EVALUATION OF AN EXISTING IMAGING SYSTEM FOR PAVEMENT SURFACE DISTRESS SURVEY

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, WiseCrax, 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. A survey of current users of WiseCrax was also conducted for this project. A report on the use of WiseCrax by Mr. Ed Block of Connecticut DOT is attached as Appendix A for reference. 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.
Acknowledgement

The principle investigators are grateful for the support provided by the research staff of AHTD. Specifically, Mr. Alan Meadors, Staff Research Engineer of AHTD, and his staff provided crack maps from manual surveys. The coordination of the project by Mr. Tom Black was extremely helpful. Mr. Phil Swope of the University of Arkansas compiled the results based on the manual surveys.
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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 de-multiplexed 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 WISECRAK 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.

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

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**

<table>
<thead>
<tr>
<th>From (m)</th>
<th>To (m)</th>
<th>WiseCrax Survey</th>
<th>Manual Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>22530</td>
<td>22610</td>
<td>0 0 3.15 0 1.13</td>
<td></td>
</tr>
<tr>
<td>22610</td>
<td>22710</td>
<td>0 0 15.44 1.59 6.29</td>
<td></td>
</tr>
<tr>
<td>22710</td>
<td>22810</td>
<td>0 0 13.95 0.66 0.4</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>From (m)</th>
<th>To (m)</th>
<th>WiseCrax Survey</th>
<th>Manual Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>13910</td>
<td>14010</td>
<td>0.42 21.38 30.02 17.73 3.54 29.99</td>
<td></td>
</tr>
<tr>
<td>14010</td>
<td>14110</td>
<td>0.00 9.6 22.86 26.83 0.94 4.31</td>
<td></td>
</tr>
<tr>
<td>14110</td>
<td>14210</td>
<td>0.00 7.54 25.15 11.1 1.23 6.96</td>
<td></td>
</tr>
<tr>
<td>14210</td>
<td>14310</td>
<td>0.14 5.16 16.91 21.42 6.12 17.48</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>From (m)</th>
<th>To (m)</th>
<th>WiseCrax Survey</th>
<th>Manual Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>21900</td>
<td>21940</td>
<td>0.00 0 0.68 0 0</td>
<td></td>
</tr>
<tr>
<td>21800</td>
<td>21900</td>
<td>0.00 0 0 0 0</td>
<td></td>
</tr>
<tr>
<td>21700</td>
<td>21800</td>
<td>1.79 0 13.32 0.54 0</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>From (m)</th>
<th>To (m)</th>
<th>WiseCrax Survey</th>
<th>Manual Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>13950</td>
<td>14010</td>
<td>0.0 0 16.8 0.5 8.2</td>
<td></td>
</tr>
<tr>
<td>14010</td>
<td>14110</td>
<td>0.0 0 3.7 0.0 0.0</td>
<td></td>
</tr>
<tr>
<td>14110</td>
<td>14210</td>
<td>0.0 0 3.8 0.0 0.0</td>
<td></td>
</tr>
</tbody>
</table>
Table 4 Data Comparison: Hwy 65- L.M. 8.8 (14.16km), SBOL

