of 3 mm in width and 25 mm in length. Cracks may include longitudinal cracks, transverse cracks, and interconnected cracks. In the AASHTO 2001 Protocol, the cracks and joints are differentiated as load-associated and non- load associated. Load-associated cracking is quantified by the cracking measured in the wheelpath areas, and the non-load-associated cracking is quantified by cracking measured in the non-wheelpath areas.

The crack severity and intensity in the AASHTO method are defined as:
Severity Level 1 (low) – crack width less than 3 mm
Severity Level 2 (medium) – crack width between 3 mm and 6 mm
Severity Level 3 (high) - crack width greater than 6 mm
Each cracking level is quantified by the total cracking length per unit area (i.e. m/m^2).

4.1.2 World Bank's CI method

The Cracking Index (CI) is the simple product of the extent, intensity and crack width. The extent is the area of cracked pavement within the defined area. The intensity is the total length of cracks within the defined extent.

For longitudinal cracking the *CI* is calculated as

$$CI_L = \left(\frac{a}{A} . \frac{l_L}{a} . w_b \right) = \frac{100 l_L w_L}{A} \qquad (4.1)$$

For alligator cracking the CI is calculated as

$$CI_A = \left(\frac{c}{A} . \frac{l_A}{c} . w_A \right) = \frac{100 l_A w_A}{A} \tag{4.2}$$

For transverse cracking the CI is calculated as

$$CI_T = \left(\frac{A}{A} . \frac{l_T}{A} . w_T \right) = \frac{100 l_A w_A}{A} \tag{4.3}$$

Where

A= total area evaluated

a,b,c = areas occupied by longitudinal, transverse, and alligator cracks respectively.

l_L, l_A, l_T = *lengths* of longitudinal, alligator and transverse cracks respectively

w_L, w_A, w_T = widths of longitudinal, alligator and transverse cracks respectively

The final CI is the sum of all three cracks.

$$CI = \frac{100(l_L w_L + l_A w_A + l_T w_T)}{A} \tag{4.4}$$

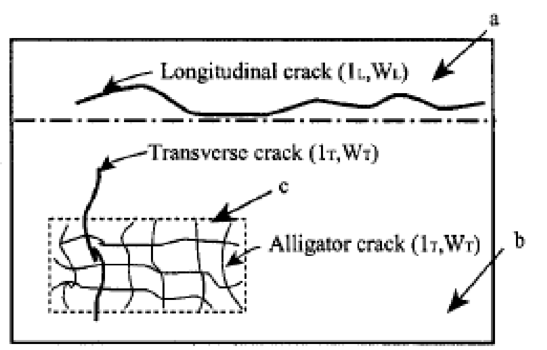

Figure 4.1 Illustration for determining Universal Cracking Indicator

4.1.3 TxDOT Method

The TxDOT method is described in the TxDOT *Pavement Management Information System Rater's Manual* (1999). Longitudinal cracking is measured as the linear feet of cracking in each 100 ft of pavement surface. Then the length of longitudinal cracking per station is determined (in feet) using tables. Transverse cracking is evaluated by counting the number of cracks in each 100 ft. of pavement. Transverse cracks that do not fully extend across the lane width are counted as partial cracks. To rate alligator cracking, first the percentage of the rated lane's total wheelpath area covered by alligator cracking is measured. Then the percentage of alligator cracking is determined using a table. The total feet of full-lane-width block-cracking percentage is measured and the percentage block cracking area is determined by using a table.

4.2 Evaluation of Multi Purpose Survey Vehicle (MPSV) Images using Vendors' Software

To compare candidate software offered by the vendors identified in Chapter 1, it is necessary to analyze the images obtained by the MPSV using each vendor's software. When the vendors were contacted it was found that most of them used their own vehicles to capture the pavement images and analyzed them in real-time. Upon the vendors' request the MPSV images were sent to them for verification of compatibility of their systems with the MPSV images. Consequently, the vendors' software was refined several times to obtain the optimum settings. It was possible to analyze images using some of the identified vendor software at the International Cybernetics Corporation (ICC), Largo, Florida. This section provides the information obtained from a few selected vendors in analyzing the MPSV images.

4.2.1 Evaluation of MPSV Images using Software Developed by Lee (2005) – *CrackPic*

In this software, the image is divided into tiles as described in Section 1.4.1. However when the images captured by the MPSV were analyzed the system was initially unable to detect the cracks very accurately. Typical results obtained by processing MPSV pavement images using the refined Lee (2005) software version is shown in Figure 4.2.

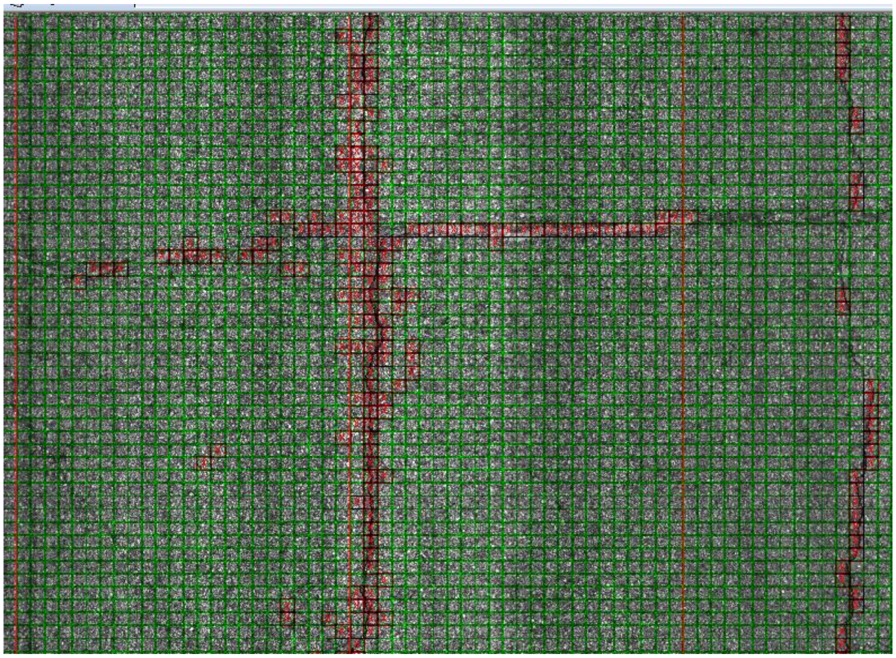

Figure 4.2 Processed image using Lee (2005) software

4.2.2 Evaluation of MPSV Images using Software Developed by Xu (2006) – *Crackscope*

When images were analyzed for the first time with the above software available at ICC, the software was unable to accurately detect the cracks. The reason for this was because Xu (2006) software (*CrackScope)* has been designed to analyze 4k images, while the images from the MPSV are 2k images. Subsequently, the software was modified by the vendor to be compatible with the images captured by the MPSV. This modification resulted in clearer cracks of the images. An image analyzed by the software *CrackScope* is shown in Figure 4.3.

4.2.3 Evaluation of MPSV Images using Software Developed by Wang (2002)

Images were also sent to Dr. Kelvin Wang to be analyzed using the Wang et al (2002) software. It was informed by this vendor that progress is being made in modifying their existing program to analyze the images captured by the MPSV. The investigators were also informed that once the sample images are processed the results would be sent. Later Dr. Wang declined to participate in the study.

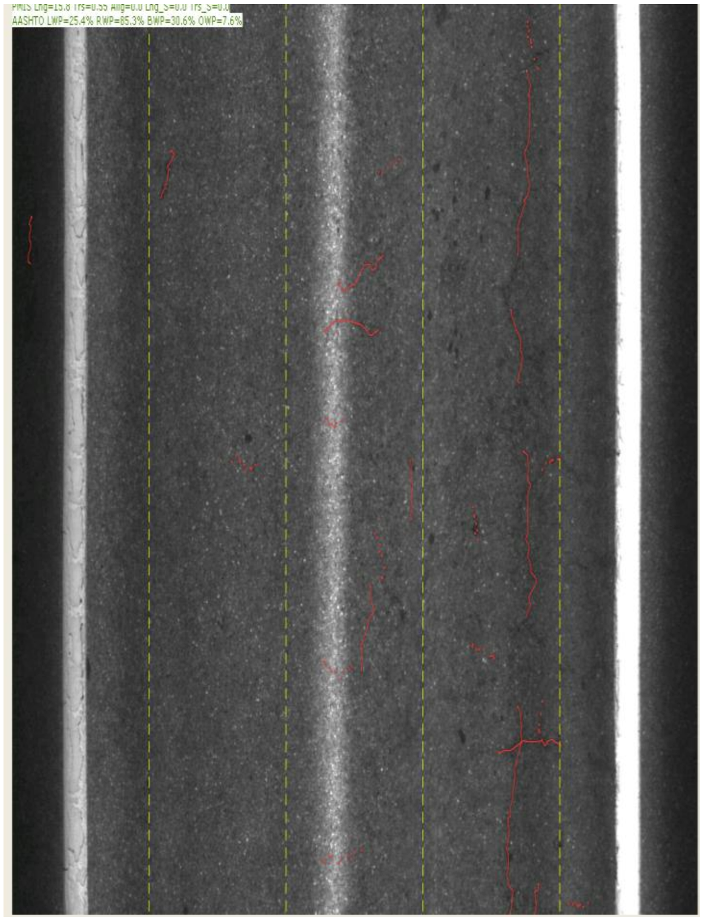

Figure 4.3 Results of MPSV image analyzed using the *Crackscope* program

4.2.4 Evaluation of MPSV Images using Software Developed by the Roadware Corporation – *Wisecrax*

Roadware Corporation, Toronto, Canada, declined to participate in the investigation. Therefore, the *Wisecrax* software was not used for the automated evaluation.

4.3 Summarized Results of Automated Crack Evaluations

The results of the automated crack evaluations are presented in the following sections.

4.3.1 Automated Evaluation Using the *Crackscope* Program

4.3.1.1 Evaluation of US 41 (Econocrete pavement)

Table 4.1 Crack evaluation on US 41using the *Crackscope* program
(The numbers in the table indicate the number of cracks in each slab
L- Low severity, M – Medium Severity and H – High severity)

SECTION	Severity Level	Transverse Cracking	Longitudinal Cracking
3B2S	L	245	165
	M	1398	867
	H	398	4
	All severities	2041	1036
3C	L	152	102
	M	1074	479
	H	1	223
	All severities	1227	804

From Table 4.1, it is seen that the *Crackscope* program severely overestimates the crack count in concrete images due to two reasons; (1) the artificial transverse texture (tined finish) is considered as cracks, and (2) the FDOT's crack counting guidelines are not incorporated in the *Crackscope* program.

4.3.1.2 Evaluation of SR 54 (Superpave pavement)

The following nomenclature is used in Tables 4.2 and 4.3:

1. Low severity
2. Medium severity`
3. High severity

OWP – Outside wheel path
IWP – Inside wheel path
BWP – between wheel paths

Table 4.2 AASHTO-based crack evaluation on SR 54 using the *Crackscope* program

SECTION	Severity Level	OWP (m/m^2)	IWP (m/m^2)	BWP (m/m^2)
Woodbine	1	0.34	0.36	0
	2	0.17	0.09	0
	3	0	0	0
	All severities	0.51	0.45	0
Wildpine	1	1.69	0.11	0.38
	2	1.07	0	0.42
	3	0	0	0
	All severities	2.76	0.11	0.80

1 – Low severity, 2 – Medium severity and 3 – High severity

4.3.1.3 Evaluation of SR 212 (Superpave pavement)

Table 4.3 AASHTO-based crack evaluation on SR 212 using the *Crackscope* program

SECTION	Severity Level	OWP(m/m^2)	IWP(m/m^2)	BWP(m/m^2)
Hodges	1	0.96	1.30	0.19
	2	0.23	0.16	0
	3	0	0	0
	All severities	1.19	1.46	0.19
Washburn	1	0.32	0.24	0.07
	2	0.02	0	0
	3	0	0	0
	All severities	0.34	0.24	0.07
Aldridge	1	0.81	0.32	0.03
	2	0.23	0	0
	3	0	0	0
	All severities	1.04	0.32	0.03

1 – Low severity, 2 – Medium severity and 3 – High severity

4.3.1.4 Evaluation of SR 91 (Florida Turnpike, Superpave pavement)

In the case of SR 91, both manual and automated evaluations were performed based on mapping the cracks of two selected pavement sections according to LTPP guidelines (Appendix D). Crack mapping on two sample images with (1) relatively high and (2) relatively low extents of cracking are seen in Figure 4.4(a) and (b) respectively. From Figure 4.4 it can be observed that almost all the longitudinal cracks (marked in red) and transverse cracks (marked in green) in the two images have been accurately mapped. The investigators observed similar results for all the other images from SR 91.

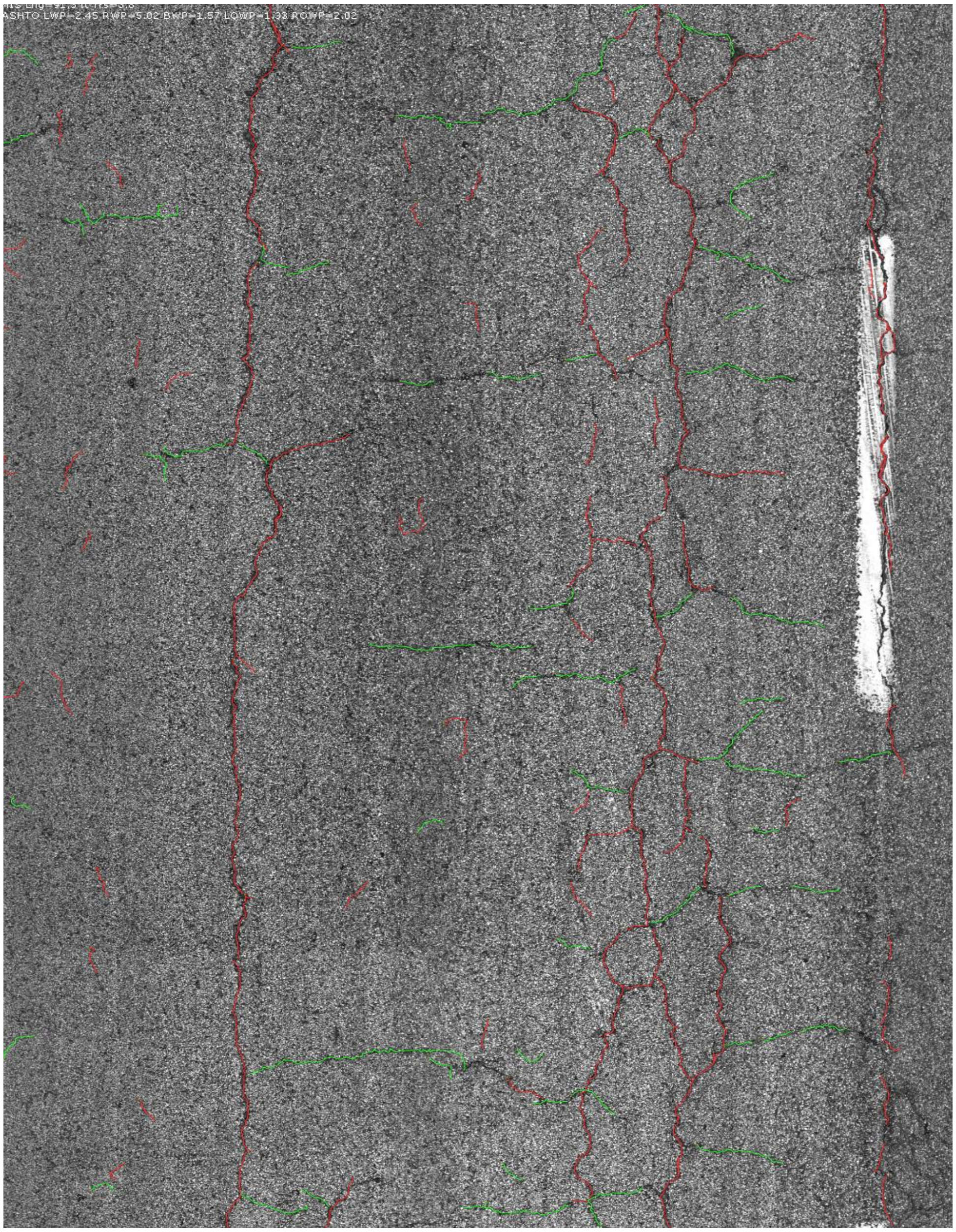

Figure 4.4 Sample crack maps for SR 91 image (high extent of cracking)

