

INVESTIGATION OF IMAGE ARCHIVING
FOR PAVEMENT SURFACE DISTRESS SURVEY

A Final Report

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Project Abstract

The categorization and quantification of the type, severity, and extent of pavement surface distress is a primary method for assessing pavement condition. The current data collection system in the Arkansas State Highway and Transportation Department (AHTD) uses an analog and frame based video van, which does not provide automated pavement surface imaging capabilities. This project includes the evaluation of a newly developed survey system by the RoadWare Corporation in Ontario, Canada. The survey system from RoadWare includes data collection and a recognition engine called WiseCrax. The evaluation compared selected results from the automated survey from RoadWare and results from manual survey by AHTD staff. The report also describes the status of technology in the area of automated pavement distress survey and possible future directions. The report concludes that there still exist limitations in accuracy, speed and degree of automation with WiseCrax and other existing systems.

Report Summary

Large infrastructures are usually constructed with materials that exhibit distresses after construction because of loading, environmental conditions, and aging. The large infrastructures include pavements, chimneys of nuclear power plants, skyscrapers, pipelines, and others. The distresses are presented in the form of surface cracking in most situations. Successful automation of surface distress surveys would reduce the overall cost of performing distress surveys and provide more objective and standardized results for rehabilitation management.

In highway management, the most widely used method of inspecting the surface distress of highway pavements is based on human observation. However, manual surveys work well only at the project level, because this approach is extremely labor-intensive, prone to errors, and hazardous. At the network level, manual surveys consume too much time and too many resources. An ideal automated distress detection and recognition system should find all types of cracking, spalling, and any other surface distress of any size, at any collection speed, and under any weather conditions. The automated device should be affordable and easy to operate. In recent decades, technological innovations in computer hardware and imaging recognition techniques have provided opportunities to explore new approaches to automating distress surveys in a cost-effective way. However, despite the performance improvements of newer generation equipment over the older systems, problems still remain in the areas of implementation costs, processing speed, and accuracy.

Currently the Arkansas Highway and Transportation Department (AHTD) has a multi-function highway data vehicle, which is used to collect pavement surface images with two analog cameras. The vehicle is also used to collect other types of data, such as roughness and rutting. The survey of pavement conditions has to be conducted manually in the office after the data are collected. In order to evaluate the technology of automated survey systems and study the future needs of pavement surface condition surveys, AHTD decided to fund this project to study an existing automated system.

Several automated systems for pavement distress surveys are available at present. In the U.S. market, two vendors probably have the dominant market share. The RoadWare Corporation of Ontario, Canada, has recently developed a survey system that includes data collection and a recognition engine called WiseCrax. A highway agency can either own the WiseCrax system or have the pavements surveyed by the vendor as a service. The other major vendor in the U.S. is TERRECON, which has developed the PAVUE system. TERRECON only provides the survey service and does not sell the PAVUE system to users, primarily because of the complexity of operating the system and the high cost of constructing such a system.

The objectives of this study were to (1) evaluate both the RoadWare data collection system and WiseCrax, and (2) make appropriate recommendations to AHTD regarding capabilities and performance of the WiseCrax system, and future needs. The data comparison between the results from WiseCrax and the results from manual surveys in this report demonstrates that there are still large differences between them. None of the

technologies reviewed in this study is fully automated with real-time processing capabilities. The accuracy of the systems is not proven. The data comparison indicates that the automated system has no difficulty in finding cracks. The problem lies in the classification and quantification of the cracks. This problem is not vendor specific and has been a research topic for years.

Despite the severe limitations on the capabilities of available automated systems, the PI believes that, when there is an immediate need to use an automated system, useful results can be obtained if proper control parameters and manual interventions are used in assisting the survey. However, it should be noted that distress information from one automated survey only reveals the relative distress levels of roadway sections that have gone through the same survey. The repeatability of automated surveys has been always a subject of discussion and research. Therefore, the results may not be directly compared with manual survey results or with results from automated surveys conducted at different times on the same locations.

Currently available technologies of automated distress surveys are all based on analog video capturing and storage. The limitations of using analog video lie in its difficulty in working with computers and its low resolution. As a result, the WiseCraX system uses two analog cameras providing lane-resolution of about 1000 pixels. The PAVUE system uses four cameras, providing lane-resolution of about 2000 pixels. In addition, the analog video information has to be digitized to be processed by computers. This process adds to the cost of the system and increases the complexity. Furthermore, pavement surface images of any roadway section are contained in analog-based videotapes. It is inconvenient for users to examine specific pavement surfaces. Therefore, better technology is needed to overcome these limitations.

Digital video and microcomputer technologies are becoming affordable and capable of high performance. When high-resolution digital images of pavement surfaces are captured, stored, and processed with high-performance microcomputers, the data flow becomes simpler and potentially the cost of developing such a system becomes lower. In addition, resolution of industrial digital cameras can be as high as 2000 pixels per line, which is equivalent to the resolution of PASCO's 35mm films used in SHRP and LTPP projects. As the capacity and performance of new disk storage systems increase, the problem of storage is eliminated. For instance, it takes about 110 gigabytes of storage to archive pavement surface images of 1,000 kilometers at the resolution of 1.83 mm per pixel (2000 pixels per 12-ft lane) after 10:1 compression. Users therefore can conveniently query images of pavement surfaces through the computer network in the office.

Furthermore, high-performance parallel processing boards that can be plugged into microcomputers can be used to process the images at real-time as the images are collected. These boards are normally populated with several ultra-fast Digital Signal Processors that can be programmed to develop crack maps and find the lengths, widths, and orientations of the cracks in parallel. New technology can help solve the problems of existing automated distress survey systems.

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INTRODUCTION

Large infrastructures are usually constructed with materials that exhibit distresses after construction due to various loading, environmental conditions, and aging. The large infrastructures include pavements, chimneys of nuclear power plants, skyscrapers, pipelines, and others. The distresses are presented in the form of surface cracking in most situations. Successful automation of surface distress survey would reduce the overall cost of performing distress surveys and provide more objective and standardized results for rehabilitation management.

For the inspection of the surface distress of highway pavements, the most widely used method to conduct such surveys is based on human observation. This approach is extremely labor-intensive, prone to errors and poses hazard. An ideal automated distress detection and recognition system should find all types of cracking, spalling, and any other surface distress of any size, at any collection speed, and under any weather conditions. The automated device should be affordable and easy to operate. In recent decades, technological innovations in computer hardware and imaging recognition techniques have provided opportunities to explore new approaches to automating distress survey in a cost-effective way. However, despite the performance improvements of newer generation equipment over the older systems, problems still remain in the areas of implementation costs, processing speed, and accuracy.

Currently, Arkansas State Highway and Transportation Department (AHTD) has a multi-function highway data vehicle, which is used to collect pavement surface images with two analog cameras. The vehicle is also used to collect other types of data, such as roughness and rutting. The survey of pavement condition has to be conducted manually in the office after the data is collected. In order to evaluate the technology of automated survey systems and study the future needs of pavement surface condition survey, AHTD decided to fund this evaluation project to study an existing automated system.

