AN ABSTRACT OF THE THESIS OF

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Title: Development of a Low-Cost Video Imaging System for Pavement Evaluation.

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Chris A. Bell

The evaluation of pavement condition is an important part of pavement management. To evaluate a pavement, a distress survey has been performed mainly by manual field inspections. Several automatic pavement evaluation systems have been developed to overcome the drawbacks of field inspections. Automated evaluation systems, however, imply their own limitations in terms of cost, technical problems, and adaptability for pavement management.

The main purpose of this research is to develop a low-cost automatic pavement video imaging system. The secondary purpose is the development of techniques to process the collected video images.

A low-cost video image-collection system and an in-office system were developed. A video test was implemented on a selected route including various pavement types and several variables. As a result of the test, seven loop tests provided acceptable results to allow image analysis. By using the video camera with fast shutter-speed, it was decided that the survey vehicle could drive at high speed (65mph) while maintaining good picture quality.

To evaluate the performance of the system, video and field inspections were performed using two approaches: the Oregon Department of Transportation (ODOT) and Metropolitan Transportation Commissions (MTC) approaches. The inspections were

conducted on 107 sample sections. Also, sample still images were digitized for analysis. To conduct a video inspection, the Global Positioning System (GPS) technique was applied for conversion of video mileage to real field mileage.

The results of video and field inspections were compared using statistical analyses. The ODOT approach shows a good correlation between video and field inspection for AC sections. In particular, patching and non-load crack indices provide good correlation. The MTC-PMS analysis showed strong linear relationships between video and field inspections. The analysis of crack indices from digitized images shows poor repeatability for each test loop. Using general linear model analysis, variable effects on crack indices were tested.

The cost for development and operation of the system was estimated as well as cost for an enhanced prototype system. Discussions on various aspects of the developed system are provided. Finally, summary and conclusion are included as well as recommendations for future system development.

Development of a Low-Cost Video Imaging System for Pavement Evaluation

By

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1. INTRODUCTION

1.1 Problem Statement

The maintenance of road networks requires enormous investment within transportation agency budgets. Thus the optimized allocation of these maintenance budgets has been one of the great challenges to the transportation agencies. As a means to optimize the allocation of funds, a number of agencies have implemented pavement management systems (PMS) to distribute funds and to preserve road conditions within acceptable levels of service.

The evaluation of pavement condition is an important part of pavement management: the more accurate the evaluation, the better chance that resources will be distributed optimally, resulting in better service conditions. To evaluate pavements, condition surveys and analyses of the surveyed results should be performed regularly. This is usually performed by pavement distress surveys. In the past, pavement condition has been evaluated mainly by the conduct of manual field distress inspections [Kalikiri et al., 1994]. However, this method of field inspection poses several drawbacks. First, it is slow, labor intensive, and expensive. Second, it is a subjective approach to the problem, generating inconsistencies and inaccuracies in the determination of pavement conditions. Moreover, repeatability is poor since the assessment of given pavement sections may differ from one surveyor to the next [Koutsopolus and El Sanhouri, 1991]. In addition, for congested multi-lane urban streets, it has been reported that detailed visual surveys are difficult to perform [Kim, 1995].

Finally, the manual field survey is dangerous to surveyors. They are exposed to the traffic and weather therefore represent a serious safety hazards [Georgopoulus et al., 1995]. The surveyors could be exposed to high speed and high volume traffic, while recording observed distress information with laptop computers or on handwritten forms.

Numerous system users have come to believe that there is a need to minimize the drawbacks listed above, replacing manual data collection systems with automated systems. In response to this demand, a number of automatic systems have been developed or are in the process of development by different agencies. Among these technologies, pavement image-collection technology is seemingly the most popular approach [Barker et al., 1987; Fukuhara et al., 1990; Hanley and Larsen, 1994; Lee, 1991; Mohajeri and Manning, 1991]. These systems generally use survey vehicles that are capable of collecting and storing pavement surface images. Most systems record pavement surface images using a video camera or a photographic camera mounted on a survey vehicle. A number of systems have been tested and evaluated over the years [Kalikiri et al., 1994].