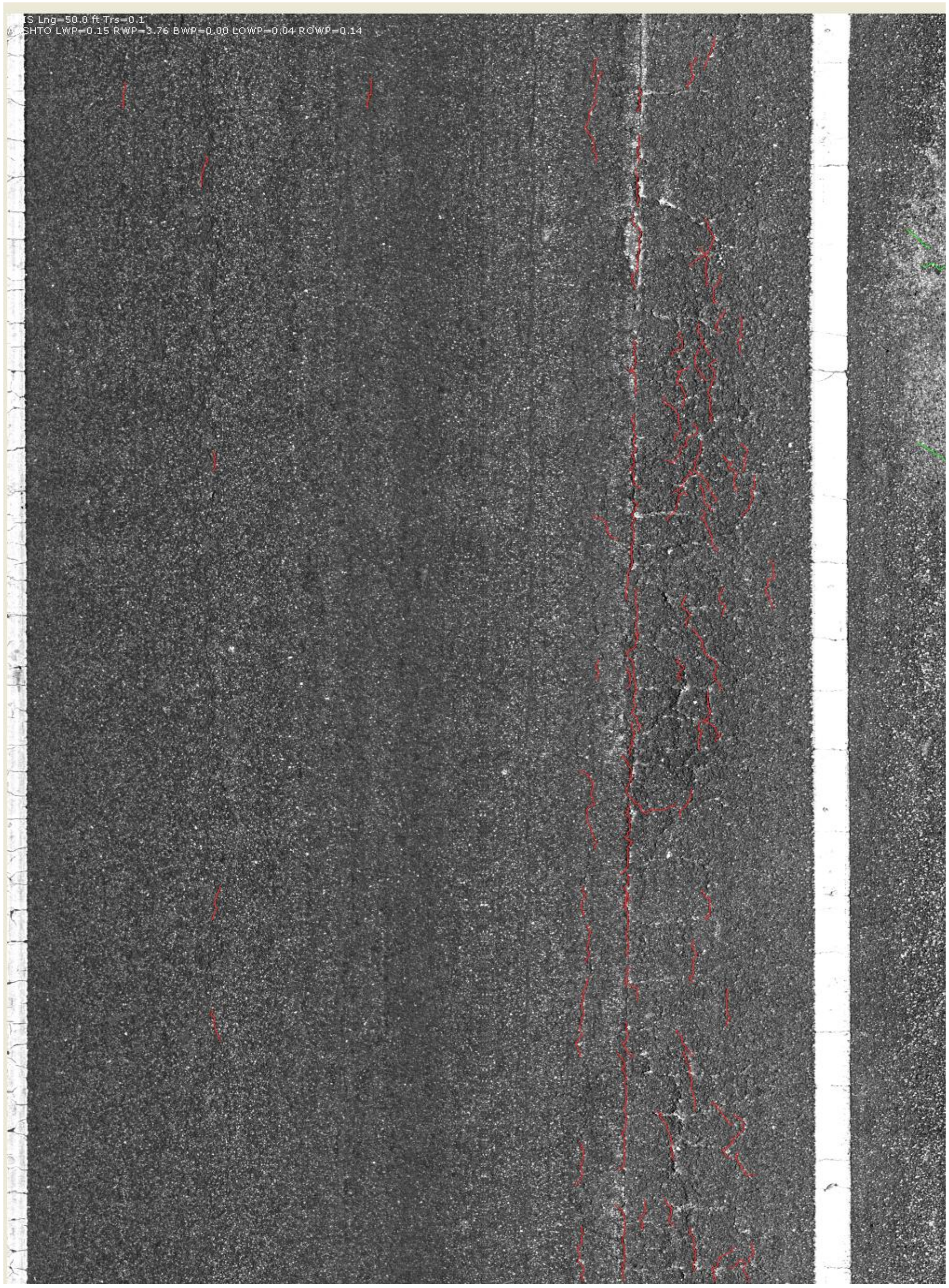

Figure 4.5 Sample crack maps for SR 91 image (low extent of cracking)

4.3.1 Automated Evaluation Using the *Workstation* program

4.3.1.1 Evaluation of US 41 (Econocrete pavement)

Table 4.4 Crack evaluation on US 41 using the *Workstation* program
(The numbers in the table indicate the number of cracks in each slab
L- Low severity, M – Medium Severity and H – High severity)

SECTION	Severity Level	Transverse Cracking	Corner Cracking	Longitudinal Cracking
3B2S	L	0	0	0
	M	1	0	0
	H	0	3	3
	All severities	1	3	3
3C	L	0	0	0
	M	0	0	1
	H	0	2	0
	All severities	0	2	1
4A	L	0	0	2
	M	0	0	3
	H	0	0	1
	All severities	0	0	6
4B	L	0	0	1
	M	0	1	0
	H	0	0	2
	All severities	0	1	3
4C	L	0	0	7
	M	1	1	18
	H	0	3	13
	All severities	1	4	38

L – Low severity, M – Medium severity and M – High severity

4.3.2.2 Evaluation of SR 54 (Superpave pavement)

Table 4.5 AASHTO-based Crack evaluation on SR 54 using the *Workstation* program

SECTION	Severity Level	OWP (m/m^2)	IWP (m/m^2)	BWP (m/m^2)
Shelby	1	0.03	0.08	0.02
	2	0.12	0.12	0
	3	0.49	0.76	0.02
	All severities	0.64	0.95	0.03
Woodbine	1	0.02	0.03	0.03
	2	0.28	0.26	0.01
	3	0.68	0.72	0.02
	All severities	0.99	1.01	0.07
Wildpine	1	0.13	0.15	0
	2	0.39	0.28	0.078
	3	0.70	0.26	0.59
	All severities	1.22	0.69	0.67

1 – Low severity, 2 – Medium severity and 3 – High severity

4.3.2.3 Evaluation of SR 212 (Superpave pavement)

Table 4.6 AASHTO-based crack evaluation on SR 212 using the *Workstation* program

SECTION	Severity Level	OWP (m/m^2)	IWP (m/m^2)	BWP(m/m^2)
Hodges	1	0.03	0	0.02
	2	0.18	0.04	0
	3	0.32	1.16	0
	All severities	0.54	1.20	0.02
Washburn	1	0.11	0.09	0
	2	0	0	0
	3	0.16	0	0
	All severities	0.24	0.09	0
Aldridge	1	0	0	0.03
	2	0.04	0.06	0
	3	0.52	0.19	0
	All severities	0.56	0.25	0.03

1 – Low severity, 2 – Medium severity and 3 – High severity

4.3.2.4 SR 91 Florida Turnpike (Superpave pavement)

ICC *Workstation* program was also used to map the SR 91 asphalt sections. The interactive nature of this program enables the analyst to map the crack configuration of an image very accurately. The results are produced in terms of the length of each crack as shown in Appendix D (Table D1) for a sample pavement section.

CHAPTER 5

COMPARISON OF MANUAL AND AUTOMATED/INTERACTVE CRACK EVALUATION

5.1 Computation of Automated/Interactive Crack Evaluation Error

Each candidate distress evaluation system was assessed based on the error of the results of that system with respect to the results of the corresponding manual crack evaluation as defined in Eqn. (5.1).

$$E(\%) = \left[\frac{\frac{\sum X_i}{n} - Y}{\frac{\sum X_i}{n}} \right] x100 \qquad (5.1)$$

Where X_i = AASHTO/FDOT crack rating of a given test section evaluated by the given evaluation system on the i^{th} repetition, n= total number of repetitions and Y= Corresponding AASHTO/FDOT crack rating obtained from the manual evaluation.

5.1.1 Sample Error Computation

<u>For SR 54 Wildpine section</u>

Extent of outside wheel path (OWP) cracks at a severity level 2
based on manual survey = 0.0129 m/m^2 (Table 3.4)

Extent of outside wheel path (OWP) cracks at a severity level 2
based on *Workstation* program evaluation = 0.39 m/m^2 (Table 4.5)

Applying Eqn. (5.1)

$$E(\%) = \left[\frac{0.39 - 0.0129}{0.39} \right] x100 \qquad = 96.7\%$$

The above result is indicated in Table 5.4

5.1.2 Comparison of the Manual and *CrackScope* Program Crack Evaluations

5.1.2.1 Comparison of the Results of US 41 (Econocrete pavement) Evaluations

No errors were computed since the automated evaluation results were incompatible with the FDOT format (see Section 4.3.1.1).

5.1.2.2 Comparison of the Results of SR 54 (Superpave Pavement) Evaluations

The following nomenclature is used in Tables 5.1 and 5.2:

1. Low severity
2. Medium severity
3. High severity

OWP – Outside wheel path
IWP – Inside wheel path
BWP – Between wheel paths

Table 5.1 *Crackscope*-based percent evaluation errors for separate sections (SR 54)

SECTION	Severity level	OWP(m/m^2)	IWP(m/m^2)	BWP(m/m^2)
Woodbine	1	94.4	100	N/A
	2	-63.7	57.1	N/A
	3	N/A	N/A	N/A
	All severities	-107.6	-51.8	N/A
Wildpine	1	100	94.1	100
	2	98.8	N/A	98.9
	3	N/A	N/A	N/A
	All severities	99.2	-452.6	98.7

1 – Low severity, 2 – Medium severity and 3 – High severity

Note: N/A denotes cases where the corresponding automatically evaluated cracking extent is zero making the denominator in Eqn. (5.1) zero.

5.1.2.3 Comparison of the Results of SR 212 (Superpave Pavement) Evaluations

Table 5.2 *Crackscope*-based percent evaluation errors for separate sections (SR 212)

SECTION	Severity Level	OWP(m/m^2)	IWP(m/m^2)	BWP(m/m^2)
Hodges	1	100	97.1	100
	2	100	89.1	N/A
	3	N/A	N/A	N/A
	All severities	100	83.4	100
Washburn	1	100	98.4	100
	2	93.4	N/A	N/A
	3	N/A	N/A	N/A
	All severities	87.2	81.1	100
Aldridge	1	100	100	100
	2	100.0	N/A	N/A
	3	N/A	N/A	N/A
	All severities	100	77.1	64.9

1 – Low severity, 2 – Medium severity and 3 – High severity

Note: N/A denotes cases where the corresponding automatically evaluated cracking extent is zero making the denominator in Eqn. (5.1) zero.

Tables 5.1 and 5.2 show mostly positive errors indicating that the *Crackscope* program has consistently over-estimated the extent of cracks. This is probably due to two reasons; (1) the manual evaluations were performed during night time with the possibility that the evaluators could have missed a significant number of hairline cracks which are correctly identified by the *Crackscope* program (2) the automated software could be mistakenly identifying discontinuities in the pixel intensity, which are generally referred to as "edges" in image processing, as additional cracks.

5.1.2.4 Comparison of the Results of SR 91 (Superpave pavement) Evaluations

Comparison of the crack maps in Figure 4.4 with Figs. D1 and D2 (Appendix D) indicate the following:

1. In the manual survey conducted during the night time the investigators have been able to map only the major cracks in both pavement sections 1 and 2.
2. The *Crackscope* program results indicate additional cracks that have not been mapped during the manual survey.
3. The *Crackscope* program results also indicate that other features originating probably from the OGFC texture have also been mapped as cracks.

The above observations from crack mapping more or less support the reasoning provided at the end of Section 5.1.2.3 to explain the significant errors seen in Tables 5.1 and 5.2.

5.1.3 Comparison of the Manual and *Workstation* Program Crack Evaluations

5.1.3.1 Comparison of the Results of US 41 (Econocrete Pavement) Evaluations

Table 5.3 *Workstation*-based percent evaluation errors for separate sections (US 41)

SECTION	Severity Level	Transverse Cracking	Corner Cracking	Longitudinal Cracking
3B2S	L	N/A	N/A	N/A
	M	100	N/A	N/A
	H	N/A	66.7	66.7
	All severities	-300	66.7	66.7
3C	L	N/A	N/A	N/A
	M	N/A	N/A	100
	H	N/A	0	N/A
	All severities	N/A	0	100
4A	L	N/A	N/A	100
	M	N/A	N/A	-100
	H	N/A	N/A	100
	All severities	N/A	N/A	0
4B	L	N/A	N/A	100
	M	N/A	100	N/A
	H	N/A	N/A	100
	All severities	N/A	100	66.7
4C	L	N/A	N/A	-57.14
	M	-100	0	-11.11
	H	N/A	100	100
	All severities	-300	75.0	18.42

L – Low severity, M – Medium severity and M – High severity

Note: N/A denotes cases where the corresponding interactively evaluated crack count is zero making the denominator in Eqn. (5.1) zero.

5.1.3.2 Comparison of the Results of SR 54 (Superpave Pavement) Evaluations

Table 5.4 *Workstation*-based percent evaluation errors for separate sections (SR 54)

SECTION	Severity Level	OWP (m/m^2)	IWP (m/m^2)	BWP (m/m^2)
Shelby	1	96.7	97.3	59.5
	2	67.5	94.7	N/A
	3	-26.6	-19.9	29
	All severities	-3.2	3.4	53.3
Woodbine	1	5.5	100	100
	2	1.7	85.3	22
	3	-11.6	10.2	69
	All severities	-6.4	32.2	79.9
Wildpine	1	100	95.5	N/A
	2	96.7	-36.1	94.2
	3	98.6	7.7	99.0
	All severities	98.5	9	99.3

1 – Low severity, 2 – Medium severity and 3 – High severity

Note: N/A denotes cases where the corresponding interactively evaluated cracking extent is zero making the denominator in Eqn. (5.1) zero.

5.1.3.3 Comparison of the Results of SR 212 (Superpave Pavement) Evaluations

Table 5.5 *Workstation*-based percent evaluation errors for separate sections (SR 212)

SECTION	Severity Level	OWP (m/m^2)	IWP (m/m^2)	BWP (m/m^2)
Hodges	1	100	N/A	100
	2	99.4	55.8	N/A
	3	15.4	83.8	N/A
	All severities	49.7	79.8	100
Washburn	1	100	100	N/A
	2	N/A	N/A	N/A
	3	-55.5	N/A	N/A
	All severities	-3.7	17.8	N/A
Aldridge	1	N/A	N/A	100
	2	97	100	N/A
	3	92	78.4	N/A
	All severities	92.4	82	100

1 – Low severity, 2 – Medium severity and 3 – High severity

Note: N/A denotes cases where the corresponding interactively evaluated cracking extent is zero making the denominator in Eqn. (5.1) zero.

It is logical to assume that suitability of a given software program for project-level evaluation must be decided based on the deviation of its evaluations from the manual evaluation, for the entire project. Hence the investigators developed Table 5.6 to illustrate the comparison of the evaluation errors of both programs for each tested section.