The goal of this project was to evaluate a newly developed survey system by the RoadWare Corporation in Ontario, Canada. The survey system includes data collection and a recognition engine called WiseCrax. The objectives were to (1) evaluate both the data collection system and WiseCrax, (2) make appropriate recommendations to AHTD regarding capabilities and performance of the WiseCrax system, and future needs.

SYSTEM DESCRIPTION OF THE SURVEY SYSTEM FROM ROADWARE

The imaging system includes three sub-systems: data collection, crack identification, and distress classification. The vehicle platform is the Automatic Road Analyzer (ARAN), which is also used to collect other types of roadway data. Only the imaging component for distress survey in the vehicle is discussed in this report. The description of the RoadWare's WiseCrax relies on the company literature and the PI's review of the system.

Data Collection of WiseCrax

Pavement surface images are collected with two continuous video cameras, covering the survey lane of about 4 meters. The cameras are black and white Charge-Coupled Device (CCD) cameras. Both cameras are supported by two stretched-out beams in the back of the vehicle and face perpendicularly to the pavement surface. Video images are recorded into S-VHS format. Each camera is about 2.4 meters above the pavement surface and covers 2-meter wide area. The cameras use the non-interlaced technique in capturing and recording. As the result, each captured image has the resolution of 640 pixels by 480 pixels after digitization. Images from each camera are stored sequentially in one tape. This storage technique is also called multiplexing. The images are demultiplexed when being processed.

A speed-encoding algorithm is applied so that simultaneous images from the two cameras and sequential images from one camera form a uniform pavement surface covering the entire lane. RoadWare indicates that the speed-encoding algorithm allows the cameras to capture images at 80 km/h. Camera shutters are synchronized with strobe lights to provide artificial lighting to ensure that (1) the cameras can get enough visual information in a very short period of time when the vehicle is traveling, (2) collected images are without shadows.

Crack Identification

In WiseCrax, the crack identification process begins with the digitizing of the pavement video collected with the two cameras. The video is in the Y/C analog format which must be converted into digital images for computer processing. 8-bit gray scale images are obtained from the digitization process. The identification process tried to identify each crack. The location of the beginning and end of each crack is referenced using an x-y coordinate system. The crack length, width, and orientation are also computed and saved. The process of digitizing to gathering statistics on individual cracks is similar to the process of “vectorizing” a raster image used in Geographical Information Systems.

Once the crack “vectors” have been identified, the system plots them, creating a crack map of the pavement surface. A statistic report is also created during the crack identification phase. Each crack is represented in a single entry in the table, showing the location, start and end points, length, width, and orientation of individual cracks.

Crack Classification

Since the definitions of distress categories vary from agency to agency, WiseCrax compares the location, length, and width of cracks against criteria for various crack distress categories. For instance, if cracks in a block pattern are more than 300 mm apart, it may be classified a block cracking. If they are closer together, it may be classified as fatigue cracking. WiseCrax has the flexibility to process data as new classification definitions are developed.

Modes of WiseCrax Operation

WiseCrax operates in two modes: automated and interactive. In automated mode, all processing is done without human intervention, once the initialization parameters on pavement type, camera and light settings, etc. are set. Interactive mode allows the user to review, validate, and edit the WiseCrax results. For instance, the automated mode can be run first, the display shows the pavement image with overlaid color lines indicating the presence of cracks. The user can then point-and-click to add, delete, or modify the results. For quality control purposes, the interactive mode is normally used to perform statistical validation of automated results using random samples of data.

DATA ANALYSIS OF THE WISECRAX RESULTS AND THE MANUAL SURVEY

The following events occurred during the evaluation of WiseCrax:

- (1) A trip was taken by the PI in October 1997 to the company site to examine the operation of the hardware and software of WiseCrax.
- (2) Hands-on operation of WiseCrax by the PI and the research team was not available as AHTD and the University never had possession of any WiseCrax hardware and software.
- (3) RoadWare collected distress data on approximately 460 miles of roadway, and delivered videotapes and data analysis report to the PI in March 1998. The attached Appendix contains the RoadWare report to the research team.

The survey locations were determined by AHTD and include the following locations:

- (1) I-30 Sections 11, 12, 13, 14, 21, 22, and 23 from Texas/Arkansas state line to the intersection with I-430 in Pulaski County. Approximately 151 miles of one outside lane.
- (2) I-40 Sections 11, 12, 21, 22, 31, 32, 33, 41, 42, 43, 51, and 52 from the Okla/Ark state line to the intersection with I-55. Approximately 277 miles of one outside lane.
- (3) US. 65 Section 12 Log Miles 8 to 9 in Pulaski County. Both Southbound lanes.
- (4) US. 65 Section 12A Log Miles 0 to 3.29 in Saline County. Both Southbound lanes.
- (5) S.H. 5 Section 7 Log Miles 14 to 15.5 in Saline County. Both lanes.
- (6) Maumelle Blvd. S. H 100 Section 0 Log Miles 0.0 (S. H. 365) to 2.0 in Pulaski County. Both outside lanes.
- (7) S.H. 367 East of Cabot Section 14 Log Mile 5.6 to Section 15 Log Mile 2.5 at intersection with U. S. 64 in White County. Northbound lane from Cabot to Beebe.
- (8) S. H. 11 Section 9 Log Miles 2.66 at I-40 to 13.63 at the intersection with S. H. 38 in Prairie County. Southbound lane.

Description of WiseCrax Used for this Evaluation

The RoadWare report (Appendix) states that the accuracy of crack detection exceeds 85% on most pavement surfaces. Processing speed for WiseCrax is largely dependent on pavement type, surface conditions, the amount of crack present, and the speed of the host computer. Typical speeds range from 3 km/h to 7 km/h for a single Pentium Pro CPU at 200 MHz. This speed range confirms with the PI's observation during the examination at the company site. It should be noted that the computation related with image processing in WiseCrax is carried out in the host CPU.

The theoretical resolution of each camera is about 640 pixels in transverse direction. The maximum possible resolution for the two cameras is about 1280 in transverse direction. Assume 3.66-meter (12-ft) wide lane, the smallest possible width of detectable crack is about 2.9 mm, or about 3 mm as reported in the Appendix.

A distress classification system was developed by the Federal Highway Administration (FHWA) in the Strategic Highway Research Program (SHRP). The SHRP method establishes a rating system to categorize pavement distress by type, severity and extent. The RoadWare analysis of the distress data was based on the SHRP method. The basic distress categories reported by WiseCrax are transverse, longitudinal, fatigue and block cracking. Longitudinal distress is further classified into distress in the wheel path and distress not in the wheel path. Each type of distress has three levels of severity: low, medium and high.

Crack maps in WiseCrax can only be saved for examination when the user makes specific requests for the computer to save a particular crack map. Therefore, except the sample crack maps illustrated in the Appendix, RoadWare did not provide any other crack maps to the PI. The output database generated for this project by RoadWare contains one row of record with fields on basic engineering data and distress information on the road for each 100-meter road segment. Samples of this database are also shown in the Appendix. The data file containing the database is in the *dbf* file format which is viewable through MS ACCESS database or EXCELL spreadsheet.