Automated survey systems, however, have their own set of limitations. First, the initial costs of sophisticated survey systems are prohibitively high [Gattani et al., 1994]. Most transportation agencies are reluctant to invest in such high equipment costs for pavement management. Second, to a large extent, these systems remain in the development and testing stage. Thus, system accuracy and performance have not been fully demonstrated. Third, the collected data may be difficult to use efficiently in conjunction with the existing agency PMS. Since automated systems have not been in use for long periods of time, their introduction will impact the existing PMS used within agencies. Finally, the automated survey systems have their own limitations. Most of systems do not detect some types of distress such as rutting or raveling. Also the evaluation can be affected greatly by environmental conditions such as shadows or natural lighting conditions.

1.2 Research Objectives and Scope of the Investigation

The primary purpose of the present investigation is to develop a low-cost automatic pavement imaging system based upon video techniques. In recent years, there have been significant advances in the technologies of computer and image sensors, presently accessible by the public at relatively low cost. Technological progress has also been effected through the increased variety of data collection, processing, and storage approaches. However, selection of the most appropriate technology may not be an easy task for most transportation agencies. Therefore, the present investigation has been directed at the selection and combination of technologies (e.g., computer, image sensor, software, and other peripheral devices) appropriate to low-cost automatic pavement image-data collection. Thus the research objective has been to determine the combination of the optimized equipment with least cost for each element of pavement imaging systems.

The proposed system is intended for application in conjunction with real PMS implementations, used in the multi-laned streets of larger cities, in small city areas, and in other situations such as the interstate or state highway systems. To accommodate future technological advances, the proposed system will be flexible in nature.

The secondary purpose of this research has been development of techniques to process the video images collected through application of the proposed automated system. The collected video data will be interpreted by selected in-office equipment, with the video logging approach applied to the collected field image data to verify the efficiency, accuracy, and repeatability of the results obtained.

To accomplish the research objectives, the following tasks have been completed:

1) Development of a low-cost system for automated pavement survey using video techniques, including the following:
   - review elements of pavement imaging systems;
   - select elements for system development; and
   - organize elements of data collection technology;
2) Conduct field video testing of the system;
3) Collect video imaging data;
4) Develop video image-inspection techniques for the collected data encompassing video logging;
5) Conduct video inspections and manual field inspections;
6) Compare and analyze the video imaging data by comparing field inspection data results;
7) Digitize sample images and analyze digitized images;
8) Evaluate the developed system; and

9) Present conclusions and recommendations for further system development.

1.3 Research Process

The research process is described in Figure 1.1. Presentation of the findings of the present investigation begins in Chapter 2 with a literature review describing the background of this study. The concepts of the PMS and surface-distress data, developed automatic pavement evaluation systems, and image interpretation techniques are reviewed. In Chapter 3, the elements of a video-imaging system are reviewed for system development. The system developed for video image collection and in-office processing is then described.

A field video-test plan was prepared and implemented using the developed system, in the selected test area, as described in Chapter 4. From the field video tests, pavement video images were collected and stored on videotapes. The system evaluation process conducted upon the developed pavement imaging system is described in Chapter 5. Collected video images were inspected in detail using video interpretation techniques for selected sections. Comparative field pavement inspections were also performed for selected sections. Selected sample video images were digitized for image processing, as also described in this chapter.

Chapter 6 presents the results obtained through video and field pavement inspection, accompanied by descriptions of the results of digital image processing. Then the analysis of the results and discussion of the evaluations are presented in Chapter 7. The analysis was obtained from comparison of video logging and field pavement inspection, as well as through processing of the digitized images. From these analyses, the developed system was evaluated in all of its various aspects.

Finally, the investigation is completed with the presentation of summary and conclusions in Chapter 8 and recommendations in Chapter 9.