Table 5.6 Comparison of software evaluation errors

(OWP – Outside wheel path, IWP – Inside wheel path, BWP – Between wheel paths)

Test section	Pavement type	Percent evaluation error					
		Crackscope program			*Workstation* program		
		OWP	IWP	BWP	OWP	IWP	BWP
US 41	Concrete	Format incompatible			-300.0	80.6	63
SR 54	Superpave	-4.2	-292.2	98.7	88.9	14.9	77.5
SR 212	Superpave	95.7	80.5	88.3	46.1	59.9	100
SR 91	Superpave	Crack mapping performed					

Tables 5.3 - 5.6 also show that the magnitudes of errors associated with the *Workstation* program are significantly lower than those computed for the *Crackscope* program evaluation except in two isolated cases. The general trend of lower error is to be expected since the former is an interactive program. This observation supports one reason previously offered by the investigators to explain the discrepancies seen in the *Crackscope* evaluation, i.e. *Crackscope* program could be mistakenly identifying discontinuities in the pixel intensity as additional cracks

However, the majority of the errors are once again positive indicating that the *Workstation* program has also consistently over-estimated the extent of cracks. The latter observation certainly supports the other previous explanation offered by the investigators that the evaluators could have missed a significant number of hairline cracks since the manual evaluations were performed during night time. The summary comparison of the results of the two programs in the evaluation of SR 54 and SR 212 test sections are illustrated graphically in Figures 5.1 and 5.2, respectively.

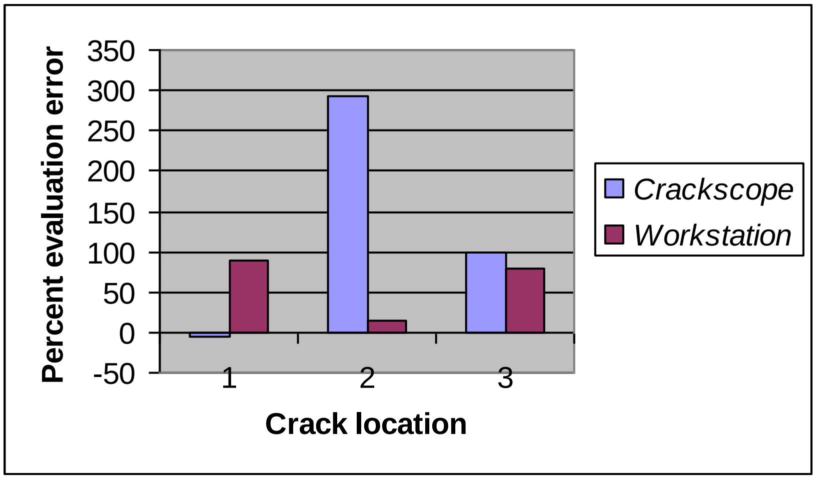

Figure 5.1 Comparison of software evaluation errors for SR 54

(1 – Outside wheel path, 2 – Inside wheel path, 3 – Between wheel paths)

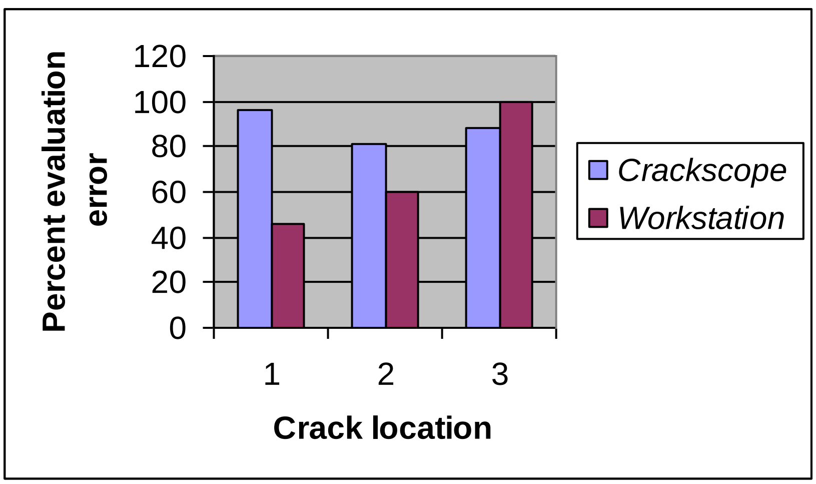

Figure 5.2 Comparison of software evaluation errors for SR 212

(1 – Outside wheel path, 2 – Inside wheel path, 3 – Between wheel paths)

5.1.4 Error estimation based on manual evaluation of images

A likely explanation of the unusually high differences between the manual crack evaluation and the *Crackscope* program-based automated crack evaluation is that many hairline cracks could have been missed during the manual evaluation. Even in the case of crack mapping on SR 91, when one compares the results of manually drawn crack maps (Appendix D) and the corresponding automated crack mapping in the images in Figures 4.4 and 4.5, one realizes that the above explanation is compelling. Hence the investigators used an alternative method of evaluation to assess the accuracy of the *Crackscope* program. For this purpose, the crack maps of a number of images of SR 91 that were generated by the *Crackscope* program were compared with the crack configuration of those images observed on the computer screen manually. Then, based on this comparison an approximate error percentage was estimated from Eqn. (5.1) for each analyzed image as shown in Table 5.7.

Table 5.7 Percent of automation error based on manual evaluation of digital images

Image No:	Percentage error (Eqn. 5.1)		
	Evaluator 1	Evaluator 2	Average
1	-10	-6	-8
2	5	15	10
3	-5	0	-2.5
4	6	5	5.5

Two evaluators (1 and 2) were employed for the above exercise in order to avoid any evaluator bias in the final estimates. The following statistics of the percent error can be obtained from the average results in Table 5.7.

Mean of percent error = 1.25%

Std. deviation of percent error = 8.1%

Estimated population std. deviation (n=4) = 8.1%/sqrt((n) = 4.05%

From the mean and the sample standard deviation of percent error, the investigators were able to predict an error estimate at a 95% confidence.

Range of error of the *Crackscope*
program at 95% confidence = **[-6.7%, 9.2%**]

Therefore, one can conclude that if the accuracy of an automated crack evaluation program can be estimated based on the results of its evaluation of a sample of images from a test section and the corresponding results of a manual evaluation performed on the computer screen, then the users could expect an accuracy above 90% from the *Crackscope* program at a confidence level of 95%. A similar conclusion has been achieved in a software evaluation study performed for the Kansas Dept. of Transportation (Raman et al, 2004) using an unnamed automated crack evaluation program.

5.2 Repeatability of Crack Evaluation

Each candidate distress evaluation system was also assessed based on the precision of the results of that system as defined in Eqn. (5.2).

$$P(\%) = \left[1 - \frac{Max\left| X_i - \frac{\sum X_i}{n} \right|}{\frac{\sum X_i}{n}} \right] x100 \qquad (5.2)$$

Where X_i = AASHTO/FDOT crack rating of a given test section evaluated by the given evaluation system on the ith repetition and n = total number of repetitions

5.2.1 Repeatability of Crack Evaluations of the *Crackscope* program

In every trial in which a given pavement section was evaluated by the above program it was seen consistently that the results were exactly similar. Hence as expected of any automatic algorithm the repeatability of the above program is 100%.

5.2.2 Repeatability of Crack Evaluations of the *Workstation* program

The investigators observed that this interactive evaluation program yielded slightly different results on repeated trials. The deviations did not show a systematic pattern but were rather random in nature. The investigators' experience with the above program leads them to believe that factors such as (1) analysts' fatigue (b) resolution of the computer monitor, and the (c) analysts' limited experience with the program can contribute to the possible slight variations in evaluation results on repeated trials. Another useful measure of the repeatability of crack evaluation using the *Workstation* program could be obtained by comparing the evaluation results obtained by two different trained evaluators.

5.3 Time Demands of Evaluation

The time demands of evaluation of the two programs are illustrated in Table 5.8.

Table 5.8 Comparison of time demands of evaluation

Comparison Criterion	*Crackscope* program	*Workstation* program
Time to transfer images from storage drive to desktop	15 min	15 min
Time to setup the preprocessing file	0	15 min
Time rate of evaluation (by trained user)	5 min/500 images (batch mode)	10 min/image
Approximate number of images per mile	230	230
Time to run 230 images in the batch mode	3 min	40 hrs
Total evaluation time per mile	18 min	40 hrs

5.4 Conclusions and Recommendations

Automated evaluation of the traffic and environmental impact on pavements based on digital imaging has become increasingly popular in the recent years due to the improved efficiency and safety it brings into pavement management. However, a major issue encountered in automated pavement evaluation is the availability of software for accurate and reliable quantification of pavement distress. The primary objectives of this research project were to (1) manually evaluate the crack condition of a number of concrete and Superpave pavements at crack threshold conditions corresponding to designated stages of pavement life, (2) identify automated/interactive software with acceptable accuracy and repeatability in crack evaluation, and (3) verify that the software can be used to detect the above threshold crack conditions.

First, the investigators developed a methodology, based on FDOT's existing crack rating (CR) system, to identify the crack threshold conditions corresponding to designated stages of pavement life. Then, a number of Superpave sections that satisfied the crack threshold criteria were selected for the field investigation phase. During the field investigation, cracks were surveyed using (1) the manual method and (2) automatic/interactive means on one concrete pavement section and three Superpave pavement sections. Although four automated crack evaluation systems were considered initially, due to various difficulties outside the investigators'control, only two automated/interactive systems were used for the ultimate evaluation. They are the *Workstation* program and the *Crackscope* program. Of these the *Workstation* program is relatively easier to use with the MPSV images in terms of compatibility and obtaining the optimum settings required for the most accurate image evaluations. The major difficulties one would encounter with the *Crackscope* software are; (1) setting of the image size for batch mode evaluation, and (2) obtaining the optimum settings required for the most accurate image evaluations. To achieve the second objective in an efficient manner, the investigators used a trial and error approach by individually evaluating a limited number of images representative of the entire image set to obtain the optimum evaluation results.

The following specific conclusions can be derived from the investigation:

1. Of the two software that were studied in detail, namely, the *Crackcsope* program and the *Workstation* program, the *Workstation* program is more compatible with FDOT MPSV images since this software has been developed by ICC, the manufacturer of MPSV.
2. The results of the evaluations show that the accuracy of both programs is not satisfactory with respect to field manual crack evaluation based on the AASHTO (2001) crack evaluation protocol.

3. When the results from manual evaluation of the corresponding pavement images on the computer monitor were considered, the accuracy of the fully-automated program (*Crackscope*) in particular improved significantly.
4. Based on (3) above, part of the inaccuracy can be attributed to the possibility of missing the hairline cracks in the tested section during the field manual evaluations performed at night.
5. The results also indicate that the *Crackscope* software could be consistently identifying texture related pixel intensity discontinuities as additional cracks.
6. The repeatability of both programs was seen to be satisfactory.
7. The *Crackscope* program proves to be more efficient for analysis of Superpave pavements.
8. In addition to its compatibility with MPSV images the other main advantage of the *Workstation* program is its applicability to concrete pavements. In the case of concrete pavements the *Crackscope* program must be modified to incorporate the evaluation format needed by the FDOT Rigid Pavement Condition evaluation methodology, in order to obtain meaningful results.
9. Although the evaluation involved with the *Workstation* program would be time consuming for projects with excessive cracking, it may be adequate for project-level evaluations such as warranty projects, which are usually 3 to 5 years old and generally tend to have less cracking.

When FDOT makes the decision to acquire a crack evaluation program, two critical issues must be considered. They are; (1) ensure compatibility between the crack evaluation system and the images collected by the FDOT MPSV so that the time for refinement and adjustment of settings can be minimized and (2) identify the specific purpose of using the evaluation program i.e. whether it is for network level evaluations that can accomplish preliminary screening of distressed pavements or for more refined and accurate project level evaluations such as warranty projects.

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APPENDIX A

CRACK RATING PERFORMANCE CURVES FOR SELECTED SUPERPAVE SECTIONS

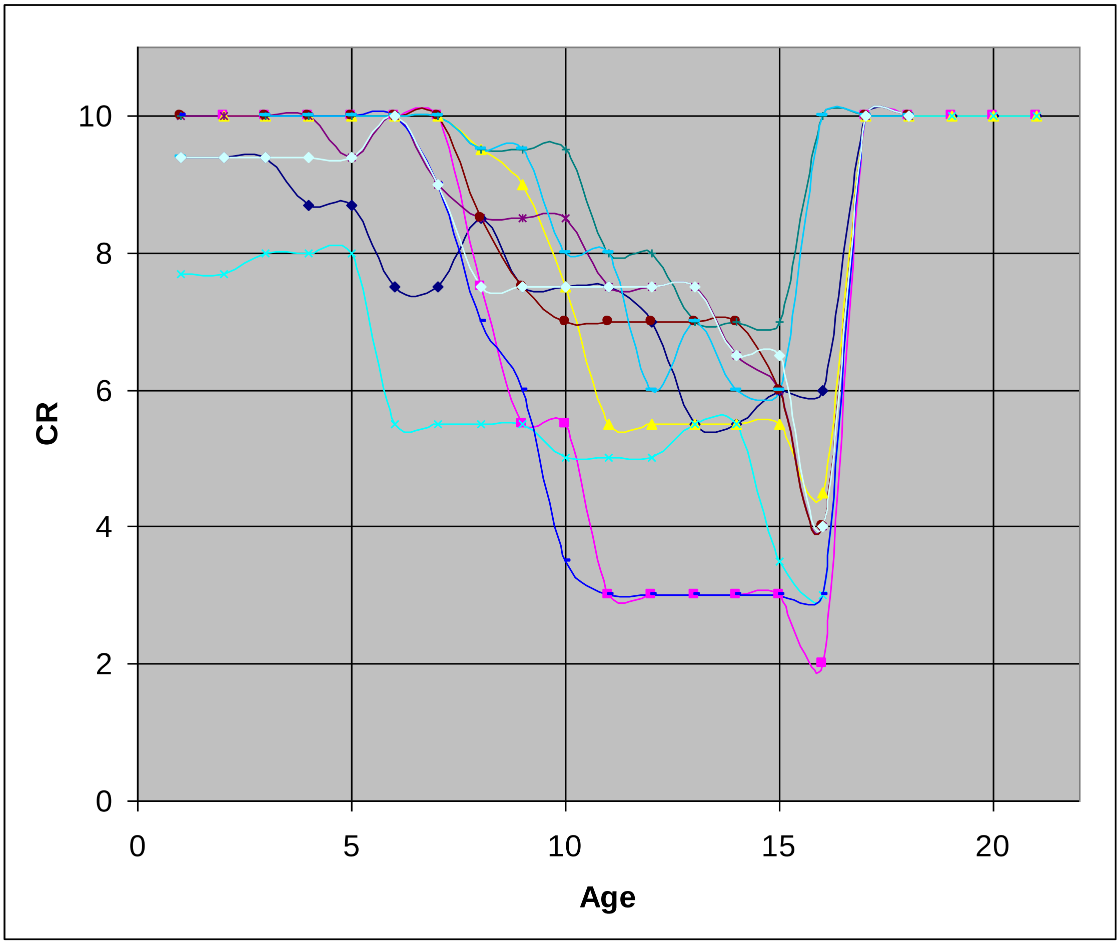


Figure A1 Crack rating curves for District 1 Superpave sections (FC5 and FC6, traffic level D)