Comparison between the WiseCrax Results and Manual Crack Map

AHTD staff manually surveyed sections of roads in the following locations. Crack maps were drawn for the following respective sections of roads.

<i>Route</i>	<i>County</i>	<i>Dir</i>	<i>Location</i>
5	Saline	Both	Section near LM 14
100	Pulaski	WB	Section ends near intersection of Maumelle Blvd & Bringler Dr.
11	Prairie	SB	About 0.3 mi. south of intersection of Hwys 11 & 38 (LM 13.6)
367	Lonoke	NB	Starts at intersection with Hwy 319 (LM 8.67) going north
40	Pope	WBOL	Starts at LM 92 (west of Atkins exit)
65	Pulaski	SBOL	Starts at LM 8.8 (approximate), Near Exit 9 off-ramp
65	Saline	SBOL	Starts about 0.5 mi. north of exit 10
30	Hot Spring	WBOL	Starts at LM 94 (directly in front of Social Hill Rest Area)

In order to have consistency in the comparison of the survey results from WiseCrax and manual survey, the methodology of distress classification used in the WiseCrax was also used in the data compilation of the manual survey. The methodology is documented on page A-2 to A-3 in the RoadWare Report (the Appendix). Five types of distress were used in the analysis: fatigue (alligator), block, transverse, and longitudinal in wheel path, and non-wheel-path longitudinal. However, as the crack maps from the manual survey generally do not contain information on the width of the cracks, severity levels therefore could not be assigned. Instead, Moderate Level of severity was assumed for all the distresses, unless the drawn crack maps specifically marked locations with high level severity. For comparison purpose, distress values of the three levels of severity from WiseCrax were also added together to have only one single value for each distress type.

Even though we had a total of nine manual surveys as listed on page 4, five of the nine surveys could not be used for comparison for the following reasons:

- (1) The manual survey did not give exact Log Mile (LM) locations (HWY 5 WB, and HWY 100 WB).
- (2) The manual survey is outside of the survey range of the WiseCrax survey (US65, SBOL LM9.5).
- (3) The direction of travel of the manual survey is not the same as that of the WiseCrax survey (I-40 LM92 WBOL, and I-30 LM 90.0 WBOL).

The field names in the tables are FAT-M, BLOCK-M, TRANS-M, LONGWP-M, and LONG-M. They represent fatigue cracking (moderate severity), block cracking (moderate severity), transverse cracking (moderate severity), longitudinal cracking on the wheel path (moderate severity), and longitudinal cracking (moderate severity). In Tables 2 and 4, TRANS-H is used to represent transverse cracking (high severity), as the two manual surveys specifically identified locations with wide transverse cracking.

The four comparisons are shown in the Tables 1 to 4. It can be seen from the tables that there exist large variations between the manual surveys and WiseCrax survey. As a matter of fact, the variations are so obvious that it would not make any sense to do a statistical analysis of the data. However, an observation can be made from looking at the tables that in most cases, the WiseCrax surveys are consistent with the manual surveys as far as identifying cracks is concerned. That is in most cases the WiseCrax surveys did find cracks as the manual survey did. The problem is that the classification and quantification of the cracks of the WiseCrax surveys are very different from the manual surveys. It should also be noted that the WiseCrax survey only provides a single value data for each distress/severity for 100-meter of roadway, which is much coarser than the manual surveys 40 to 50 feet.

There can be two factors contributing to the variation of the two types of surveys:

- (1) The WiseCrax system was not accurate enough to match manual surveys.

(2) The exact positions of the start and ending locations in the WiseCrax surveys are not accurate enough, resulting in data shifting.

Table 1 Data Comparison: SH5 - LM 14-15.5 (22.53km-22.84km), EB

		FAT-M	BLOCK-M	TRANS-M	LONGWP-M	LONG-M
WiseCrax Survey						
From (m)	To (m)					
22530	22610	0	0	3.15	0	1.13
22610	22710	0	0	15.44	1.59	6.29
22710	22810	0	0	13.95	0.66	0.4
Manual Survey						
From (m)	To (m)					
22530	22628	0	77.4	24.5	15.2	115.2
22628	22725	0	0	28.8	1.5	24.4
22725	22835	0	0	30.5	4.3	111.6

Table 2 Data Comparison: SH367 - LM 8.67 (13.95km), NB

		FAT-M	BLOCK-M	TRANS-M	TRANS-H	LONGWP-M	LONG-M
WiseCrax Survey							
From (m)	To (m)						
13910	14010	0.42	21.38	30.02	17.73	3.54	29.99
14010	14110	0.00	9.6	22.86	26.83	0.94	4.31
14110	14210	0.00	7.54	25.15	11.1	1.23	6.96
14210	14310	0.14	5.16	16.91	21.42	6.12	17.48
Manual Survey							
From (m)	To (m)						
13950	14010	0.0	0.0	22.3	0.0	6.1	32.0
14010	14110	1.0	0.0	19.3	0.7	12.0	44.7
14110	14210	0.0	0.0	24.0	0.0	20.4	25.8
14210	14255	11.1	0.0	11.1	0.0	1.5	11.9

Table 3 Data Comparison: SH11 - LM 13.6 (21.89km), SB

		FAT-M	BLOCK-M	TRANS-M	LONGWP-M	LONG-M
WiseCrax Survey						
From (m)	To (m)					
21900	21940	0.00	0	0.68	0	0
21800	21900	0.00	0	0	0	0
21700	21800	1.79	0	13.32	0.54	0
Manual Survey						
From (m)	To (m)					
13950	14010	0.0	0.0	16.8	0.5	8.2
14010	14110	0.0	0.0	3.7	0.0	0.0
14110	14210	0.0	0.0	3.8	0.0	0.0

Table 4 Data Comparison: Hwy 65- L.M. 8.8 (14.16km), SBOL

		FAT-M	BLOCK-M	TRANS-M	TRANS-H	LONGW P-M	LONG-M
WiseCrax Survey							
From (m)	To (m)						
14110	14210	0.91	2.27	10.61	0	0	17.65
14210	14310	0.00	0	10.43	0.19	0.36	6.18
14310	14410	1.91	0.37	0.76	0	0	39.29
14410	14430	0.00	0	0	0	0	2.24
Manual Survey							
From (m)	To (m)						
14160	14210	0.0	0.0	7.3	0.0	6.6	54.1
14210	14310	0.0	0.0	15.0	0.0	0.0	135.2
14310	14410	0.0	0.0	9.2	0.0	1.8	139.0
14410	14465	0.0	0.0	3.0	0.0	0.0	50.6

ISSUES AND STATUS OF DEVELOPING AN AUTOMATED SURVEY SYSTEM

Humans can detect and classify pavement surface distress with ease. For instance, humans can perceive the connectivity of cracks without hesitation. Computer vision systems distinguish cracks through identifying disturbances in the brightness range of the surrounding texture and must be designed to seek connected regions through mathematical algorithms. It is not trivial for a computer vision system to segregate cracks from pavement surface texture at high-speed, particularly for the texture of bituminous materials.