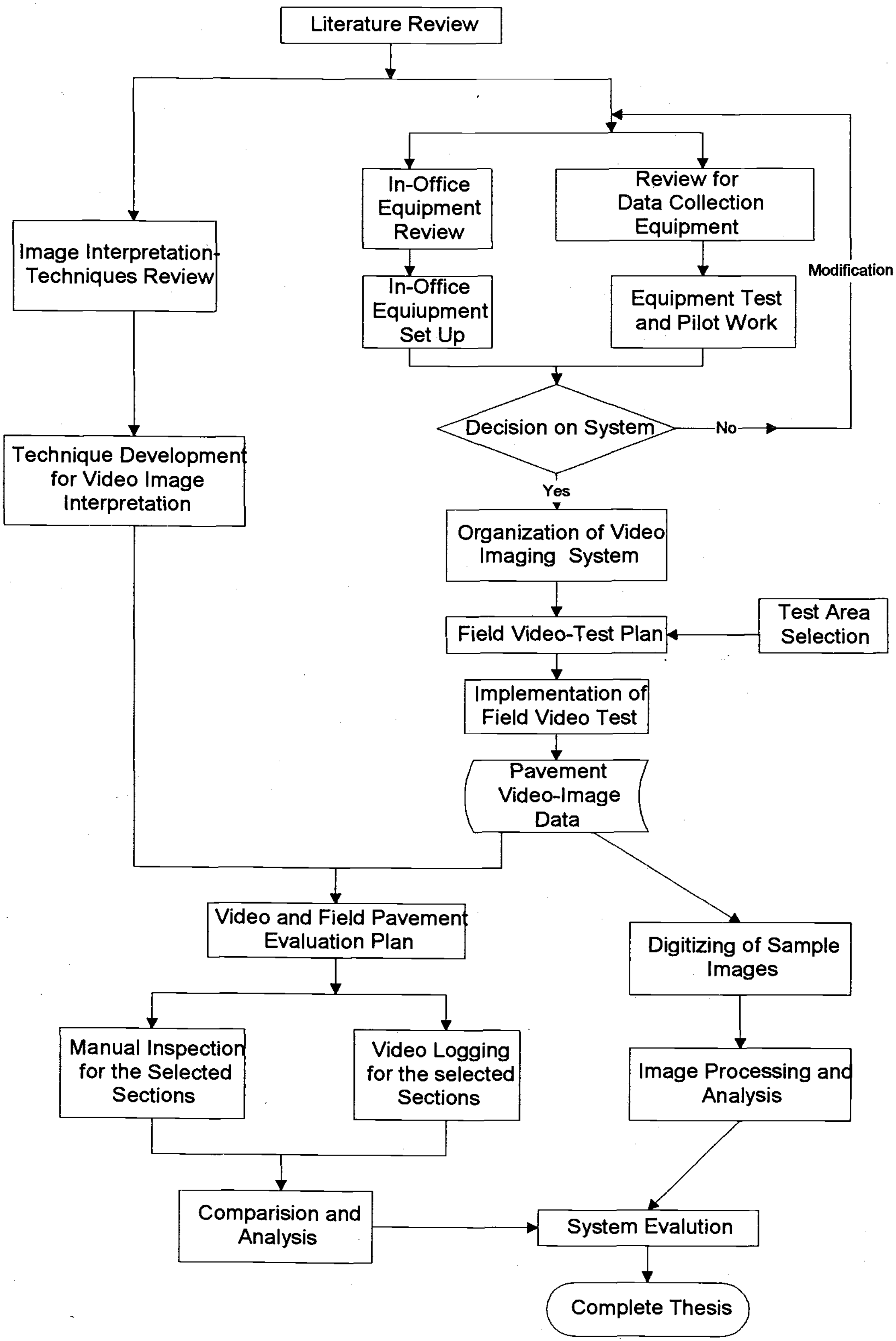

Figure 1.1 Research Process.

2. BACKGROUND

This chapter provides a general background description of research related to the present investigation, including review of the literature related to this research. Pavement management concepts and their relationship to pavement distress data are described. Currently available automatic pavement evaluation systems also are reviewed. As an approach to pavement condition analysis, video logging and digital image processing concepts and their interactions in pavement analysis are described.

2.1 Pavement Management and Surface Distress Data

Pavement management encompasses all activities involved in the planning, design, construction, maintenance, evaluation, and rehabilitation of the pavement portions of a public works program. A pavement management system (PMS) is a tool developed to assist in the selection and timing of cost-effective strategies for the maintenance of pavements in a serviceable condition during a given period [AASHTO, 1993]. Pavement condition determination at particular times is an important part of the pavement management process, helping highway engineers determine the most cost-effective maintenance or rehabilitation procedures for each pavement section.