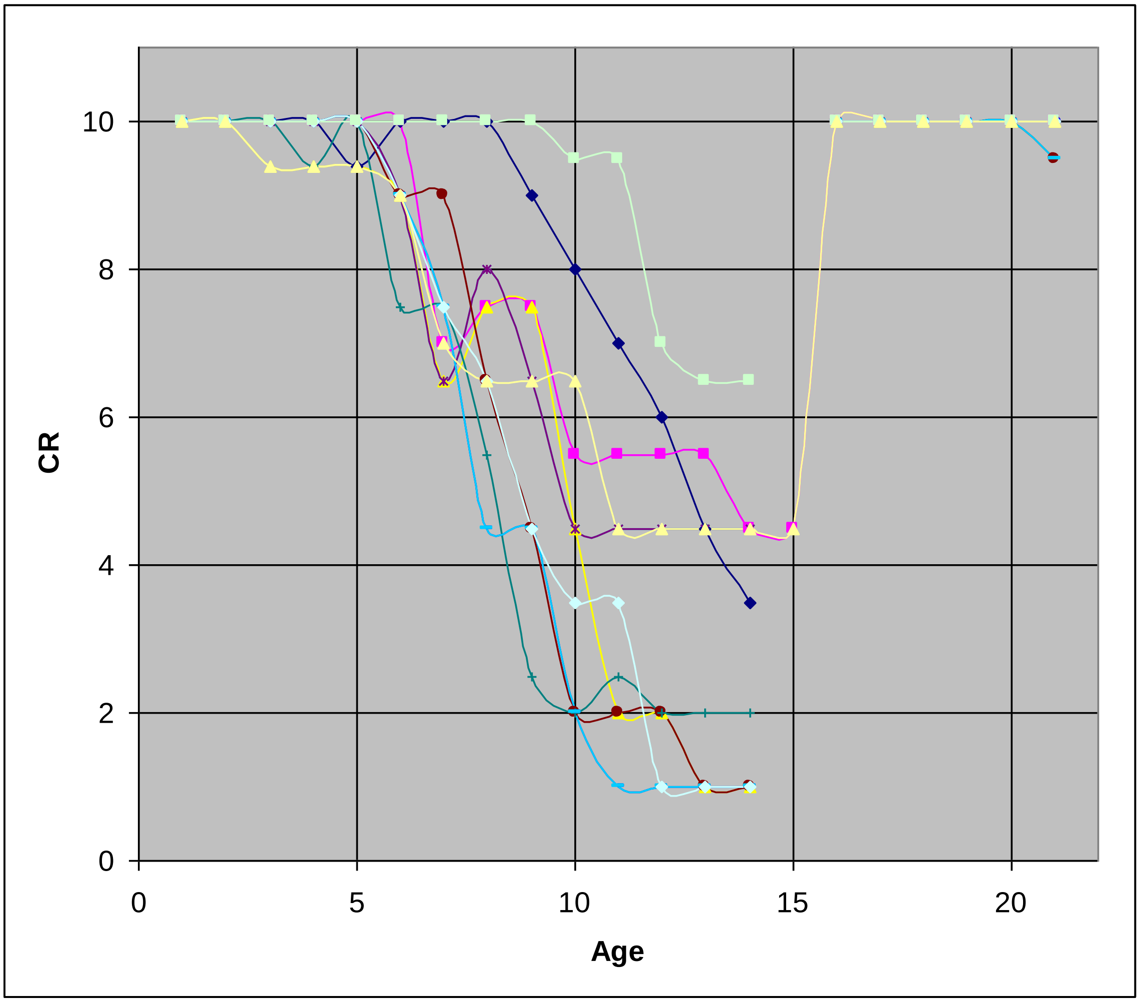


Figure A2 Crack Rating curves for District 2 Superpave sections (FC5 and FC6, traffic level D)

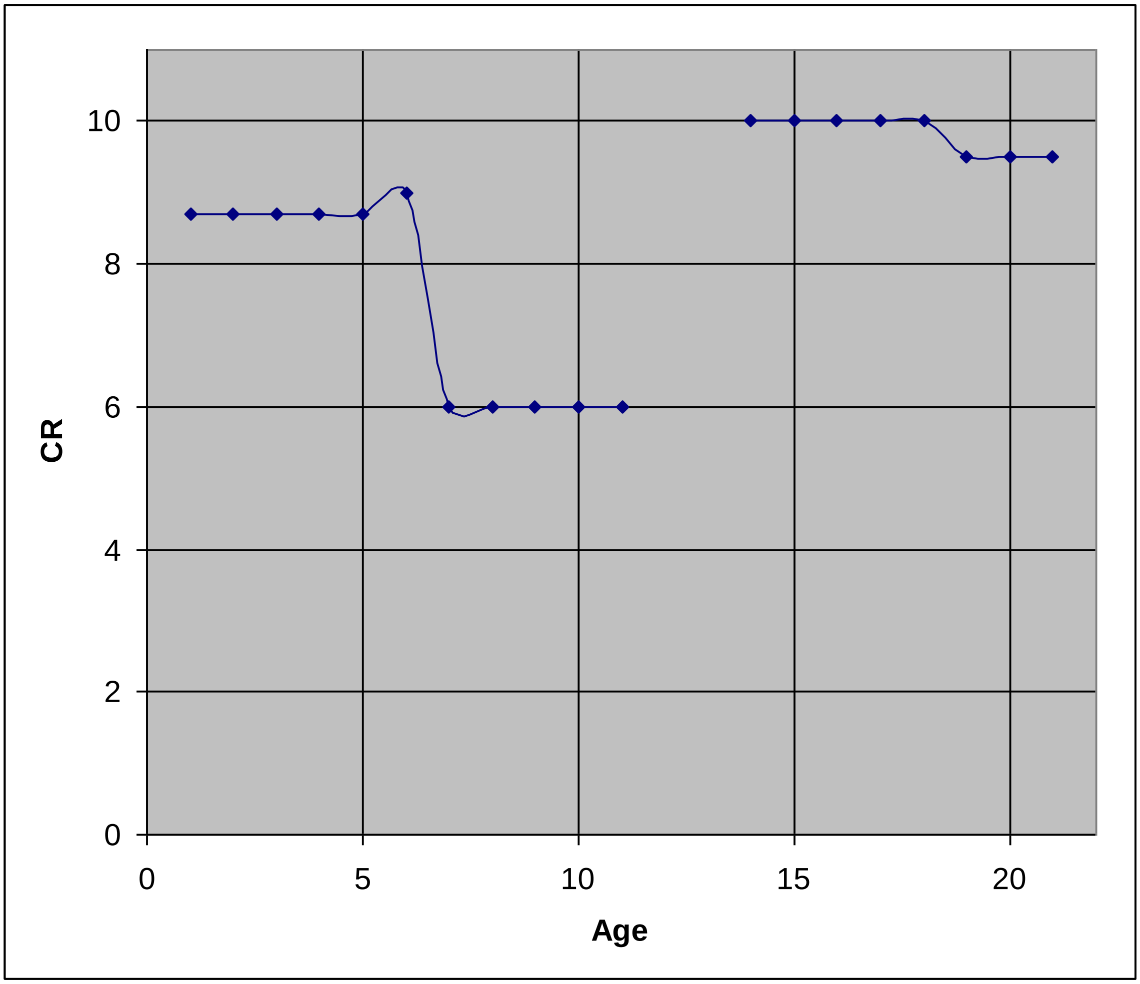


Figure A3 Crack rating curves for District 3 Superpave sections (FC5, traffic level D)

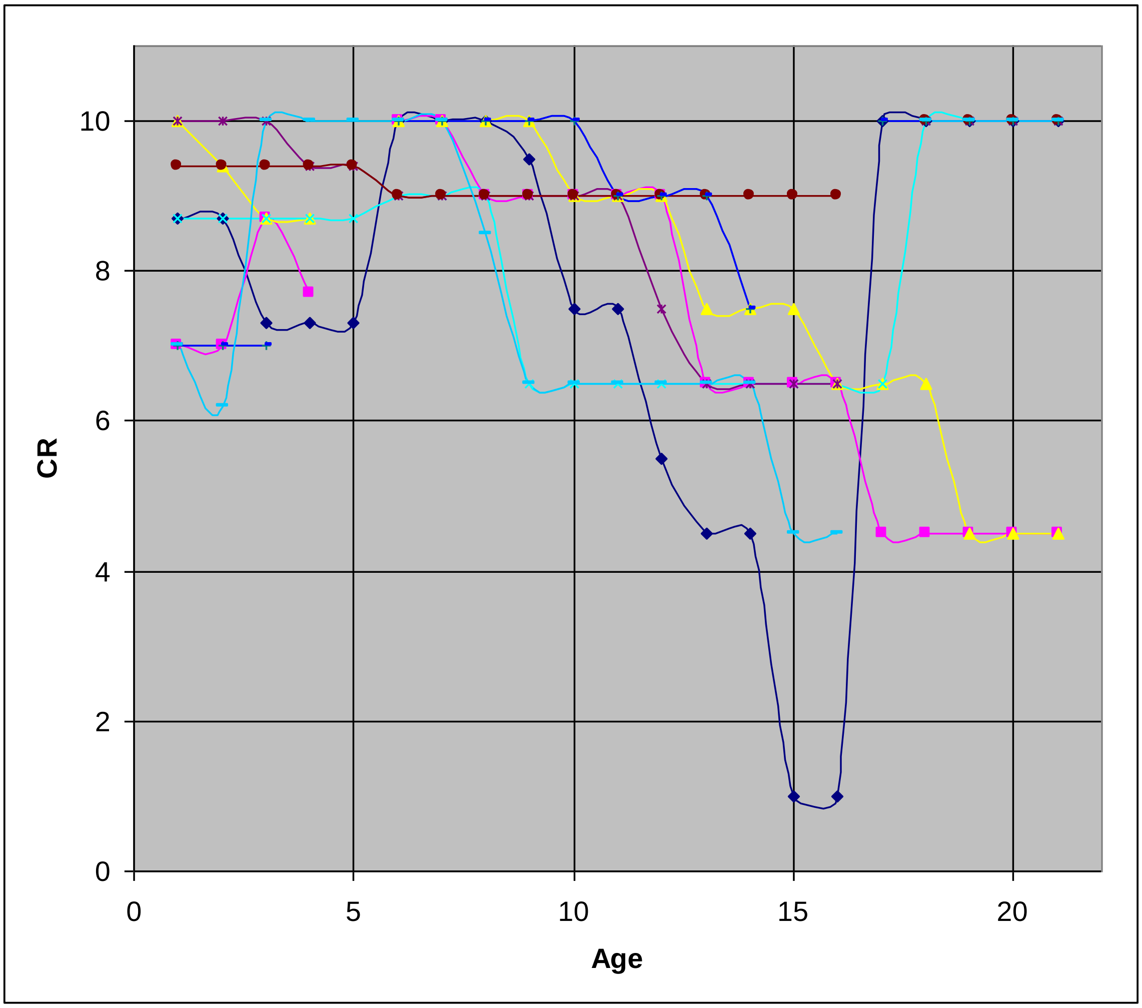


Figure A4 Crack Rating curves for District 4 Superpave sections (FC5 and FC6, traffic level C)

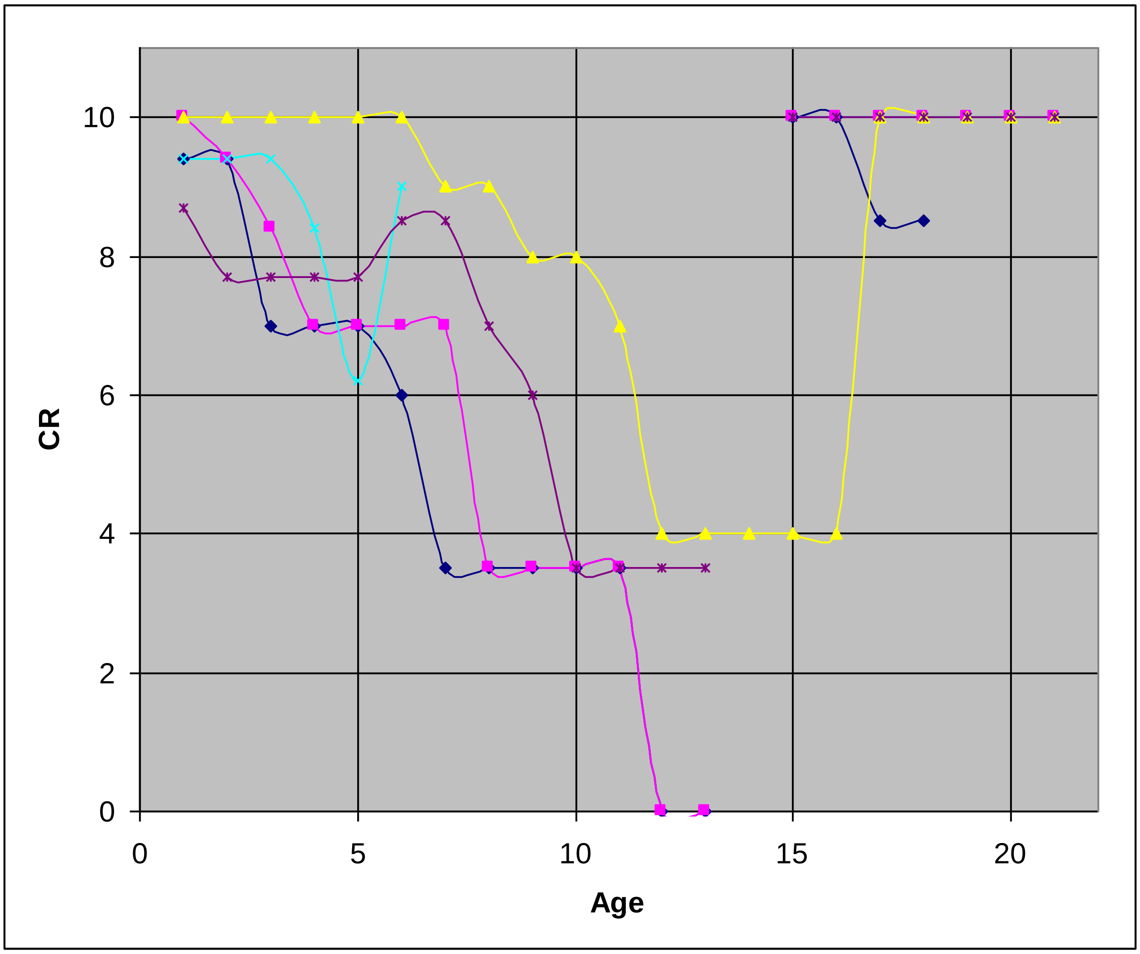


Figure A5 Crack rating curves for District 5 Superpave sections (FC5 and FC6, traffic level D)