<table>
<thead>
<tr>
<th>WiseCrax Survey</th>
<th>FAT-M</th>
<th>BLOCK-M</th>
<th>TRANS-M</th>
<th>TRANSH</th>
<th>LONGW</th>
<th>LONG-M</th>
</tr>
</thead>
<tbody>
<tr>
<td>From (m) To (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14110 14210</td>
<td>0.91</td>
<td>2.27</td>
<td>10.61</td>
<td>0</td>
<td>0</td>
<td>17.65</td>
</tr>
<tr>
<td>14210 14310</td>
<td>0.00</td>
<td>0</td>
<td>10.43</td>
<td>0.19</td>
<td>0.36</td>
<td>6.18</td>
</tr>
<tr>
<td>14310 14410</td>
<td>1.91</td>
<td>0.37</td>
<td>0.76</td>
<td>0</td>
<td>0</td>
<td>39.29</td>
</tr>
<tr>
<td>14410 14430</td>
<td>0.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manual Survey</th>
<th>FAT-M</th>
<th>BLOCK-M</th>
<th>TRANS-M</th>
<th>TRANSH</th>
<th>LONGW</th>
<th>LONG-M</th>
</tr>
</thead>
<tbody>
<tr>
<td>From (m) To (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14160 14210</td>
<td>0.00</td>
<td>0.0</td>
<td>7.3</td>
<td>0.0</td>
<td>6.6</td>
<td>54.1</td>
</tr>
<tr>
<td>14210 14310</td>
<td>0.00</td>
<td>0.0</td>
<td>15.0</td>
<td>0.0</td>
<td>0.0</td>
<td>135.2</td>
</tr>
<tr>
<td>14310 14410</td>
<td>0.00</td>
<td>0.0</td>
<td>9.2</td>
<td>0.0</td>
<td>1.8</td>
<td>139.0</td>
</tr>
<tr>
<td>14410 14465</td>
<td>0.00</td>
<td>0.0</td>
<td>3.0</td>
<td>0.0</td>
<td>0.0</td>
<td>50.6</td>
</tr>
</tbody>
</table>

SURVEYS OF WISECRAX APPLICATIONS IN OTHER AGENCIES

Telephone surveys were conducted in May 2000 on several agencies who either contracted RoadWare for service work of distress data collection, or purchased WiseCrax hardware and software and conducted data collection and analysis in house.

In September 1999, Alabama DOT hired RoadWare to collect and analyze pavement distress data with WiseCrax. Mr. Herman Moore of Alabama DOT stated that this is the first time for them to use WiseCrax and there are no results regarding the performance of the system in the field yet. The service contract includes data collection and reporting on the amount and severity of cracks. RoadWare is required to collect 100% images of pavement surface. The reporting data is at the interval of 50 meter and one kilometer. However, Alabama DOT does not receive any visual information from RoadWare.

Quality control of the data collection and analysis was conducted through the use of control sites. First, manual rating was conducted at the control sites. Then RoadWare’s ARAN vehicle was used to survey the control sites with WiseCrax. The error range is about ±5%. Mr. Moore states that Alabama DOT is reasonably happy with WiseCrax. RoadWare uses distress definitions of Alabama DOT for the surveys. The network being surveyed by RoadWare includes the entire state highway system: highways in National Highway System, Non-NHS highways, and interstate highways. Total lane-mile for the service is about 17,000.

Another user of WiseCrax is Iowa DOT. Iowa DOT contracted the overseeing service to Iowa State University’s transportation center. Mr. Omar Smadi of the university manages the service for Iowa DOT. Iowa used RoadWare’s service for distress data collection and analysis for four years. They awarded RoadWare another service contract early in year 2000. The network in the contract is 2,800 miles. The network is surveyed on a two-year cycle. They also established control sites for quality control, which is conducted every year. Iowa DOT only requires RoadWare to provide data on transverse...
and longitudinal cracks. Mr. Smadi stated that the average deviation from WiseCrax data to manual survey is about % to 10%. Iowa DOT uses the definitions of distress and classification in the SHRP Distress Manual for the surveys.

The third agency that was contacted for this project is Connecticut DOT (ConnDOT). ConnDOT purchased a high-end multi-function data vehicle, ARAN, from RoadWare. They had one WiseCrax computer station to process data. A new WiseCrax station was purchased recently. ConnDOT has used WiseCrax for about four years. The engineer who manages WiseCrax data processing is Mr. Ed Block. There are 7,450 miles of pavements to be surveyed with WiseCrax every year. ConnDOT established two control sites and manually created crack maps of the sites. In year 2000, they also established 15 control sites, with five levels of cracking. That is there are three sites of each level of cracking. The length of each control site is 300 meters. Only transverse and longitudinal distresses are used in the surveys. The error ranges given by Dr. Block are larger than those from Iowa and Alabama. The error for longitudinal distress from WiseCrax is about 30%. The error for transverse distress is about 20% to 30%. However, based on experiences gained while using WiseCrax stations, Mr. Block stated that accuracy of WiseCrax also depends on the manual tuning of the parameters used in WiseCrax software. For instance, changing the background brightness and image contrast can improve the analysis results of WiseCrax. That is, the operation of WiseCrax is not entirely automatic. Monitoring of the processing and tuning the parameters for each batch of tapes are important in maintaining the accuracy of the processing. In many cases, video shot at different time of the day or even in different seasons may possess varying illumination properties for the images, due to the influence of sunlight in data acquisition. It was pointed out by Mr. Block that tuning WiseCrax parameters is a tedious process and it requires good experience of using WiseCrax.