To assess pavement condition, four types of condition assessment are used [Stevens et al., 1985]:

1) distress surveys,
2) roughness testing,
3) structural testing, and
4) skid resistance.

To obtain an accurate overall indication of pavement condition, a condition rating that encompasses each of these factors is the most desirable approach to evaluation. However, some of these factors are not easily measured, nor are all in routine use by public works personnel [Smith, 1986].

Many of transportation agencies such as Oregon Department of Transportation (ODOT) have various automatic data collection equipment for pavement evaluation. For example, falling weight deflectometer (FWD) for structural testing, skid tester for skid resistance, and rut-meter for rutting distress evaluation are already used. The only missing element in automatic data collection is for distress surveys.

Road surface distress consists of damage observed on the pavement surface [Smith, 1995]. Pavement distress is caused by either environment, traffic, or a combination of both. Distress surveys performed to determine the type, severity, and extent of surface distress are used to measure and evaluate various types of cracking, raveling, disintegration, and deformation as well as other conditions of interest. Distress types are placed in various classifications and a wide variety of manuals for the classification and definition of pavement distress have been made available.

Most transportation agencies conduct periodic surveys for pavement surface distress evaluation by manual or by measuring equipment, or a combination of both. Using manual distress surveys, pavement distress may be determined by walking along the pavement or from a moving survey vehicle. Walking surveys provide precise data about pavement condition. However, they are time consuming and they are thus usually confined to only samples of road networks. Several agencies collect distress data while driving along sections of roads, usually on the shoulder at slow speeds. The primary advantage of this approach is the ability to cover all of a road network. The disadvantage is that the quality of the data is not as good as that obtained from walking surveys [Haas et al, 1994].

The above two distress survey approaches collect data in the field using the naked eye to observe surface distress, implying a certain number of drawbacks as described in Chapter 1. Thus, many agencies try to use visual survey equipment such as film cameras, video cameras, or scanners. The intent of these approaches is to implement automatic data collection and analysis techniques that can draw advantage from available new technologies.

The need to automate the acquisition and interpretation of distress data is presently recognized by many pavement engineers and researchers. With advances in image sensors and computer technologies, the automation of data collection and analysis is a major goal of contemporary pavement management.

2.2 Automated Pavement Evaluation Systems

In response to the demand for increased automation, a number of computerized pavement evaluation systems have been developed. A number of transportation agencies, research groups, and manufacturers have undertaken the development and implementation of automated pavement-evaluation systems.

2.2.1 Commercially Available Systems

A number of manufacturers have developed systems for automated pavement evaluation, some of which are presently commercially available. The most common technology for automating detection of distress has been road-surface image collection [Ritchie, 1990].

1) The *Komatsu System* was developed in Japan, using laser scanner, photo multiplier tube (PMT), video camera, and image processing techniques. [Fukuhara et al., 1990; Ritchie, 1990]. The system consists of a survey vehicle and a data-processing system, used to measure cracking, rutting, and longitudinal profiles simultaneously. Maximum crack resolution is obtained at a vehicle speed of 10 km/h, although speeds up to 60km/h can be used. Significant accomplishments include a unique line-finding algorithm that can extract cracks from a road image. However, the system does not output the type of cracking, that is, whether it is transverse, longitudinal, or alligator, with associated extents and severities.
2) The *Swedish Laser RST* is a laser-based, computer-automated, non-contact road profilometer system with the ability to collect and simultaneously process a variety of data about road surfaces [Acosta et al., 1994]. The device uses 11 laser rangefinders that are mounted on a support beam in front of the vehicle. Operated in daylight at full highway speeds, the system is able to measure longitudinal profiles, cross profiles, rutting, texture, road geometry and cracking by image processing. However, a "windshield"

distress survey must be performed in real time to classify the distress types [Ritchie, 1990; Haas et al., 1994].

3) The *PAS1*, an automated distress measuring device, was developed by Pavedex Inc. [Lee, 1991; Pavedex, 1997]. Pavement data are collected using four video cameras: two in front and two in the rear of a vehicle. The video images are recorded in three S-VHS VCR and then processed at office work stations. A trained analyst evaluates pavement condition by observing still-frame video images and inputting detected levels of distress via a keyboard. It has been claimed that the PAS1 can detect and interpret the following types of distress: alligator, longitudinal, block and transverse cracks, patching, and potholes.