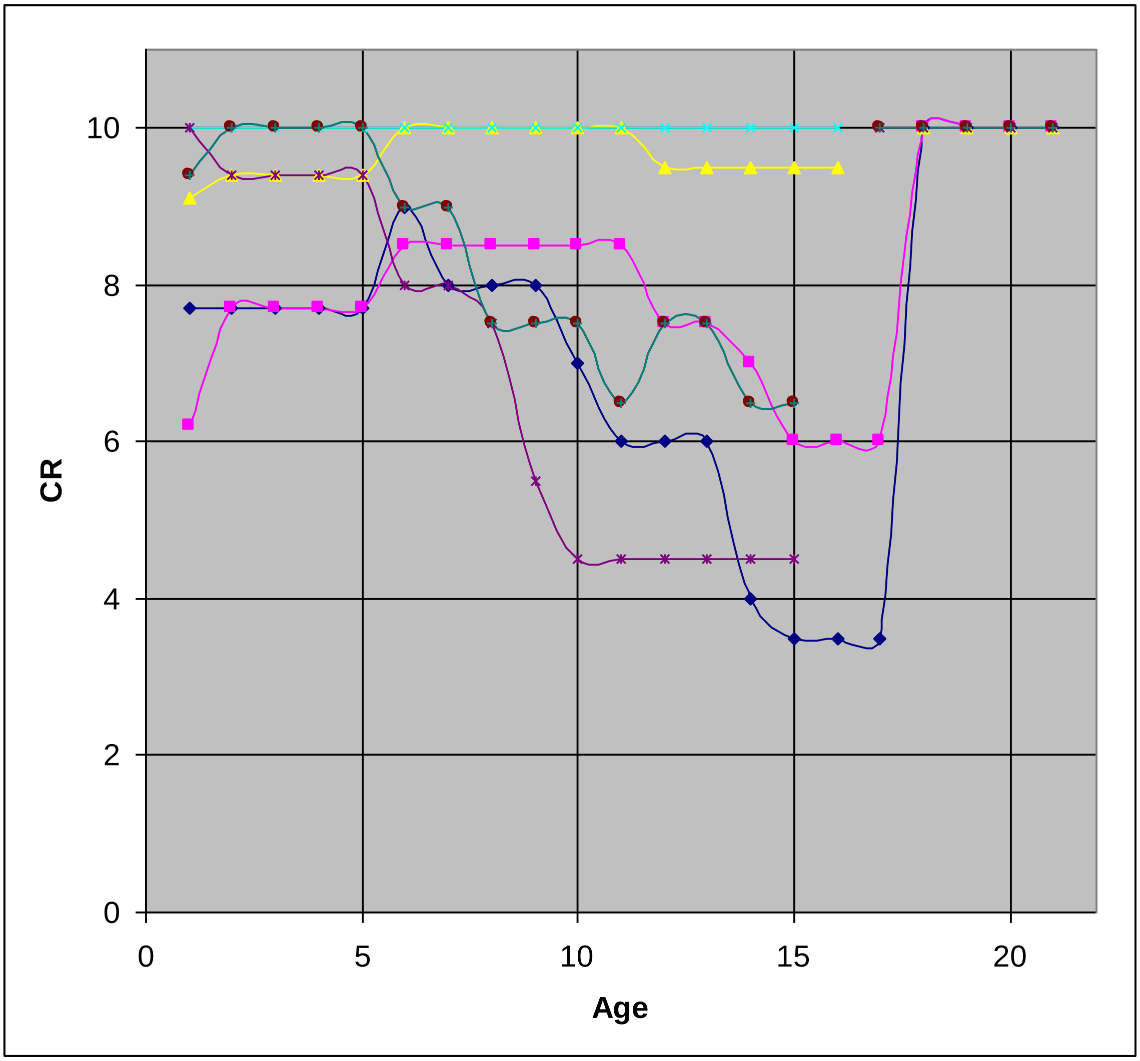


Figure A6 Crack rating curves for District 6 Superpave sections (FC5 and FC6, traffic level D)

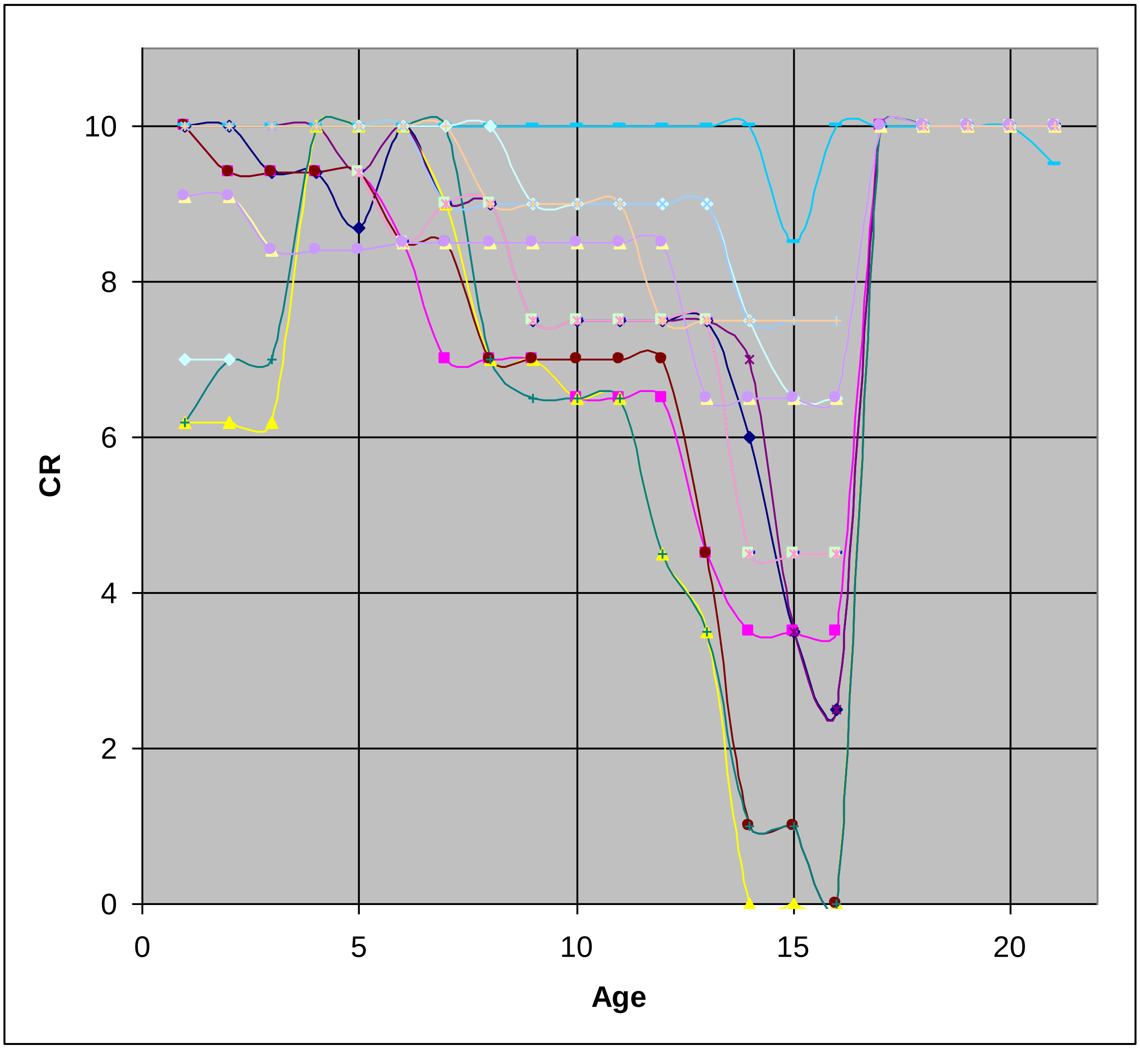


Figure A7 Crack rating curves for District 7 Superpave sections (FC5 and FC6, traffic level D)

APPENDIX B

RIGID PAVEMENT CRACK SURVEY GUIDELINES

NAME OF DISTRESS: **Transverse Cracking**

DESCRIPTION: A crack or break approximately at a right angle to the pavement centerline.

EXPLANATION: Thermal expansion and contraction along with normal shrinkage of a slab may result in the formation of transverse cracking. Compared to longitudinal cracking, this category will have a greater effect upon the serviceability of the pavement because load transfer across the cracked slab results in a more rapid rate of deterioration. As long as the cracks are hairline or closed so as to prevent the intrusion of water and provide aggregate interlock, the cracks are not considered detrimental to pavement serviceability. However, cracks that open excessively permit the intrusion of water and cause the loss of aggregate interlock resulting in loss of load transfer between slabs.

SEVERITY OF DISTRESS:

Light - Visible cracks less than ⅛" (3.18 mm) wide that show no evidence of faulting, loss of aggregate interlock, or the intrusion of debris.

Moderate - Cracks ⅛" (3.18 mm) to ¼" (6.35 mm) wide that exhibit little or no faulting and no evidence of the intrusion of debris.

Severe - Cracks greater than ¼" (6.35 mm) that show loss of aggregate interlock and the obvious intrusion of water and debris. Faulting and spalling may also occur.

MEASUREMENT AND COMPUTATION OF DISTRESS:

Transverse cracks are measured and coded by the number of cracks for the rated section.

Any or all of the severity levels may be coded.

Columns 37, 38, and 39 are specified for light transverse cracks.

Columns 40, 41, and 42 are specified for moderate transverse cracks.

Columns 43, 44, and 45 are specified for severe transverse cracks.

The total number of transverse cracks for each rated section is identified on Line 1 of the output under the respective heading.

Line 2 represents the average number of cracks per mile for each rated section based on the SLD net length of the rated section.

Line 3 of the output is the negative defect value for each of the severity levels based on the number of transverse cracks per mile of the SLD net length.

Light distress - 0.30 per crack

Moderate distress - 0.38 per crack

Severe distress - 0.50 per crack

NOTES:

1) If cracks have been routed but not properly sealed, then record as severity level observed (Rater <u>cannot</u> determine width of underlying cracks).

2) If a section of pavement has been rehabilitated to the extent that the pavement has been ground and the cracks have been properly sealed, then the cracks must be classified as light severity. Note in remarks that pavement has been rehabilitated.

3) Joints at replaced slabs will <u>not</u> be recorded as cracks.

NAME OF DISTRESS: **Longitudinal Cracking**

DESCRIPTION: A crack or break approximately parallel to the pavement centerline.

EXPLANATION: Although this category is unsightly, it is not necessarily detrimental to the serviceability of the pavement. As long as the crack is not open or faulted to the extent that aggregate interlock is lost, load transfer across the crack will occur and the pavement will be serviceable. If the crack opens and permits the intrusion of water and/or debris, the deterioration of the pavement will be accelerated.

SEVERITY OF DISTRESS:

Light - Visible cracks less than ⅛" (3.18 mm) wide that show no evidence of faulting, loss of aggregate interlock or the intrusion of debris.

Moderate - Cracks ⅛" (3.18 mm) to ¼" (6.35 mm) wide that exhibit little or no faulting and no evidence of intrusion of debris.

Severe - Cracks greater than ¼" (6.35 mm) that show loss of aggregate interlock and the obvious intrusion of water and debris. Faulting and spalling may also occur.

MEASUREMENT AND COMPUTATION OF DISTRESS:

Longitudinal cracks are measured and coded by the number of cracks for the rated section.

Any or all of the severity levels may be coded.

Columns 46, 47, and 48 are specified for light longitudinal cracks.

Columns 49, 50, and 51 are specified for moderate longitudinal cracks.

Columns 52, 53, and 54 are specified for severe longitudinal cracks.

The total number of longitudinal cracks for each rated section is identified on Line 1 of the output under the respective heading.

Line 2 represents the average number of cracks per mile for each rated section based on the SLD net length of the rated section.

Line 3 of the output is the negative defect value for each of the severity levels based on the number of longitudinal cracks per mile of the SLD net length.

Light distress - 0.15 per crack

Moderate distress - 0.19 per crack

Severe distress - 0.25 per crack

NOTES:

1) If cracks have been routed but not properly sealed, then record as severity level observed (Rater cannot determine width of underlying cracks).

2) If a section of pavement has been rehabilitated to the extent that the pavement has been ground and the cracks have been properly sealed, then the cracks must be classified as light severity. Note in remarks that pavement has been rehabilitated.

3) Joints at replaced slabs will not be recorded as cracks.

NAME OF DISTRESS: **<u>Corner Cracking</u>**

DESCRIPTION: A crack or break which intersects both the transverse and longitudinal joint.

EXPLANATION: The formation of a corner crack may result from loads imposed on a slab that has insufficient support. This can be caused by the presence of free water and loss of subgrade material that has been pumped out from beneath the slab at the transverse or longitudinal joint. Even though a hairline corner crack may not affect the serviceability of the pavement, it indicates a loss of support that may have been caused by pumping. As the severity of the corner crack increases and permits the intrusion of water, the loss of support may progress to the adjacent slab and significantly reduce serviceability.

SEVERITY OF DISTRESS:

Light - Visible cracks less than ⅛" (3.18 mm) wide that show no evidence of faulting, loss of aggregate interlock or the intrusion of debris.

Moderate - Cracks ⅛" (3.18 mm) to ¼" (6.35 mm) wide that exhibit little or no faulting or evidence of intrusion of debris.

Severe - Cracks greater than ¼" (6.35 mm) that show loss of aggregate interlock, obvious intrusion of water and debris. Faulting and spalling may also occur.

MEASUREMENT AND COMPUTATION OF DISTRESS:

Corner cracks are measured and coded by the number of cracks for the rated section.

Any or all of the severity levels may be coded.

Columns 55, 56, and 57 are specified for light corner cracks.

Columns 58, 59, and 60 are specified for moderate corner cracks.

Columns 61, 62 and 63 are specified for severe corner cracks.

The total number of corner cracks for each rated section is identified on Line 1 of the output under the respective heading.

Line 2 represents the average number of cracks per mile for each rated section based on the SLD net length of the rated section.

Line 3 of the output is the negative defect value for each of the severity levels based on the number of corner cracks per mile of the SLD net length.

Light distress - 0.25 per crack

Moderate distress - 0.31 per crack

Severe distress - 0.40 per crack

NOTES:

1) If cracks have been routed but not properly sealed, then record as severity level observed (Rater cannot determine width of underlying cracks).

2) If a section of pavement has been rehabilitated to the extent that the pavement has been ground and the cracks have been properly sealed, then the cracks must be classified as light severity. Note in remarks that pavement has been rehabilitated.

3) Joints at replaced slabs will not be recorded as cracks.

Table B.1 Numerical deduct values for rigid pavement distresses

TYPE OF DISTRESS	SEVERITY	NUMERIC VALUE
Surface Deterioration	Moderate	0.003 per square foot (0.032 per square meter)
	Severe	0.006 per square foot (0.065 per square meter)
Spalling	Moderate	0.01 per linear foot (0.033 per linear meter)
	Severe	0.02 per linear foot (0.066 per linear meter
Patching	Fair	0.018 per square yard (0.022 per square meter)
	Poor	0.045 per square yard (0.054 per square meter
Transverse Cracking	Light	0.30 per crack
	Moderate	0.38 per crack
	Severe	0.50 per crack
Longitudinal Cracking	Light	0.15 per crack
	Moderate	0.19 per crack
	Severe	0.25 per crack
Corner Cracking	Light	0.25 per crack
	Moderate	0.31 per crack
	Severe	0.40 per crack
Shattered Slab	Moderate	1.15 per shattered slab
	Severe	1.50 per shattered slab

TYPE OF DISTRESS	SEVERITY	NUMERIC VALUE
Faulting		1.0 per 1/32 inch (1.26 per mm) faulting
Pumping	Light	1% - 25% -- 2
		26% - 50% --- 3
		51% - 75% --- 4
		76% - 100% --- 5
	Moderate	1% - 25% --- 4
		26% - 50% --- 6
		51% - 75% --- 8
		76% - 100% --- 10
	Severe	1% - 25% --- 6
		26% - 50% --- 9
		51% - 75% --- 12
		76% - 100% --- 15
Joint Condition	Partially Sealed	5
	Not Sealed	10

APPENDIX C

CRACK EVALUATION IN SUPERPAVE PAVEMENTS

Table C1 Detailed description of cracks in Superpave pavements

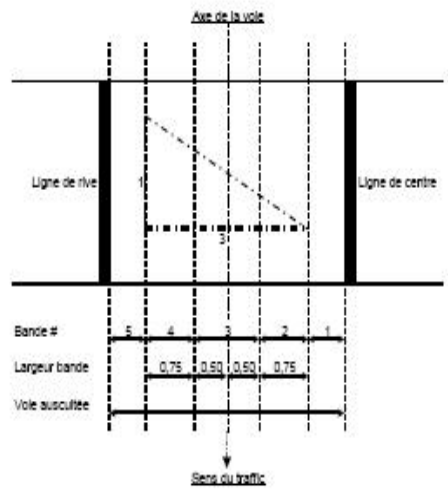
TYPE	DESCRIPTION	SCHEME OR PICTURE
Crack definition	Minimum length: 0,15 m Minimum width: 1 mm	N/A
Transversal cracking	Crack with an orientation ≤ 1:3 (1 parallel et 3 perpendicular to the road axis) and which is present on 2 or more longitudinal strips.	
Longitudinal cracking	Crack with an orientation > 1:3 (1 parallel and 3 perpendicular to the road axis).	
Edge cracking	Longitudinal crack distant less than 0.25 m from the edge of the road.	