A report on the use of WiseCrax by ConnDOT is included as Appendix A. ConnDOT has been a leader in the area of using visual data for pavement management. They are also the only US agency that purchased RoadWare ARAN vehicles, and WiseCrax hardware and software for pavement data collection and analysis.
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 filed 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 form 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 photomultiplier 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 MC86020 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.

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 refereed 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 now 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. 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.
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).
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.

![CREHOS Survey Vehicle](image.png)

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

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 of 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. Each MFHOE is composed of thousands of HOEs of 5x5-mm size. One photodetector is positioned 60 cm above each of the two the 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 very every $80 \mu s$, 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 $512 \times 480$ 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, $\Delta h$, can be approximately expressed as:

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

Based on this known $\Delta h$ and the contour map, which is created though 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 WISECRAK

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 were 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. Recently, TERRECON scaled back its operation of PAVUE and is not active in state contracts.

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, we
believe 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 always been 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 microprocessors can be used to process the images at real-time as the images are collected. The Pentium-III processors and Athlon processors already have parallel processing capabilities built-in each processor, which, based on initial experimentation at the university, can be programmed to conduct image processing for pavement distress survey.

Lastly, we recommend that AHTD establish a number of formal control sites for pavement data collection, so that pavement condition data can be monitored manually and also used to evaluate automated systems when AHTD is ready to do so.
REFERENCES


APPENDIX A: IMPLEMENTATION OF A NETWORK-LEVEL AUTOMATED DISTRESS SURVEY

Connecticut’s Experience

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ABSTRACT

This paper describes the Connecticut Department of Transportation’s experience in implementing a network-level automated distress survey in 1997. The survey tool utilized was the Wisecrax® system installed on two data-collection vans. Images were acquired for the entire state highway network, and the survey was conducted on the vast majority of the length. The survey emphasized distress-detection aspects while using simple, aggregated distress-classification definitions. The survey method proved repeatable, although crack measurements differed significantly from quantities measured in field test sections. A distress index used for reporting purposes was defined as a function of total cracking per 10-meter length of highway. In order to extract roadway features not detected by the automated system, the automated survey was complemented by a drive-over using front-facing photolog images collected on the same vehicle pass. The state highway network was evaluated in just under 1,000 hours of processing time; the drive-over survey consumed approximately the same amount of time. A second distress survey, using 1998 data, will be used to test the time stability of the system. Although distress-classification issues need to be addressed and the drive-over proved time-consuming, it is expected that these issues can be overcome as the system matures.
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BACKGROUND

Since 1989, the Connecticut Department of Transportation (ConnDOT) has been a leader in the measurement of pavement-surface distress through inspection of video images. The efforts of the Department have been based on the tenet that objective, quantitative distress surveys are necessary to realize the full potential of a pavement-management system as a decision-support tool. The Pavement Rating System (PRS) (1), which allowed operators to measure and classify surface distress from close-up images of the roadway, is representative of ConnDOT's accomplishments in this field. The PRS was used to complete the annual network-level distress survey for the Department's Pavement Management System (PMS) until 1996. The rating system was subject to the image-acquisition, processing, and interpretation limitations imposed by ambient illumination, image resolution and perspective, and operator variability:

In order to improve the video distress survey, it was necessary to address the image-quality issues and to minimize operator subjectivity. In 1996, ConnDOT equipped its two ARAN® data-collection vehicles with Wisecrax® image-acquisition systems, and purchased a workstation where the images could be viewed and evaluated either manually or using the automated crack-detection and classification software available with the system.