Facing this tremendous challenge, many academic and industrial efforts have attempted to automate the evaluation of pavement surface distress. The developed systems include vehicles equipped with video gear traveling at or near normal travel speeds. Pavement surface images are collected into analog storage devices through camera(s) mounted on the vehicle. The predominant storage device in use today is based on VHS tape technology.

It has been a frustrating period in the past two decades for developers to implement distress survey systems based on the requirements by the highway industry in the areas of real-time processing, consistency and repeatability of surveys, and accuracy. There are a number of reasons why serious problems still exist after so many years' research and development.

- (1) Image processing for pavement surface distress survey at any practical speed requires very high performance computing equipment. When such equipment is not available or a compromise is made in respect of performance, data quality, processing speed, or both are affected.

- (2) Image processing as a field of study is still evolving. There are many aspects of image processing in human brain that are not understood yet.
- (3) In the detection and recognition of pavement surface distress, a particular difficulty is related with the surface texture and foreign objects on the pavement surface, such as oil spoil.
- (4) There are no standard indexes to quantitatively define the types, severity, and extent of pavement surface distress. However, efforts are underway to initialize a set of standards (Paterson, 1994 and FHWA, 1997).
- (5) Data collection is not standardized, especially in the areas of image resolution, and collection approaches. For instance, as there is no standardized way to define a crack map of a pavement area in terms of resolution and dynamic range, images from one survey system would differ from images from another system.
- (6) The available implementations employ different image processing algorithms and different hardware design, which are not compatible with each other. From the user's perspective, it is not necessary to have compatibility of hardware and software with different vendors' systems. However, this incompatibility introduces non-comparable survey data from different vendors.

Even though the difficulties in implementing a useful survey system are multiple-fold, the data collection is the first step toward a fully automated system. Traditionally, analog-based area-scan cameras are used in automated pavement surface distress survey. The format of output signal is frame-based following a standard defined in the 1950s by the US National Television Standard Committee, NTSC. Similar formats are used in other parts of the world. There are two distinct problems with analog-based cameras. First, it requires a digitization step to convert the wave signal based data to digital data that is understood by computers. Second, the highest possible digital resolution from data with analog cameras is about 400 pixels per line. In addition, area-scan cameras have an inherent problem in the inspection of a moving surface, when the complete and exact coverage of the surface is required. The problem is surface overlapping or discontinuity of adjacent images. Additional computation is needed to have exact and complete coverage of pavement surface.

The overwhelming difficulty in the automated survey of pavement surface distress is the high data rate and associated extraordinary computation needs when real-time or near real-time processing is necessary. Real-time processing is defined as processing the data at the same data throughput as the vehicle is collecting images at highway-speed normally between 80 to 100 KPH. Off-line processing can also be done with captured images on tape or computer storage. When the processing speed is equivalent to vehicles' traveling highway speed, the off-line processing can be viewed as real-time processing.

Currently, image processing is normally conducted off-line in an office environment after the data is collected. All existing applications of automated distress survey use the

off-line processing as the dominant approach. This is primarily due to two factors: (1) on-line processing requires the complete imaging operations be conducted at the same speed as the vehicle's traveling speed, which is not achievable at this time, (2) even if such on-line speed is achievable, the size of the equipment for such processing would not fit into a full-size VAN. However, on-line processing as the vehicle is collecting data is the ideal approach for users to obtain data quickly. For example, if a robust database management is running along the image processing tasks, an integrated highway information system can be established at real-time. When the data vehicle returns from a data collection trip, the database in the information system can be quickly downloaded into a central computer server, and pavement distress data including images and analysis results can be reviewed by users.

Current Status of Research and Development

In the early 1990s, Texas Department of Transportation and US Federal Highway Administration organized a trial test of existing automated systems. Sections of roads in Texas were carefully selected and surveyed manually. Vendors in highway data collection business were invited to conduct surveys with their automated equipment. There was not much agreement among the results from different vendors, for this reason the trial test did not produce a comparison evaluation of the various devices. Recently, Smith (Smith et al. 1998) led a team and conducted a study on the existing survey equipment on pavement surface distress. Four vendors were invited and participated in the study. Apparently, the emphasis of the study was not on the comparison of the designs and performances of the vendors' equipment. Most of the four vendors only have capabilities of collecting pavement surface images and the analyses of surface distresses were conducted either manually, or with the assistance of a vision system under manual control.

Since the 1980s, a number of working equipment was produced for the automation of pavement surface distress survey. Five major efforts that produced working systems with the capability of at or near real-time processing are described in detail in this report: the Japanese Komatsu system, the US PCES system, the Swedish PAVUE system, the Swiss CREHOS, and the Illinois Automated Road Inspection System. Several other efforts are discussed in less detail, primarily due to the lack of documentation.

It should be noted that the focus of this portion of the report is the review of the technologies, capabilities and technical features of several important developments in the area of automated survey of pavement surface distress. Devices from all vendors differ in virtually all aspects of design and implementation. Many of them do not reveal technical information of their equipment. Therefore, a direct comparison of the features and performances of various implementations is not presented in the report.

The Komatsu System

In the late 1980s, the Japanese consortium Komatsu built an automated-pavement-distress-survey system (Fukuhara, et al. 1990), comprising a survey vehicle and data-processing system on board to simultaneously measure cracking, rutting, and longitudinal profile. Maximum resolution of 2048 x 2048 is obtained at the speed of 10 km/h. The

Komatsu system works only at night to control lighting conditions. Figure. illustrates the basic design of the survey vehicle. When survey is conducted with the moving vehicle, the road surface is illuminated with argon laser light through the laser scanner in the lateral direction. The deflected light from road surface is detected at an angle by a photo multiplier tube (PMT) and a video camera that are attached to the front bumper of the vehicle. When cracks are present on the surface, the quantity of received light by the PMT is reduced. Therefore, the change of output from the PMT indicates the existence of cracks at the scanning position. The video cameras are used to capture rutting, as the scanning line observed from an oblique angle is curvy when rutting is present. The integration of the collected information over time presents cracking and rutting data on the two-dimensional road surface. The longitudinal profile is measured based on the distance between the survey vehicle and the road surface. The profile is calculated based on three sets of data collected at three locations in the vehicle: the first being the rutting measurement, the two others being measurements collected by the two line sensors under the body of the vehicle shown in Figure 1. The data storage devices include a High Density Video Tape Recorder (HDVTR) at the data rate of 100 Mega bits per second (Mbps), and a general purpose Video Tape Recorder (VTR). Pavement surface images are archived with the HDVTR. Digital image processing techniques are applied to crack image data in a post-processing mode. Parallel processing is used at two stages to determine cracking parameters such as the number, width, and length of cracks, which are then stored in the pavement data bank.