Table C1 (Contd.). Detailed description of cracks in Superpave pavements

Alligator cracking	Agglomeration of pavement cracks in the form of a grid, with at least 3 pieces in each direction, and where the diameter of each piece is less than 300 mm. If the diameter of the pieces is greater than 300 mm, then the cracks are considered as distinct.	 *alligator cracking (d ≤ 300 m)*  *distinct cracks (d > 300 mm)*
Multiple cracks	Agglomeration of pavement cracks that run parallel and that are less than 300 mm apart. If they are more than 300 mm apart, then the cracks are considered as distinct.	
Pothole	Hole with an area larger than 50 mm by 50 mm. The bottom of the hole should be in granular basis (full thickness of the pavement).	

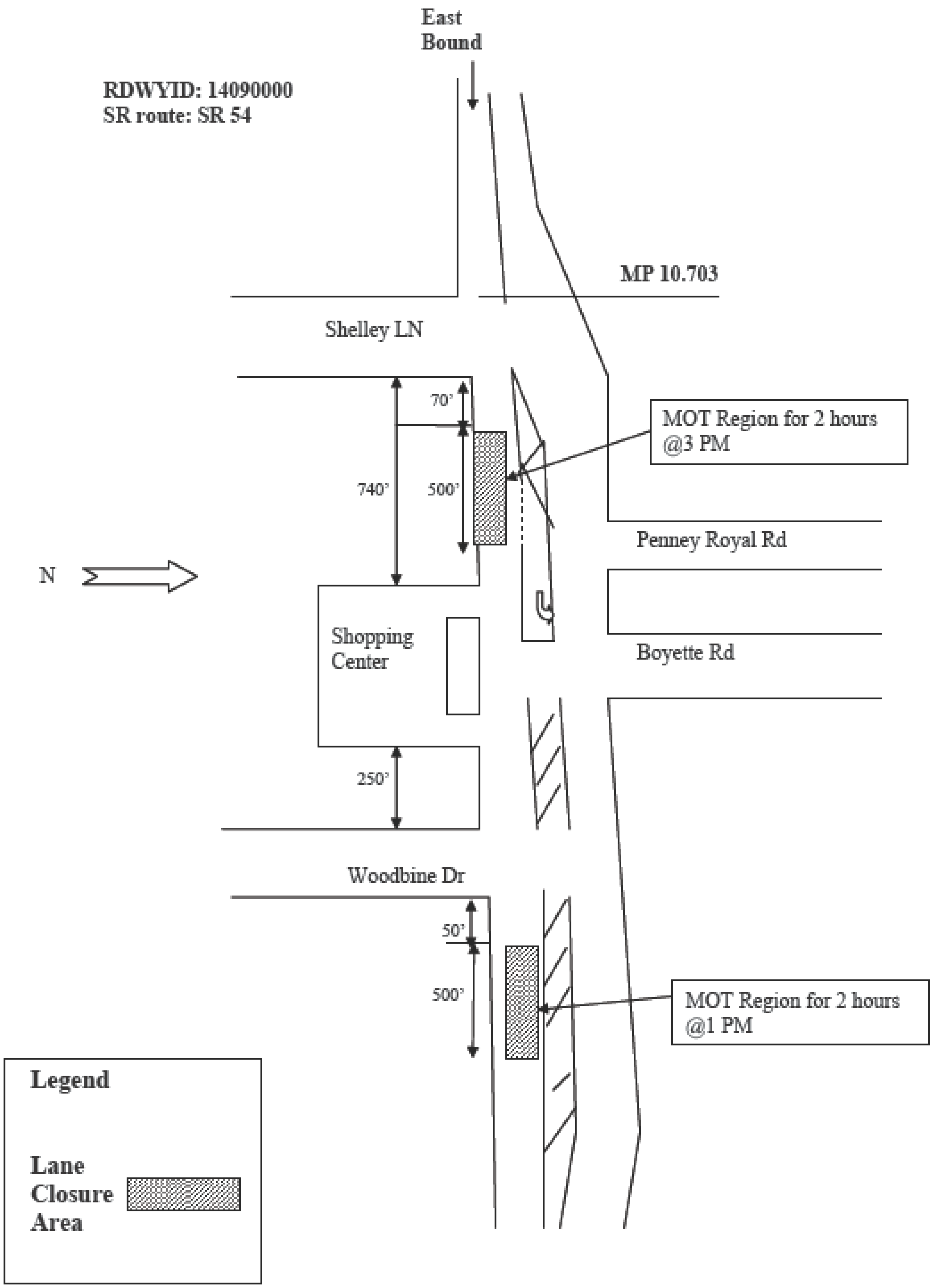


Figure C1 Maintenance of traffic for SR 54 manual crack evaluation

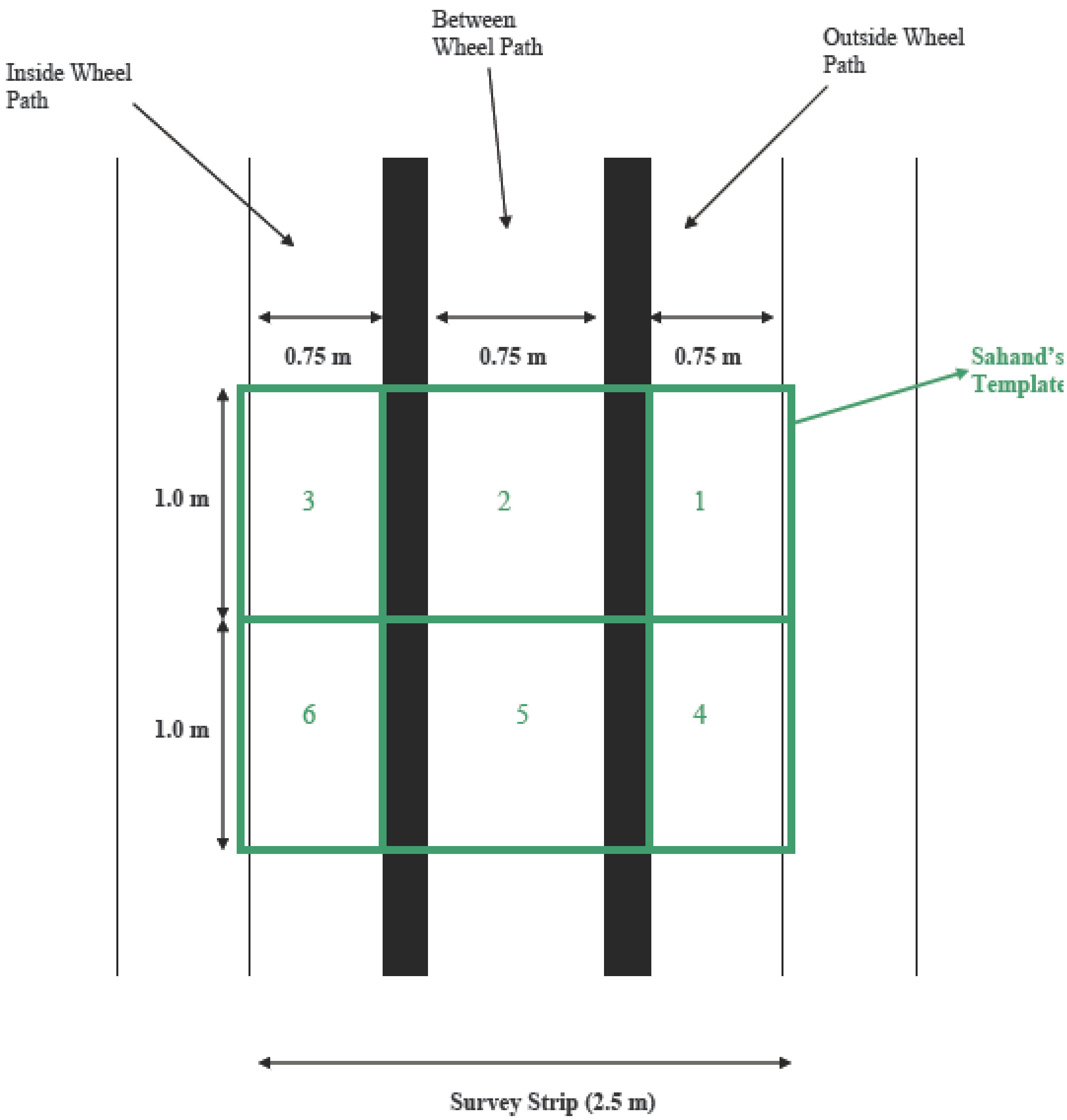


Figure C2 Template for crack evaluation

Table C2 Detailed manual crack survey data for SR 54 (Inside Wheel Path)

(The numbers in the table indicate the width (W) and length (L) of cracks in inches, Crack type notation: T – transverse, L – Longitudinal and A – Alligator, Severity level notation: L- Low, M – Medium and H – High)

Section: 1 - Shelby Lane

Inside Wheel Path

Template Area ID	Type	W	L	Severity	Type	W	L	Severity	Type	W	L	Severity	Type	W	L	Severity
3	T	1/2	11	H												
6				-												
9				-												
12	T	1/4	9.75	M												
15	T	1/4	7.5	M												
18	T	1/2	17	H												
21				-												
24				-												
27	T		4	-												
30				-												
33				-												
36				-												
39				-												
42				-												
45	T	1/2	13.5	H	L	1/2	18	H								
48	T	1/2	3	H				-								
51	L	1/2	5	H				-								
54	T	1/2	12	H	T	1/4	6	M								
57	L	1/2	39	H	T	1/2	9.75	H	T	1/2	9.5	H				
60	L	1/2	39	H	T	1/2	8	H	T	1/4	6.5	M				
63	L	3/4	39	H	T	1/2	17.5	H	T	1/2	9.75	H				
66	A	17	39	H				-								
69	A	14.5	39	H				-								
72	A	15.75	39	H				-								
75	A	12	39	H				-								
78	T	1/2	18	H	L	1/2	6	H								
81	L	3/4	39	H	T	1/2	15	H								
84	L	3/4	39	H	T	1/2	13.5	H								
87	A	12	36	H				-								
90	T	3/4	26	H	T	1/2	12	H								

Table C3 Detailed manual crack survey data for SR 54 (Between Wheel Paths)

(The numbers in the table indicate the width (W) and length (L) of cracks in inches, Crack type notation: T – transverse, L – Longitudinal and A – Alligator, Severity level notation: L- Low, M – Medium and H – High)

Section: - Woodbine Driv

Between Wheel Path

Template Area ID	Type	W	L	Severity	Type	W	L	Severity	Type	W	L	Severity	Type	W	L	Severity
2																
5																
8																
11																
14																
17	T	1/4	6	M												
20				-												
23				-												
26				-												
29	T	3/4	4	H												
32																
35																
38																
41																
44																
47																
50																
53																
56																
59																
62																
65																
68																

Table C4 Detailed manual crack survey data for SR 54 (Outside Wheel Path)

(The numbers in the table indicate the width (W) and length (L) of cracks in inches, Crack type notation: T – transverse, L – Longitudinal and A – Alligator, Severity level notation: L- Low, M – Medium and H – High)

-

Section: 1- Shelby Lane

Outside Wheel Path

Template Area ID	Type	W	L	Severity	Type	W	L	Severity	Type	W	L	Severity	Type	W	L	Severity
1																
4	T	1/8	2	L												
7				-												
10				-												
13				-												
16				-												
19				-												
22				-												
25	T	1/4	11	M												
28	L	1/4	6	M												
31	T	1/4	8	M												
34	L	1/4	12	M												
37	L	1/4	10.5	M												
40				-												
43				-												
46				-												
49	L	1/4	14.5	M	L	1/4	5.5	M								
52				-												
55				-												
58				-												
61	L	1/2	36	H												
64	L	1/2	39	H												
67	L	1/2	16.5	H												
70	L	1/2	13	H												
73				-												
76				-												
79				-												
82	L	1/2	9.5	H												
85																
88																
91																

APPENDIX D

CRACK MAPPING DATA

D.1 Crack Mapping data on Florida Turnpike Based on the Distress identification Manual for LTPP

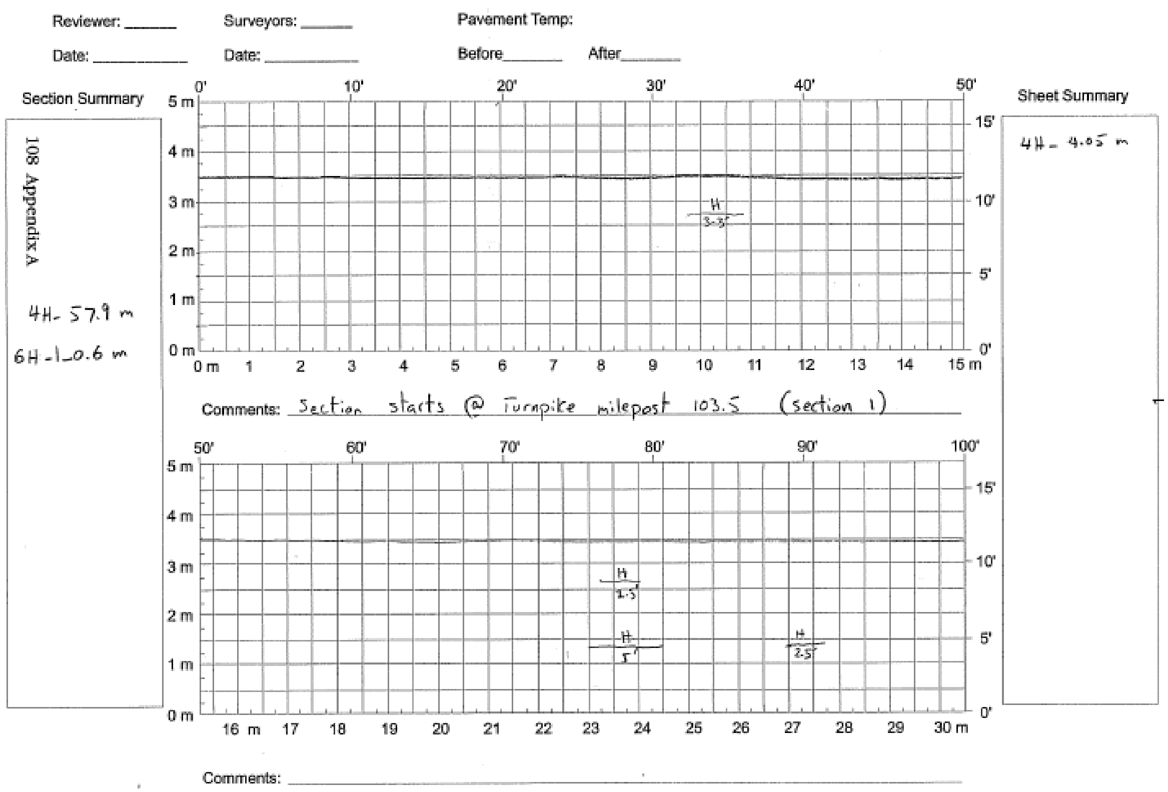


Figure D1(a) Manual crack map on Section 1 of SR 91 (0-100 feet)