In 1997, ConnDOT studied the feasibility of implementing an automated network-level distress survey using the Wisecrax® system, with the expectation of obtaining the following benefits: improvements in survey accuracy and objectivity; independence of data from survey methodology, through measurement of actual physical features; referential integrity with other pavement information, through data collection on a single vehicle pass; reduction of labor costs; and, development of engineering applications beyond the network-level condition survey with little additional data-collection effort.

In the first year of implementation, the Pavement Management Unit has centered its efforts on the distress-detection aspect of the survey, which was conducted on the vast majority of the state highway network, comprising over 12,000 directional kilometers of highways ranging from Interstates to rural secondary roads. Distress-classification issues are to be addressed at a later stage. This paper describes ConnDOT's experience in the initial implementation of the automated distress survey, and the issues encountered in the process.

DESCRIPTION OF AUTOMATED DISTRESS-SURVEY TOOL

Image Acquisition

The Wisecrax® system is one of several data-collection modules installed in the two ARAN® vehicles owned and operated by ConnDOT. The system consists of two digital cameras aimed at the pavement surface from horizontal booms that extend back from the
top rear of the vehicle. Synchronized strobe lights provide consistent illumination in a variety of ambient conditions. Each camera captures an image 1.5 meters long by 2 meters wide, allowing 100-percent coverage of the traveled pavement length, at a width of 4 meters. The images are stored on S-VHS videotape and are time-coded for retrieval.

The pavement-surface images used by Wisecrax® are acquired simultaneously with other types of information, including photolog and right-of-way images, road-geometry data, Global Positioning System (GPS) coordinates, and pavement roughness and rutting measurements. The use of a unified platform and a single pass for data collection minimizes costs and ensures the referential integrity of the data.

Image Processing

The processing workstation consists of a personal computer, an S-VHS tape deck, and a black-and-white video monitor where the contents of the videotape are displayed. The personal computer is equipped with a video board that allows digitization of the S-VHS images.

The pavement images are digitized, normalized, and assembled into roadway segments 10 meters long by 4 meters wide. Image normalization results in a pavement “background” with constant luminance properties, from which the distress features can be extracted. Once the 10-m x 4-m image is assembled, roadway zones (lane boundaries, position and width of the wheelpaths) are delineated. Lane boundaries are automatically detected; in cases where lane demarcation is not present, the lane is assigned a default width and position within the image.

Image Analysis and Interpretation

Proprietary pattern-recognition software is used on the assembled images to first detect and then classify cracking according to length, width, orientation, and shape. The software allows user specification of detection-sensitivity parameters, and supports three classification systems with varying degrees of complexity. It is possible to process batches of multiple segments contained in a single videotape; in addition, although 100 percent sampling of the pavement length is attainable, lower sampling rates, at regular intervals, can be adopted in order to accelerate the rating process. As of this date, the system does not identify patches, potholes, or spalling. In Connecticut we have been unable to consistently identify longitudinal reflection cracks in asphalt-concrete overlays of portland-cement concrete pavements, mainly because they are usually located at the lane striping or outside the viewing area altogether. Additionally, we have not been able to obtain crack-width values with which we are comfortable.

System Output

The system produces data files that summarize distress data for each 10-meter segment. These files can be exported to a spreadsheet or text file. The distress detection and classification information can then be used to rate the pavement segment according to user-specified criteria.
SURVEY DESIGN AND IMPLEMENTATION

Survey Requirements

The first step in the implementation process was to establish requirements for the network-level distress survey, drawing on the state’s considerable experience with condition surveys from video. These are listed below:

- The survey must be objective and quantitative, to allow comparison of distress states among the various segments of the highway network.
- The survey should record measurements of actual physical features, so that survey methodology has a minimal effect on the survey data.
- The process must be repeatable.
- The survey must represent an improvement over previous methods.
- Labor intensity should be reduced.

In addition to these requirements, the PMS unit wanted to collect data somewhat independently of pavement sections, to allow future re-segmentation of the network based on pavement condition.