In the first processing stage (image segmentation), a massive 64 MC68020 parallel microprocessors are used. The MC68020 is also called the Extracting Processor (EP), the performance of which is equivalent to that of an entry level Intel 386 chip. The system design permits up to 512 EPs to be used in parallel to further improve performance. In segment extraction, the image is divided into 32-pixel by 32-pixel square areas, called slits. A value of a curve is an average gray level of pixel series in the projected direction in the slit. Pixels in a dark area, such as the presence of a crack, have higher levels in the gray scale. In order to determine the angle, the length, and width of the crack in a slit, it is necessary to rotate the projection directions in the image until a peak of the crack appears, indicating that the actual width of the crack is found. The portion of the crack that is contained in the slit is represented by a rectangular element. Each of the MC68020 processor is used to process one slit at a time in parallel with all other processors. After the processing, all found cracks are represented by segmented slits.

In the second stage (crack connectivity), seven T800 transputers are used in parallel to determine the connectivity among the extracted segments, and eliminate noises. The connectivity is determined by the relative positions of cracks in neighboring segments. The transputers produce a line image of the pavement surface, or a crack map.

The Komatsu system represents an implementation of the most sophisticated hardware technologies at that time. However, it does not output the types of cracking and only works during the night. Another barrier to implement the Komatsu system is that it virtually requires the power of multiple super-computers to carry out the two stage analyses. The Komatsu survey vehicle did not proliferate to the market place.

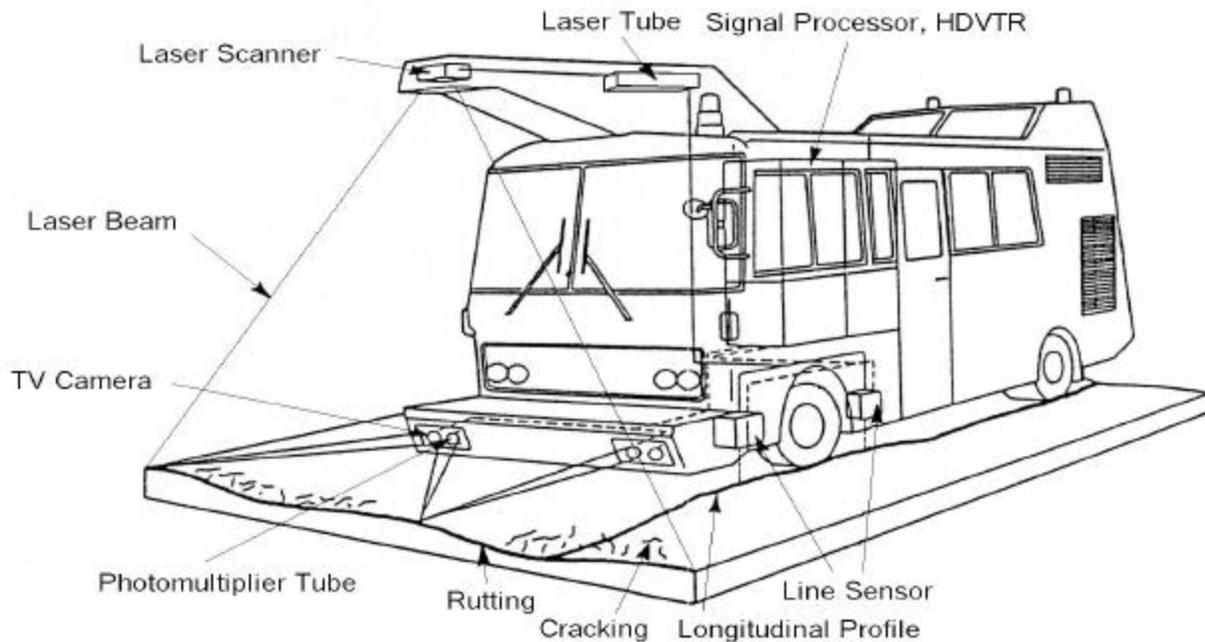


Figure. 1 Komatsu Survey Vehicle (Based on Fukuhara, T., et al. 1990)

The PCES System of USA

From late 1980s to early 1990s, Earth Technology Corporation launched a large-scale research on the automation of pavement surface distress survey, resulting in the creation of a research arm, the Pavement Condition Evaluation Services (PCES). The automated system created by PCES was the first to use line-scan cameras to collect pavement data. For decades, line-scan cameras had been primarily used for surface inspection in the areas of manufacturing, agriculture and semiconductor business. Surface inspection is also referred to as web inspection. This type of inspection is mainly concerned with part or product defect identification. The inspected objects are traveling at high speed on the web and the image is captured with stationary cameras through capturing one line of image at a given moment. PCES's approach was unconventional at that time, as line-scan cameras were never used in the field of pavement engineering. In addition, even though line-scan camera's resolution and performance were better than conventional area-scan camera's, it required many customized efforts, such as special boards and software to support the cameras.

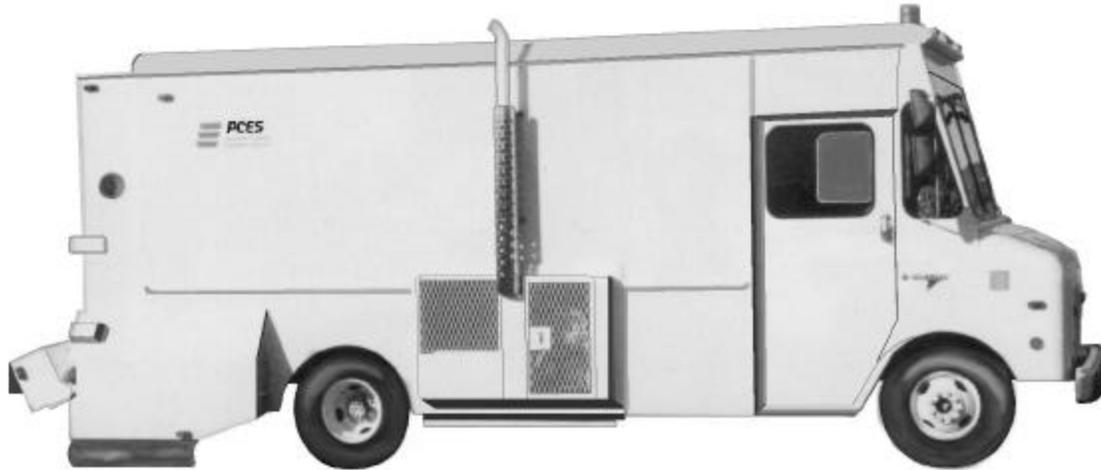


Figure 2 PCES Survey Vehicle

In the PCES system, digital signal processing was used in real-time, using custom-made filter circuits, which are 3 x 3 neighborhood convolver boards. The boards contain special processors with built-in imaging algorithms to filter images very quickly. Each of the two 512-element line-scan cameras continuously covers four-foot pavement, for a total of eight feet of pavement width. Each camera is supported by an 8-bit analog-to-digital converter, a convolver board, and a 68020 processor. An additional 68020 processor supervises the system activity. The system was intended for daylight use throughout a normal range of highway speeds.