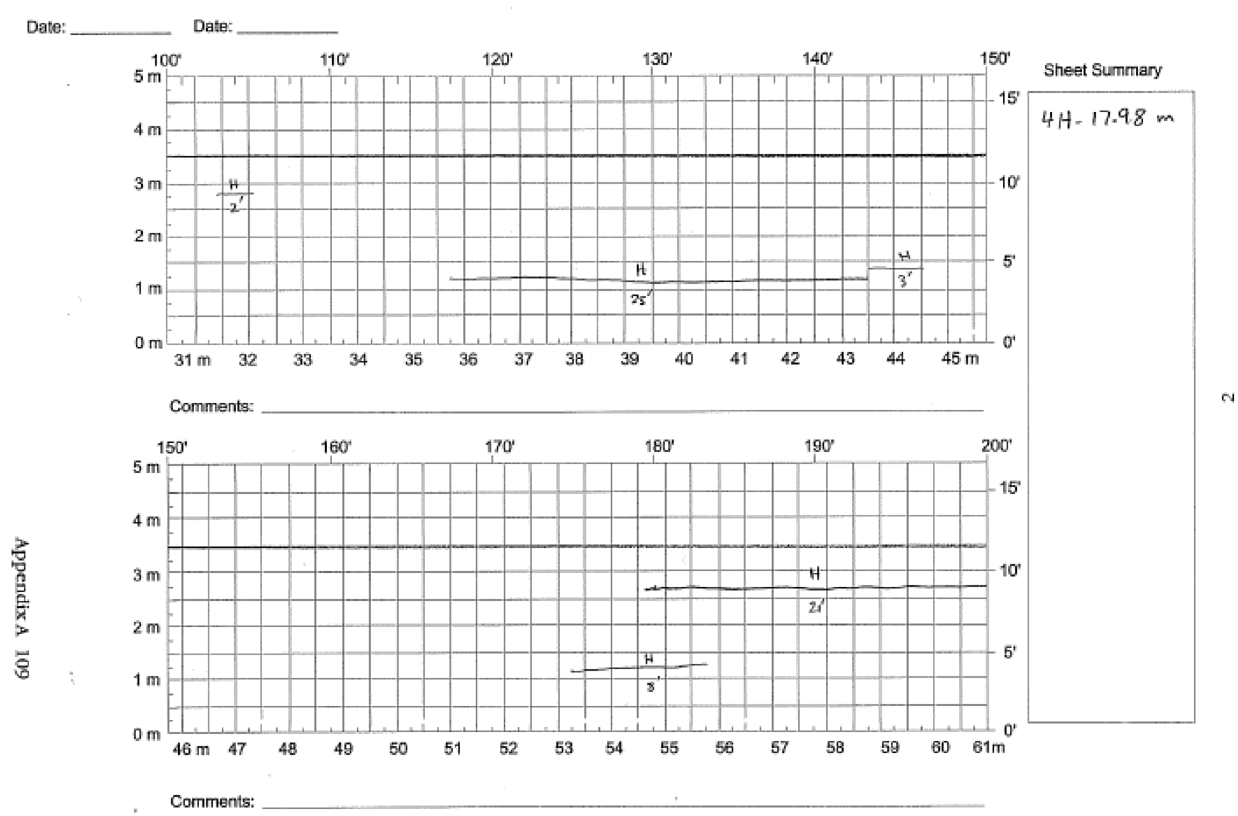


Figure D1(b) Manual crack map on Section 1 of SR 91 (100-200 feet)

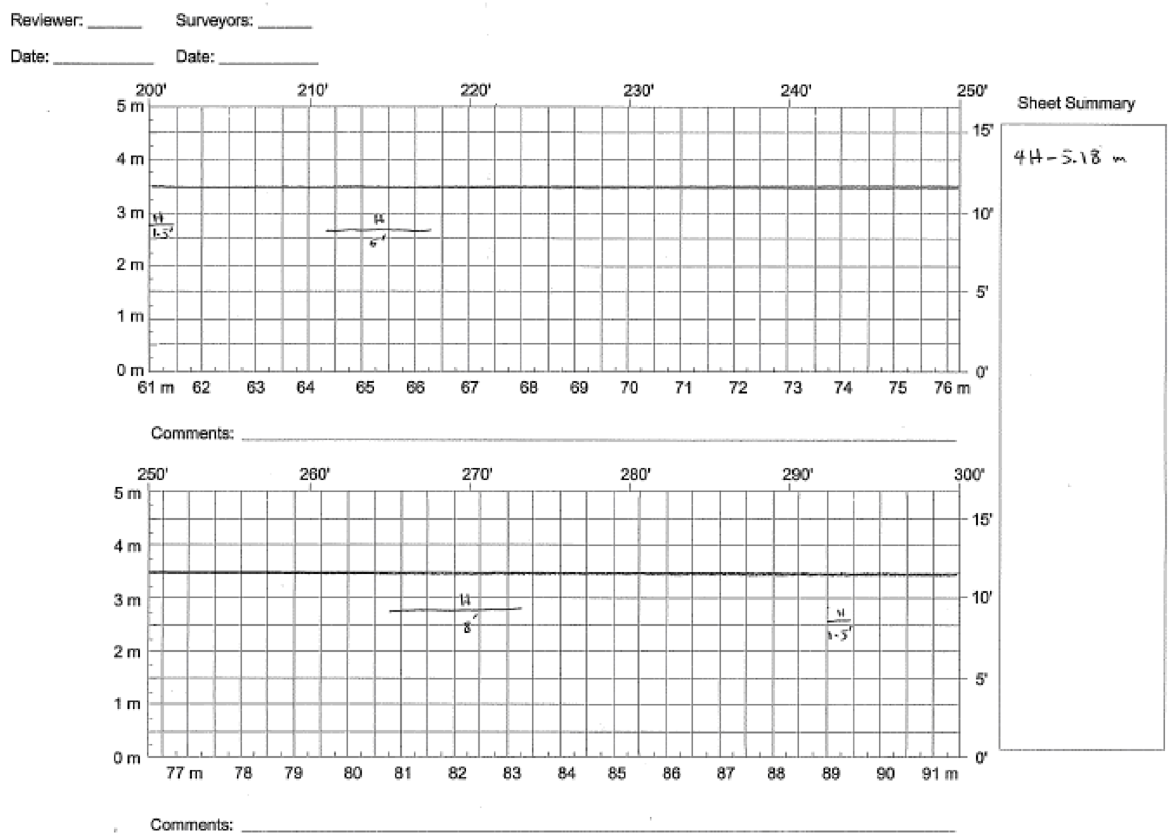


Figure D1(c) Manual crack map on Section 1 of SR 91 (200 -300 feet)

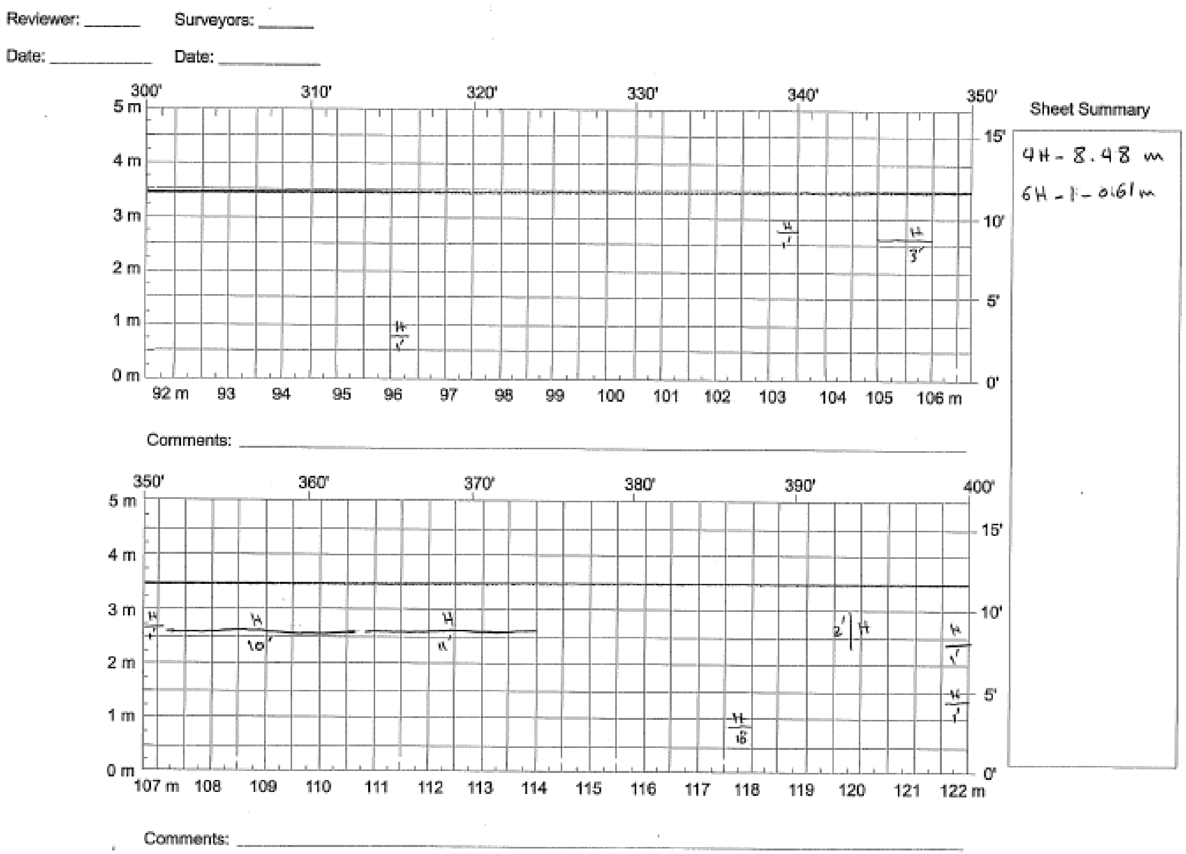


Figure D1(d) Manual crack map on Section 1 of SR 91 (300 - 400 feet)

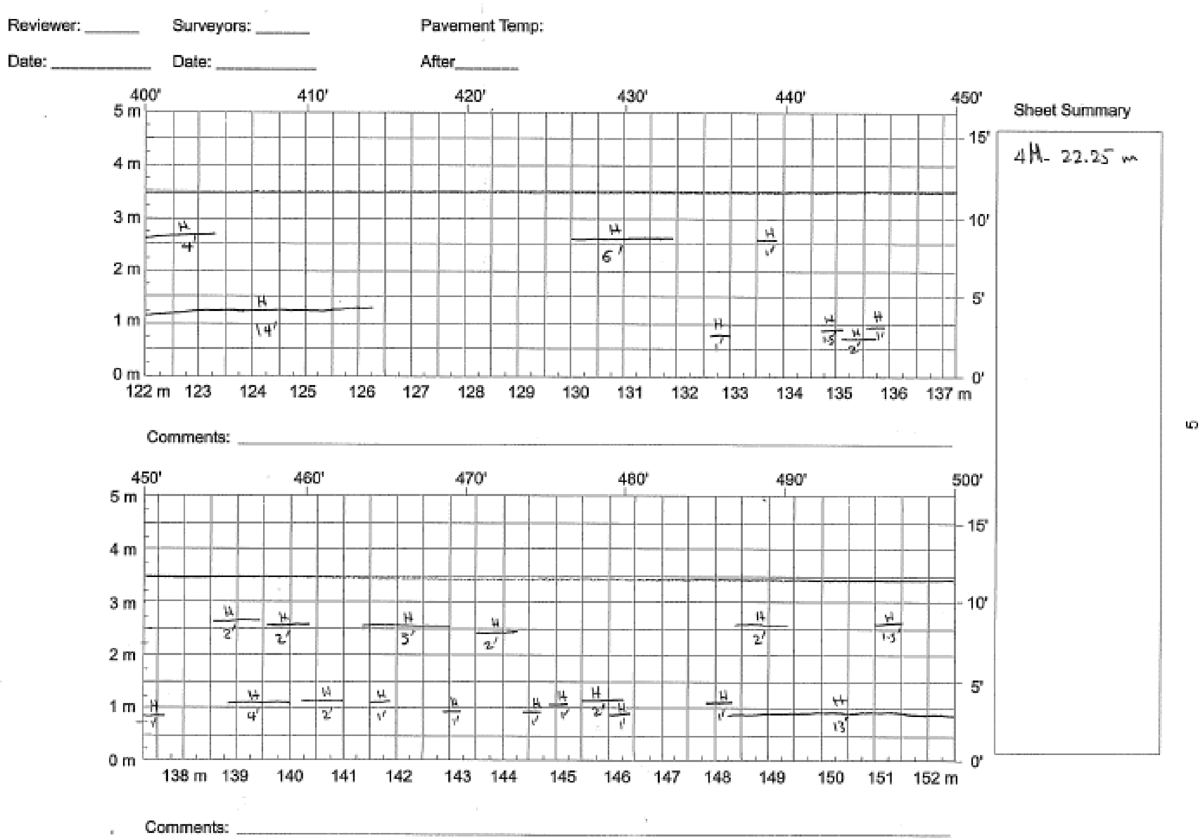


Figure D1(e) Manual crack map on Section 1 of SR 91 (400-500 feet)

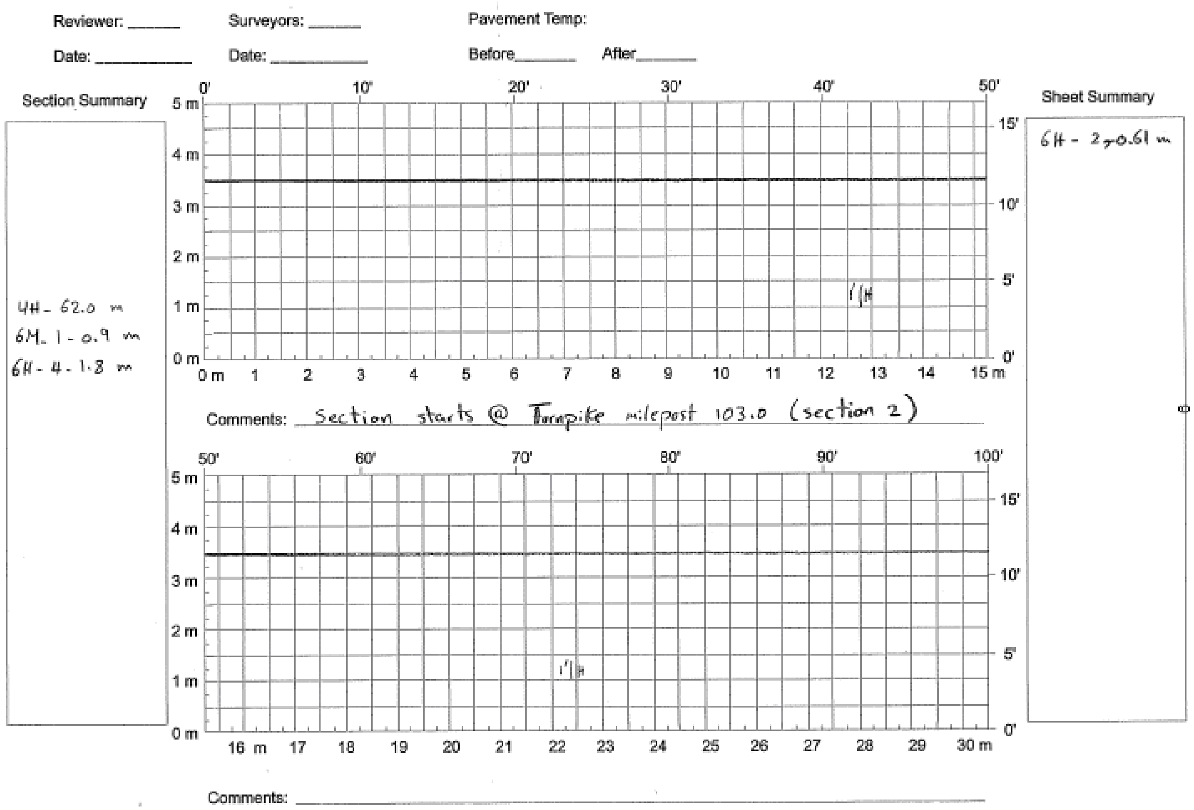


Figure D2(a) Manual crack map on Section 2 of SR 91 (0 - 100 feet)