A system meeting these minimum standards should produce data that can be assimilated by subsequent, more advanced systems. We expect the full implementation of the automated distress survey to be an ongoing process taking several iterations as we exploit all of the system capabilities and assimilate advances in technology.

Familiarization with Survey Tool and Qualitative Testing of System

When the Wisecrax® system was installed on the vans and the workstation arrived in the PMS office, the first task was to become familiar with the operation of the system, to observe the various steps of the image-acquisition and analysis process, and to evaluate the capability of the system to process the wide range of image types present in a 12,000-km highway network. A two-day, on-site system-operation training service was included with the purchase of the system, which was more than adequate for the completion of this task.

At this early stage, some system limitations were identified. In particular, establishing the exact location of the pavement-surface image with respect to the highway-referencing system required an external aid, in this case the front-facing photolog digital image that had been gathered on the same vehicle pass. Distress forms other than cracking (such as patching, spalling, or raveling) could not be consistently identified. Lastly, we could not measure crack width with sufficient reliability to assign crack severity.

Based on this preliminary evaluation of system features and capabilities, it was decided to focus on the detection aspects of the system and use simple, highly aggregated crack-classification definitions that still afford the possibility of analyzing the cause and nature of the distress. The crack-classification definitions selected are listed in Table 1.
Connecticut Additions to the System

Initial testing of the system had indicated that the distress survey would have to be complemented with an examination of the front-facing photolog images of the roadway. A drive-over survey of the roadway network, using these digital images, was implemented to extract roadway features not detected by the automated survey. These items include:

- Presence of sealant in the cracks. The presence of sealant causes the system to see a higher percentage of the total cracking length.

- Extent of “skid box” applications, or placement of a thin layer of sand-asphalt, a treatment that in our state is normally utilized to re-surface a badly deteriorated section until a rehabilitation treatment is applied.

- Severity of transverse and longitudinal joint-reflection cracks in composite pavements (bituminous-concrete overlays of portland-cement concrete). The location of longitudinal joint-reflection cracks often coincides with lane striping, and is sometimes completely outside of the surveyed lane. Sealed transverse joint-reflection cracks are often induced at the time of placement of the overlay, in a procedure known as “sawing and sealing.”

- Quantity of patching and potholes.

- Presence of segregation and/or raveling in the surface course.

- Identification of the exact limits of resurfacing projects.

In addition, the drive-over could help to filter out roadway segments with undesirable features that could cause data-interpretation errors. These features include bridge decks, vehicle lane changes, construction zones, milled surfaces, and railroad crossings, among others.

With the incorporation of a section “drive-over” using the front-facing images of the roadway, it is possible to reduce the number of variables that can affect the survey results. At the same time, the drive-over can be used to tie the data collected with the vans to the state roadway-referencing system; this is necessary to link ancillary data, such as functional class, traffic volumes, or accident records. It has been our experience that the drive-over is extremely important for the successful implementation of an automated condition survey. On the other hand, there is an additional cost and substantial first-time effort required to complete the drive-over survey; nevertheless, we expect that system capability will improve to the point where the drive-over survey will not be needed.

In addition to the survey function, the drive-over survey was used to define “homogeneous” pavement sections, or network analysis units. We expect that this task
will not have to be executed for much longer, since we plan to develop automatic network segmentation tools based on user-specified criteria in the near future.

**EVALUATION OF ADEQUACY OF AUTOMATED DISTRESS SURVEY COMBINED WITH DRIVE-OVER**

By crack-mapping sections of roadway, it was hoped to find the minimum crack width that the system could reliably detect. We found that the minimum crack width that can be reliably detected is between 2 and 3 mm. Finer cracks can sometimes be detected by the system, but the increased detection sensitivity introduces "noise," into the distress quantity, as it becomes more difficult to distinguish distress from the background. For a more detailed discussion of this topic the reader is referred to El-Korchi and Wittels (2) and Kotsoupoulos and El Sanhouri (3). One of the major requirements of the distress survey was the capacity to rank the network segments based on the survey data.