The PCES system also includes

- (1) A VME bus based 32-bit computer to power the image processing engine,
- (2) Interrupt-driven software and proprietary pipeline hardware to accomplish real-time processing,
- (3) An imbedded operating system that was contained in Read-Only-Memory (ROM),
- (4) Random-Access-Memory (RAM) for data storage,

The developed vehicle is shown in Figure 2. The vehicle is a 21-foot Grumman truck body, which contains space for all system hardware, and operating console and an observer station. Two 15-kilowatt diesel generators power the computer, lighting and other equipment. It should be noted that in order to obtain lines of images at required speed, line-scan cameras need much higher intensity lighting than conventional area-scan cameras. The lighting from the PCES system could burn the asphalt surface if it directed on the same areas for a few minutes.

Earth Technology Corporation did not continue to fund the research after the first operational PCES system was built. There were several factors attributing to the decision. One important factor is that the necessary technologies associated with the

image capturing and processing were not mature enough. For instance, a high-performance line-scan camera only contained 512 elements in the linear array. Today's line-scan cameras can exceed 4096 elements with a much higher frequency. In addition, PCES designed, produced their own processing boards, and made their own system level software, which were not only costly, but also limited the research team from obtaining higher performance equipment from third parties at a later time, due to incompatibility.

The Swedish PAVUE System

Infrastructure Management Services (IMS), the previous marketing arm in the US of the same Swedish company that manufactures Laser RST, is owned by the civil engineering firm TERRECON. IMS markets its service with the PAVUE system, consisting of the acquisition equipment to collect distress data and the off-line analysis workstation to diagnose the gathered images. The acquisition equipment includes four video cameras, a proprietary lighting system, four S-VHS videocassette recorders, and the speed-compensation module. This image collection subsystem is integrated into a Laser RST van which also collects other pavement information. The off-line workstation is based on a set of proprietary and custom designed processor boards in one cabinet to analyze continuous pavement data from the recorded video images.

Figure 3 illustrates the data flow of the PAVUE system. Each of the four video cameras cover about one-fourth of the pavement surface, resulting in the resolution about 1,400 pixels per lane. The speed compensation device allows the van to drive at any speed between 5 - 55 mph to ensure continuous video image with uniform resolution in both longitudinal and lateral directions. The detectable size crack is about 2.5 mm (1/8 inch). A strobe lighting system is also used.

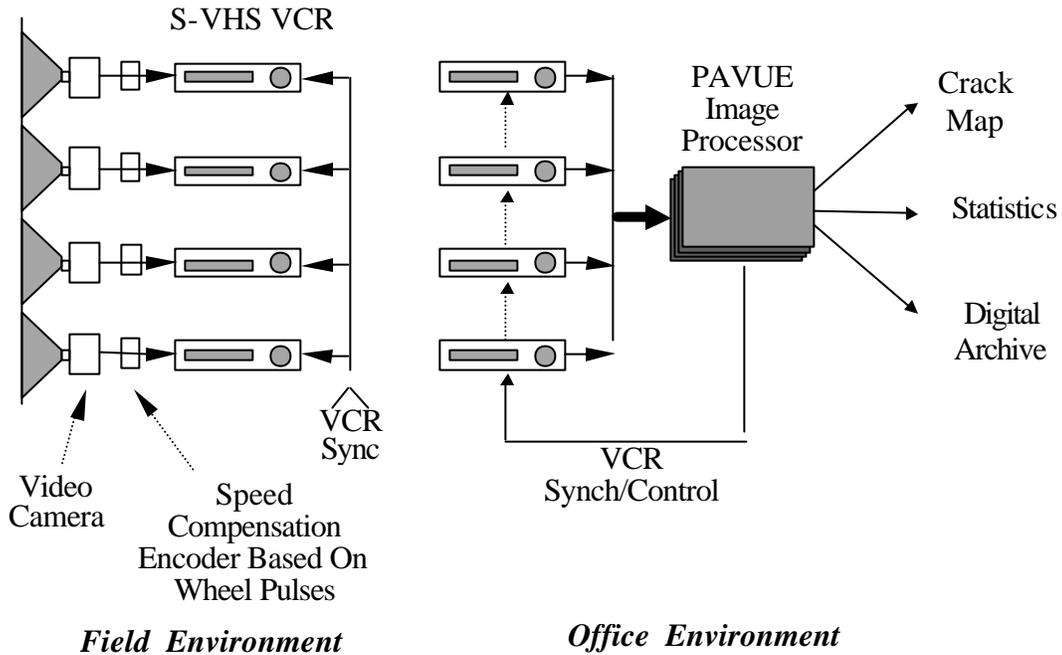


Figure 3 Data Flow in IMS's PAVUE System (based on IMS literature, 1996)

The unique feature of the PAVUE system is with its image processor boards. A total of twelve different VME based boards were developed by IMS to form the core of the image processing. A total of 80 boards can be used in a full PAVUE processor system. The boards were constructed with a combination of various customized and off-the-shelf circuits. Image processing algorithms were also coded in hardware to speed up the processing.

The image processing technique used in the PAVUE is generally referred to as pipeline processing where image data is piped through series on-board computational elements, or chips, which contain algorithms in hardware. The elements perform a broad range of image processing tasks and are connected through a tight on-board and among-board communication network. Images are processed at various stages in the pipeline simultaneously. The high performance hardware allows the PAVUE system to process pavement images up to 55 mph at a high resolution. However, surface distress is stored on S-VHS tapes in analog format.

The Swiss CREHOS

Considering the limitations of systems in the early 1990s, the Swiss Federal Institute of Technology (EPFL) launched a research effort to develop a new automated device to conduct pavement surface distress survey. Dr. Max Monti of EPFL's Laboratory of Stress Analysis (IMAC) completed his Ph.D. work with this project. The goal of the project was to design and implement a new system "in a complete and lasting way." (Monti, 1995).