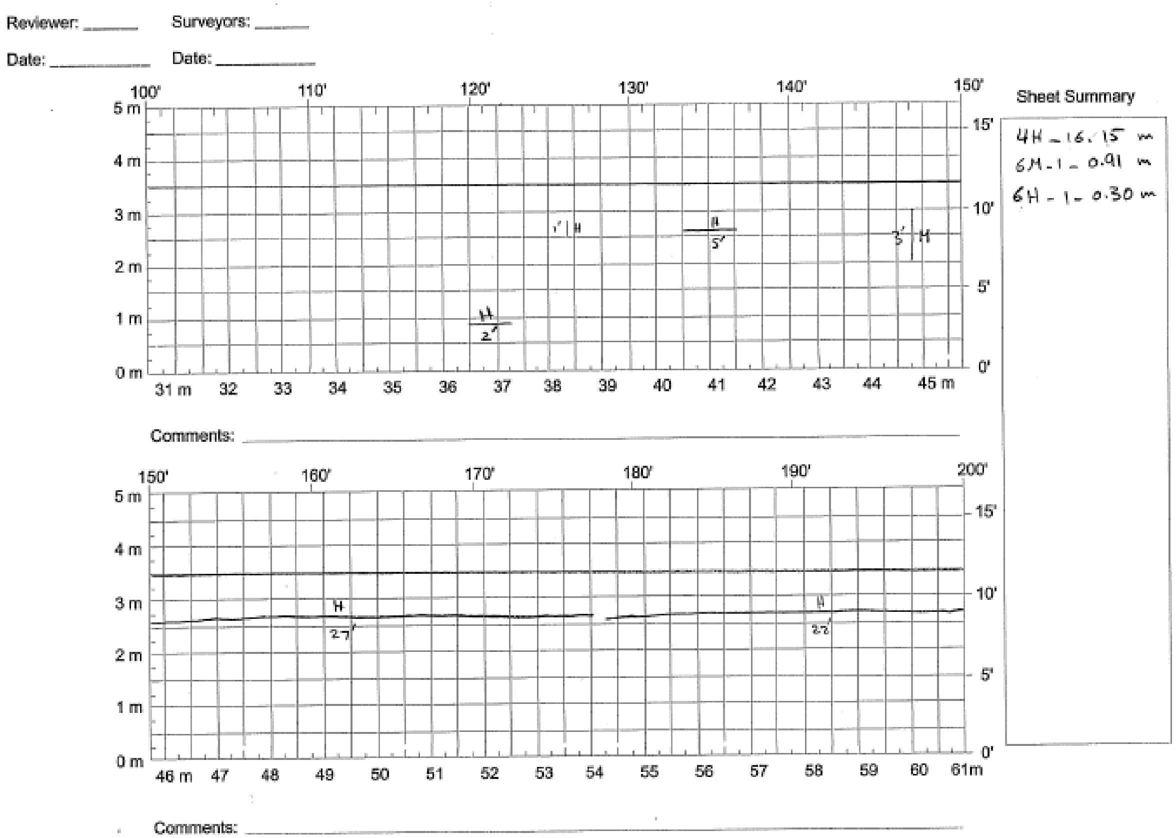


Figure D2(b) Manual crack map on Section 2 of SR 91 (100 -200 feet)

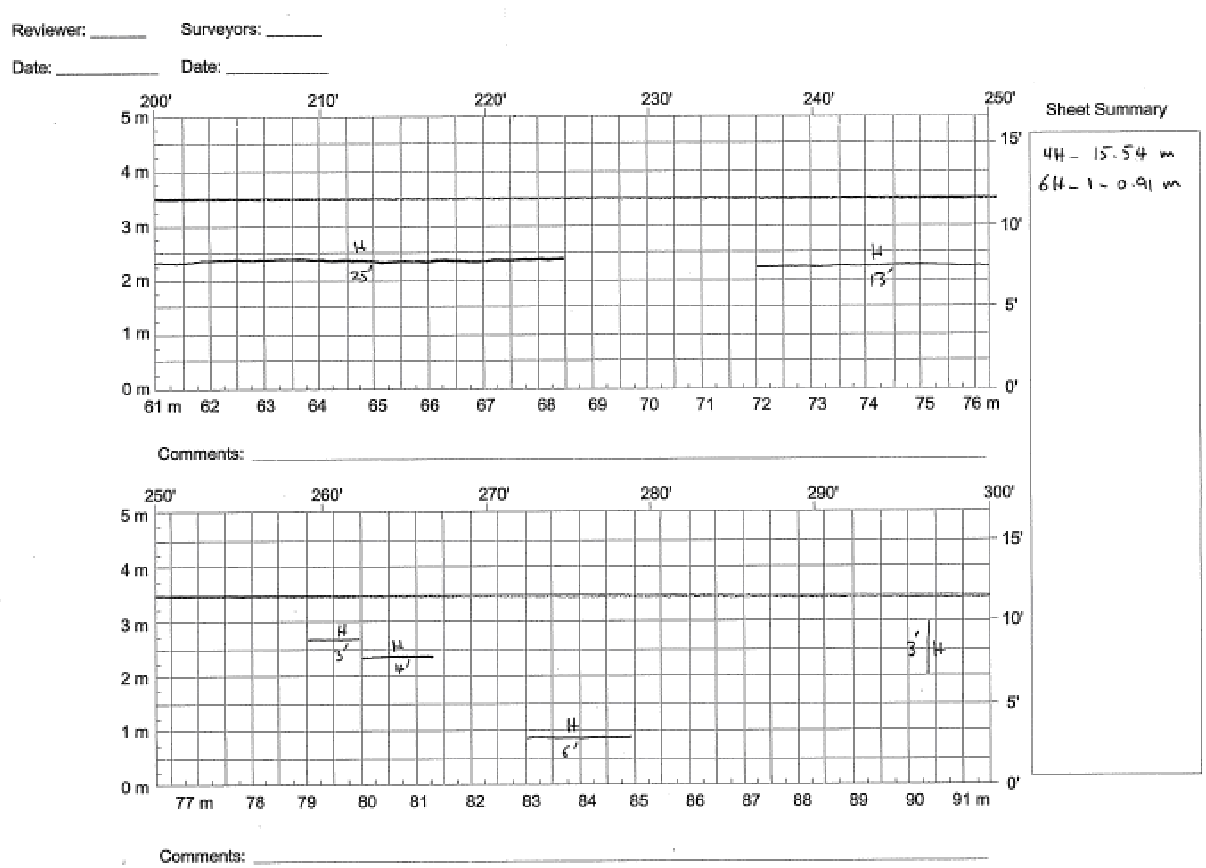


Figure D2(c) Manual crack map on Section 2 of SR 91 (200 - 300 feet)

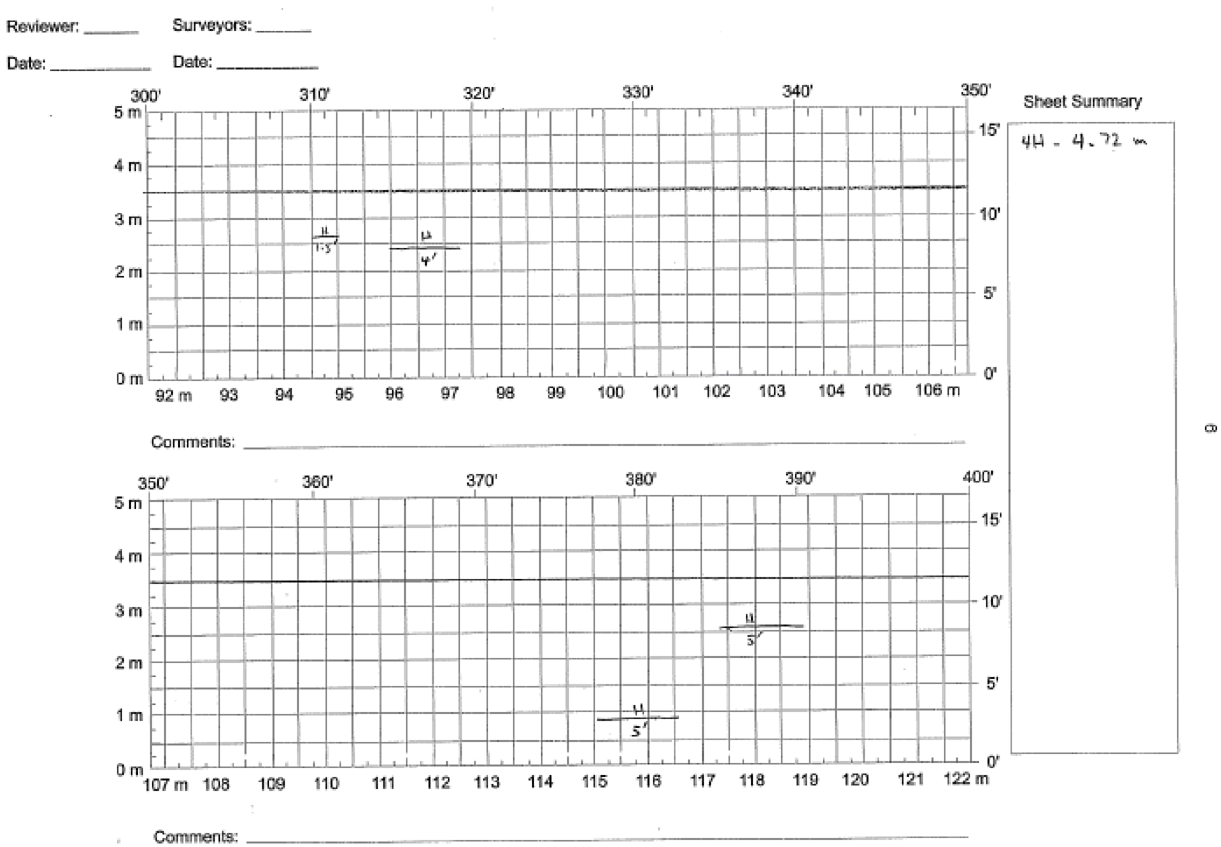


Figure D2(d) Manual crack map on Section 2 of SR 91 (300 - 400 feet)

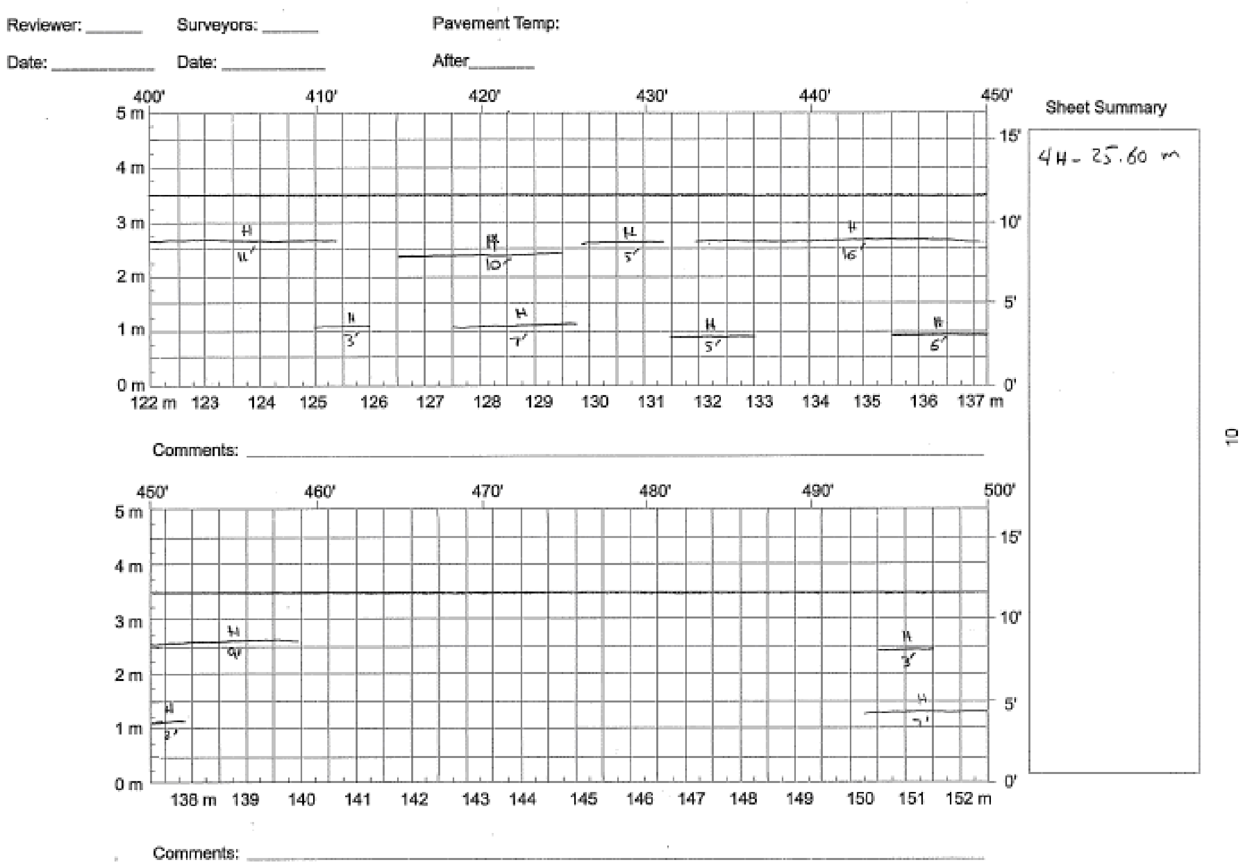


Figure D2(e) Manual crack map on Section 2 of SR 91 (400 - 500 feet)

Table D1 Crack mapping output from the *Workstation* program for SR 91

Segment (Section)	Name (Crack Type)	Severity	Length (ft)	Width (ft)	Area (ft^2)	Weight	Weighted Length (ft)	Distance From Offset (ft)	Distance To Offset (ft)	From Adjusted Accumulated Distance (ft)	To Adjusted Accumulated Distance (ft)
0	Longitudinal	High	1.44	0	0	*Not used	**NA	157224	157226	4221	4222
0	Longitudinal	High	2.04	0	0			157228	157230	4217	4219
0	Longitudinal	High	3.49	0	0			157229	157233	4214	4217
0	Longitudinal	High	2.29	0	0			157301	157304	4143	4145
0	Longitudinal	Medium	1.97	0	0			157329	157331	4115	4117
0	Longitudinal	Medium	1.69	0	0			157331	157333	4114	4116
0	Longitudinal	Medium	3.52	0	0			157333	157337	4110	4113
0	Longitudinal	High	11.64	0	0			157337	157348	4098	4110
0	Longitudinal	High	12.99	0	0			157348	157361	4085	4098
0	Longitudinal	High	2.33	0	0			157362	157364	4082	4085
0	Longitudinal	High	3.7	0	0			157364	157368	4079	4082
0	Longitudinal	Medium	0.8	0	0			157367	157368	4079	4079
0	Longitudinal	High	8.65	0	0			157388	157397	4050	4059
0	Longitudinal	High	2.85	0	0			157403	157406	4041	4043
0	Longitudinal	High	3.52	0	0			157408	157411	4035	4039
0	Longitudinal	Medium	1.38	0	0			157408	157409	4037	4039
0	Longitudinal	Medium	1.81	0	0			157410	157412	4034	4036
0	Longitudinal	Medium	2.17	0	0			157420	157422	4024	4026
0	Longitudinal	Medium	1.06	0	0			157425	157425	4022	4022
0	Longitudinal	High	7.93	0	0			157428	157436	4010	4018
0	Longitudinal	High	4.01	0	0			157437	157441	4005	4009
0	Longitudinal	High	4.3	0	0			157443	157447	3999	4004

*Not used – Weights are not used for evaluating different severities

**NA – Weighted crack length is not computed since weights are not used.