Two tests were performed to test the ability of the system to compare different sections of the network. The first consisted of using the cumulative-differences method of segmentation described in Appendix J of the AASHTO Pavement Design Guide (4) to find the location of major changes in condition along a highway. This was compared to subjective ratings performed by pavement engineers on those sections. The system not only found the pavement changes to within the nearest 10 meters, but the sections were also properly ranked. A second, similar test consisted of selecting sections known to be in one of five distress states ranging from excellent to poor, and performing the automated distress survey. Once again, the sections were properly ranked.

The repeatability of the process was evaluated by comparing two or more runs on the same section; the image processing aspect of the system was tested by repeating the survey on a single set of images. The entire survey process was tested by comparing separate data-collection runs over sections where routes overlap. In all cases, the results for the different runs produced results that were not statistically different with a 95% confidence interval. Figure 1 shows the results of two such runs on a particular road section.

Overall, we are confident that the distress-survey system works as a network crack-detection and classification tool.

**SURVEY EXECUTION**

**Reduction of Total Surface Area to be Surveyed**

After the testing period, we settled on a procedure and methodology for surveying the entire network. Because of time constraints during the initial survey year, the following measures were taken to reduce the amount of pavement surface surveyed:

A 25% sampling rate was adopted. This provides an adequate characterization of the pavement surface for sections that are at least 0.5 km in length in most cases. The minimum section length can be determined by examining the distribution and variability of the distress. The introduction of sampling introduces sampling error, reducing the precision of the survey results; we expect to overcome some of the time constraints and survey 100% of the pavement surface in subsequent surveys.
Undivided highways were surveyed in only one direction

If the drive-over had been completed, sections with a surface age of two years or less were excluded from the survey.

Detection Issues

Since detection-sensitivity parameters are defined by the user, it is possible to aim to either measure the maximum possible percentage of crack length, or to minimize the amount of false positives. The most repeatable results were obtained by setting stringent detection-sensitivity parameters (to minimize the number of false positives). Although the quantity of cracking varies significantly from field measurements, the results are reliable for network characterization.

More than one detection parameter set can be used in the survey; images with differing visual properties could be processed using different sets of detection parameters. Although a more accurate crack quantity can be obtained by this method, some surveyor intervention is required in terms of defining sections as well as selecting a particular parameter set for the road conditions observed. This introduces an element of subjectivity into the process; therefore, we selected a single parameter set that could meet survey requirements and used it for all highway sections.

Classification Issues

Since the emphasis was on the crack-detection aspects of the system, the simple definitions listed in Table I were deemed appropriate for the first survey. At this stage of implementation and at the network level, it is better to aggregate distress types than to obtain less, more variable quantities of many distress types. As we become more familiar with the distress-survey tool and its capabilities improve, additional classification will be evaluated. Since the raw cracks are being saved, it is a simple task to apply new classification algorithms to the detection output, with relatively little effort and time.

Pavement Rating Issues

For reporting purposes, a distress index, called the Distress Score (DS), was developed as a function of total crack length, using a zero to 100 scale, 100 denoting a pavement with no distress. The distress index equation, presented as Equation (1), is intended to reduce the aggregating effect of additional cracking at high distress levels. The equation has the form

\[
DS = 100 \times e^{(-a \times (LC-B))}
\]  

(1)

where

\[
DS = \text{DISTRESS SCORE}
\]

\[
e = \text{base of the natural logarithm},
\]

\[
a = \text{parameter to determined by non-linear regression},
\]
\[ LC = \text{length of cracking, and} \]
\[ B = \text{a constant to eliminate the background cracking in some composite pavements.} \]

The parameters \( a \) and \( B \) were estimated separately for flexible and composite pavements, and for sealed, partially sealed, sawed-and-sealed, and unsealed cracks.

**Data Storage**

All detected cracks have been stored on a computer. The survey results that are exported to text files are actual distress quantities summarized for 10-meter sections. The resulting data files and relational database table used by the Pavement Management System consume nearly two gigabytes of computer storage space per year for a 12,000-km network. Although the distress-survey tool can process long batches of images, there remains a lot of effort to reduce the data and incorporate it into the PMS database. Knowledge of relational database software and programming skills can greatly reduce the effort required in this aspect of the survey, and can greatly enhance the utility of the end product.