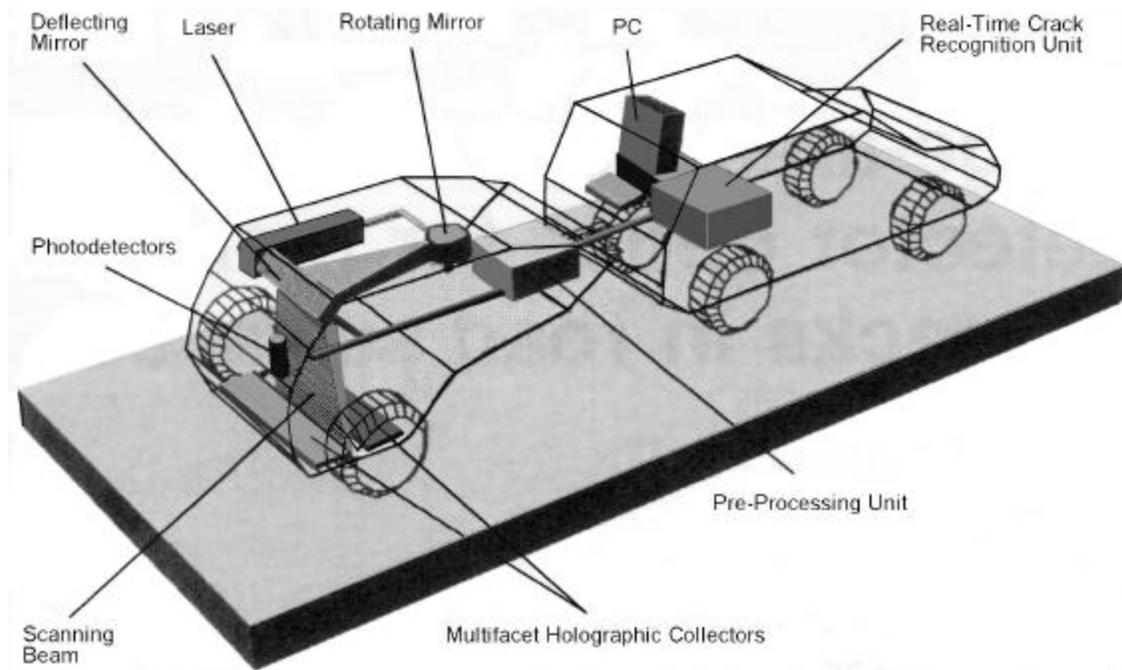


Figure 4 CREHOS Survey Vehicle (Based on Max Monti, 1995)

The developed system is called Crack Recognition Holographic System, or CREHOS. With this system, the pavement surface is scanned with a focused laser beam along a straight line in the lateral direction, while the longitudinal scan is conducted with the movement of the vehicle. The reflected light from the surface is collected with a collector, which was a customized holographic element. When the laser light falls into a crack, the strength of the signal collected by the holographic element decreases. This signal is filtered and binarized to obtain sets of binary pulses representing the crack. These sets of data are then formatted, pre-processed, and stored at real-time with a parallel processor.

A major advantage of this laser solution over conventional imaging techniques is the elimination of illumination of a large and rough surface of pavement. Figure 4 shows the basic configuration of the CREHOS system, which is mounted on a trailer. There are three sub-systems: the scanning device, the holographic light-collection system, and the image processing system. The scanning device emits laser light to pavement through a rotating polygonal mirror, with the following specifications: 30,000 rpm, 24 facets, 12,000 scan lines/second, focusing distance of 4 meters, and spot size of 1 mm. A 4-meter long line can be scanned in 83 *ms*. To have square millimeter resolution for the pavement surface, the vehicle can travel at the maximum speed of 43.2 KMH. However, higher speed can be achieved when longitudinal resolution can be relaxed to over 1 millimeter. Two multifacet holographic collectors (MFHOE) are placed on both sides of the scan line at 10 cm from the pavement surface, shown in Figure 4. Each MFHOE is composed of thousands of HOEs of 5x5-mm size. One photodetector is positioned 60 cm above each of the two MFHOEs. The photodetectors convert the light signals from the MFHOEs into analog signals, which are usually noisy. The pre-processing unit transforms the analog signals into binary pulses, indicating the probability of the presence of a crack. Therefore, CREHOS does not work on an "image", but on a continuous temporal, one-dimensional signal. An image is obtained through illuminating point by point and integrating the points over space. The output signal is analog pulses, which is thresholded adaptively into binary format before entering the digital-processing unit.

The processing unit, a parallel processor, was built for CREHOS to further filter noise, recognize cracks, and vectorizes their shapes at real-time. This parallel processor consists of a number of tracking units, or processing units, each of which works on a single crack-representing pulse at one time. It should be noted that the processing units are not the same as conventional digital microprocessors. They are simple electronic devices based on analog technology and with the capability of identifying crack-representing pulses. Each tracking unit can complete processing in every very 80 *ms*, which is about the duration of scanning one line. Both the Komatsu system and CREHOS use laser scanning to obtain pavement distress data. This is where the similarity ends. CREHOS applies analog approaches to data collection and pre-processing. In addition, the parallel processing is unique that no actual digital microprocessors were used. CREHOS was constructed in a research environment. The effort did not produce a commercial system.

The Illinois Automated Road Inspection System

A team from the Illinois Institute of Technology headed by Professor Sidney Guralnick produced an Automated Road Inspection Vehicle (Guralnick and Eric Suen, 1995). The system was developed using the shadow Moire optical interference method. The vehicle can acquire out-of-plane road surface distress information at highway speed. The image resolution is about 512 x 480 pixels for a one-lane pavement surface.

The shadow Moire method is demonstrated in Figure 5. Both the light source and the camera are placed at the same observing plane and at a distance of d from each other. The grating plane is parallel to the observing plane. The distance between both planes is H . The spacing of the black grating lines is p . Contour planes, h_n , are generated by the intersection of the projected lines from the light source and the sight lines from the camera's position. The contour interval, Δh , can be approximately expressed as:

$$\Delta h = p \frac{H}{d} \quad (1)$$

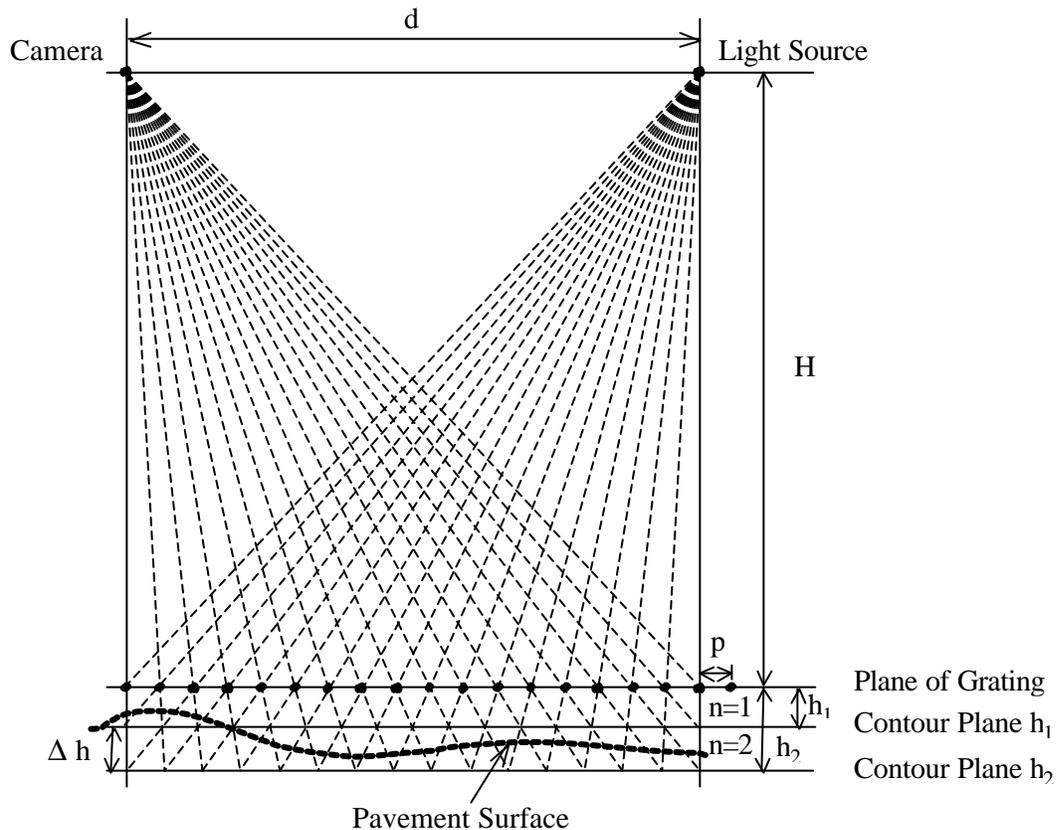


Figure 5 Demonstration of the Shadow Moire Method

Based on this known Δh and the contour map, which is created through the shadow cast by the light source through the grating lines on the pavement surface, a digital terrain surface of the pavement is then established. Through the analysis of this terrain surface,

certain aspects of pavement condition survey can be conducted. It should be noted that this method does not allow the detection of surface cracks on the same plane. The developers believe that the complete system can be built with \$60,000 worth of materials.

Triple Vision's NCHRP Project

In the Triple Vision project that was sponsored by the National Cooperative Highway Research Program (NCHRP) and completed in 1991, sample video data from PASCO 35 mm films were transferred to a video disk (Fundakowski, et al. 1991). The data acquisition was conducted by PASCO using a special 35-mm film camera that is longitudinally continuous. The 35-mm filming approach is still being used for collection of pavement images in the Long-Term Pavement Performance (LTPP) program of the US Federal Highway Administration (FHWA). The video image processing were distributed across two computer systems. The bulk of the image processing operations (i.e. image preprocessing and segmentation) was performed in a DSP-1000 image processing system (a product of Datacube, Inc., Peabody, Massachusetts). The feature extraction and classification stages of the video image processing system were implemented in a 386 PC. The DSP-1000 incorporates several image processing boards, a digitizer/frame grabber and a display board. The comparison of the machine generated cracking recognition, and the data based on the two experts on pavement engineering was quite poor (Fundakowski, et al. 1991). In addition, the applicability of the system for actual highway use is questionable. An upgraded system with a 33 MHz 486 computer and the Data Cube processor can only process 1 frame of image per minute. That is equivalent to 29 hours of processing time per one lane-mile.

ADAPT and RoadWare's WISECRAX

From 1995, the Pavement Performance Division of the US Federal Highway Administration awarded two continuing contracts to LORAL Defense Systems in Arizona, now a unit of Lockheed-Martin, to provide an Automated Distress Analysis for Pavement, or ADAPT for short (FHWA, 1995). The then LORAL Defense Systems was trying to apply state-of-the-art imaging techniques based on an artificial neural net (ANN) developed for military purposes for pavement distress analysis. This project does not include data collection, but only data analysis. The data source is based on PASCO's 35-mm film, the same as the one used in the Triple Vision's project. The images were directly digitized from 35-mm film to digital format. The resulting resolution is approximately 4000 pixels per 12-foot-lane, or about 1 mm per pixel. ADAPT is not being used in any operating products.

Since late 1996, RoadWare, a Canadian highway data collection company, has been actively using a new product, WiseCrax, for automated survey of pavement surface. Initially, RoadWare was trying to apply the technology developed in ADAPT to WiseCrax. Subsequently, RoadWare developed its own algorithms into WiseCrax. The data collection uses two analog cameras synchronized with a strobe illumination system, with each camera covering about half-width of a pavement lane. The image processing is done in the off-line office environment. WiseCrax cannot process pavement images at traveling speed. WiseCrax solely relies on the CPUs in a x86 based computer to process images.

RECOMMENDATIONS AND CONCLUSION

Currently, there are several automated systems for pavement distress survey. From the data comparison documented in this report and the review of the technologies, none of them is fully automated with real-time processing capabilities. The accuracy of the systems is not proven. The data comparison between the results from WiseCrax and results from manual survey in this report demonstrates that there are still large differences between them. It appears that from the data comparison between results of WiseCrax and results from manual survey that the automated system has no difficulty of finding cracks. The problem lies in the classification and quantification of the cracks. This problem is not vendor specific and has been a research topic for years.

In the US market of automated distress survey, there are two vendors that probably have the dominant market share. The two systems are WiseCrax of RoadWare and PAVUE of TERRECON. For WiseCrax, a highway agency can either own the system or have the pavements surveyed by the vendor as a service. TERRECON only provides the survey service and does not sell the PAVUE system to users, primarily due to the complexity of operating the system and the high cost of constructing such a system.

There is a need to use an automated system for distress survey at AHTD. Manual survey works well only at project level. Manual surveys at network level will take too much time and resources. Even though there are severe limitations on the capabilities of available automated systems, if there is an immediate need to use an automated system, the PI believes that useful results can be obtained if proper control parameters and manual interventions are used in assisting the survey. However, it should be noted that distress information from one automated survey only reveal the relative distress levels of roadway sections that have gone through the same survey. The repeatability of automated surveys has been always a subject of discussion and research. Therefore, The results may not be directly compared with manual survey results or with results from automated survey conducted at different times on the same locations.

Current available technologies of automated distress survey are all based on analog video capturing and storage. The limitations of using analog video lie in its difficulty in working with computers and its low resolution. As the result, WiseCrax system uses two analog cameras providing lane-resolution about 1000 pixels. PAVUE system uses four cameras, providing lane-resolution about 2000 pixels. In addition, the analog video information has to be digitized to be processed by computers. This process adds to the cost of the system and increases the complexity. Furthermore, pavement surface images at any roadway section are contained in analog-based videotapes. It is inconvenient for users to examine specific pavement surface. Therefore, better technology is needed to overcome these limitations.

Digital video and microcomputer technologies are becoming affordable and high performance oriented. When high-resolution digital images of pavement surface are captured, stored and processed with high-performance microcomputers, the data flow becomes simpler and potentially the cost to develop such a system becomes lower. In addition, resolution of industrial digital cameras can be as high as 2000 pixels per line,

which is equivalent to the resolution of PASCO's 35mm films used in SHRP and LTPP projects. As capacity and performance of new disk storage gets higher, the problem of storage does not exist anymore. For instance, it takes about 110 gigabytes of storage to archive pavement surface images of 1,000 kilometers at the resolution of 1.83 mm per pixel (2000 pixels per 12-ft lane) after 10:1 compression. Users therefore can conveniently query images of pavement surface through the computer network in the office.

Furthermore, high-performance parallel processing board that can be plugged into microcomputers can be used to process the images at real-time as the images are collected. These boards are normally populated with several ultra-fast Digital Signal Processors that can be programmed to develop crack maps and find the lengths, widths and orientations of the cracks in parallel.

In all, new technology can help solve the problems of existing automated distress survey systems.

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