**LABOR REQUIREMENTS**

ConnDOT’s Wisecrax® workstation is capable of conducting the distress survey at an average speed of 1.8 km/hr of actual surveyed length; newer workstations are capable of surveying at speeds of over 5 km/hr. The actual speed depends on the particular image color characteristics and the amount of distress present; pavements with little cracking and smooth texture are processed the fastest. In Connecticut, we were able to complete the distress survey at a 25% sampling rate in just under 1,000 hours. Operator intervention is minimal, and once an image batch is set for processing, he or she can perform other tasks; however, the production rates stated are only achieved with some supervision of the process, to avoid costly “down time” when the system loses control of the VCR (the most common cause of stoppage). Most of the effort is spent in the drive-over, which takes almost the same amount of time as the automated survey. This is especially true during the initial year; for subsequent years the previous drive-over needs only to be updated, as most of the needed data are already recorded.

**FINDINGS AND RECOMMENDATIONS**

An automated distress survey has been successfully implemented in Connecticut. The survey has met our goals for initial implementation. The image-processing system can reliably detect cracks greater than 2 mm wide, is repeatable, and, when combined with a drive-over survey, is acceptable for comparing the various segments of an extensive highway network. The drive-over can also serve as a highway-inventory tool and as a link to data that is referenced with another system that may be in place at the state.

The second annual automated distress survey, to be performed in 1998, will provide data that can be used to test the time stability of the data. We expect to conduct 100% sampling of the pavement surface, to reduce sampling error and allow a more detailed study of pavement conditions over short highway segments.
There is additional work required in the area of distress classification. The distress index needs to be further developed and refined. On ConnDOT's end, effort will be placed on reducing the time to complete the drive-over, and on recommending system improvements that will result in the elimination of the drive-over survey altogether.

REFERENCES


TABLE 1 Distress-Classification Scheme for Network-Level Survey

<table>
<thead>
<tr>
<th>Distress Form</th>
<th>Quantity Measured</th>
<th>Extent</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse Cracking</td>
<td>Length (m)</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Fatigue Cracking (longitudinal cracking in the wheelpath)</td>
<td>Length (m)</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Non-wheelpath Longitudinal Cracking</td>
<td>Length (m)</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

MODIFICATIONS AFTER DEVELOPMENT OF USER-DEFINED RATING SCHEMES

For the second cycle of data collection, a new version of Wisecrax was used which allows the user to specify rating (summarization) criteria. Our philosophy is to collect at the lowest level of aggregation at the detection level. In other words, if possible, we would collect and store each data vector that describes an individual crack. The smallest aggregation scale available from Wisecrax is the length of the image (10 m) in the longitudinal direction, and five “road zones” in the transverse direction. By selecting the scheme in Table 1a, it is possible to aggregate the measurements (into total length of cracking, for instance, by simple addition of the values in the columns) while retaining the maximum amount of detail.

TABLE 1a (Changes to crack classification and rating for second collection cycle)

<table>
<thead>
<tr>
<th>Distress Form</th>
<th>Location</th>
<th>Quantity Measured</th>
<th>Extent</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse Cracking</td>
<td>Left Edge</td>
<td>Length (m)</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Left Wheelpath</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lane Center</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right Wheelpath</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right Edge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal Cracking</td>
<td>Left Edge</td>
<td>Length (m)</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Left Wheelpath</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lane Center</td>
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<td></td>
<td>Right Wheelpath</td>
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<tr>
<td></td>
<td>Right Edge</td>
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<td></td>
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</tr>
</tbody>
</table>
Comparison of Two Automated-Distress Surveys on a Route Overlap
Conn. Rtes 318 and 181

**FIGURE 1** COMPARISON OF AUTOMATED-DISTRESS DETECTION MEASUREMENTS USING DIFFERENT IMAGES OF THE SAME SECTION