4) The *Automated Road Image Analyzer* (ARIA) was developed by MHM Associates Inc. [Mohajeri, 1991]. Road-surface images are collected using the ARIA videolog van. Digital image processing and pattern recognition are then performed on video images of pavements. The ARIA system can recognize and quantify the following types of pavement defects: alligator, longitudinal, and lateral or transverse cracking.

5) The *PASCO ROADRECON* is a photographic survey vehicle used to obtain a continuous photographic record of pavement with coupled 35 mm slit cameras at night. [Acosta et al., 1994; Richter, 1989; Solminihac and Roper, 1991]. Three laser sensors are utilized to measure longitudinal profiles and rutting. Following the field survey, all exposed films are developed under quality control procedures. Pavement data are reduced using an analysis system consisting of a film-motion analyzer and a personal computer. Through manual film analysis, the types and severity levels for distress are determined.

6) The *GERPHO* system has been used extensively in France. Similar to the ROADRECON, the GERPHO system records a continuous image of the pavement surface on 35 mm film [Haas et al., 1994]. The GERPHO also operates at night. Distress information is extracted from the film using a specially designed display table.

7) The *PDI-1* (Pavement Distress Imager-1) was developed by PCES, Sparks, Nevada, based upon intense illumination with two CCD line-scan cameras that cover 8 feet of pavement [Haas and McNeil 1990; Ritchie, 1990]. The cameras acquire image data line by line, processing the data as the vehicle moves at speeds up to 60 mph. It uses feedback image processing, by selecting binary thresholds based on histogram techniques.
8) The *Automatic Road Analyzer* (ARAN) was developed by Highway Products International, Ontario, Canada, and is used to measure rut depth and transverse profiles with ultrasonic sensors as well as ride/roughness quality measured with an accelerometer mounted on the rear axle [Acosta et al., 1994; Haas et al, 1994]. The video system includes two video cameras. One camera takes a video picture of the road right-of-way. The other camera takes a video picture of the pavement surface. The observer-operator records and stores distress data manually.

2.2.2 Public Transportation Agency and Research Group Systems

A number of public agencies and research groups are also conducting research for automated pavement evaluation. *The Automated Pavement Distress Data Acquisition and Evaluation* (ADDA) system was one of the first attempts to develop an automated distress-survey system. ADDA was developed by the University of Waterloo under the sponsorship of the Ontario Ministry of Transportation [McNeil and Humplick, 1991]. The system uses a video camera mounted on a vehicle traveling at maximum speed of 18 mph (30 km/h). However, the overall system was unable to assure accurate recognition, leading to object misclassifications [Acosta, 1994].

Baker and colleagues [Baker et al., 1987] developed and implemented an automated highway management model for the *Idaho Transportation Department*. The system videotaped road surface images of Idaho highways. In addition, computer software was used to determine crack type and size by image analysis.

The *Connecticut Department of Transportation* (DOT) developed a photolog laser videodisc-based technology that allowed personnel to conduct a network-level pavement distress survey using videodiscs in an office setting [Hanley and Larsen, 1992; Hudson and Seitz, 1996]. Interpretation of distress is performed manually using a computer program.

The *Ohio DOT and Case Western Reserve University* conducted research for development of an automated pavement evaluation system using based upon video-image processing [Acosta et al., 1992; Acosta et al., 1994; Acosta et al., 1995]. The system was used to collect surface distress data using video camera and depth measurement devices. Through digital image processing, the system is able to identify and classify most pavement distress types. The system is combined with a rating procedure, Pavement Condition Rating (PCR), to obtain a quantitative measure of pavement condition.

The *National Co-operative Highway Research Program* (NCHRP) carried out research for video image processing for evaluating pavement surface distress [Fundakowski et al., 1991; Fundakowski, 1991]. The NCHRP project demonstrated the fundamental capabilities of video image-processing systems for the determination of distress type, severity, and extent. The system developed was shown to produce reasonable extent estimates for the following distress types: (1) PCC pavements (longitudinal cracking, transverse cracking, joint deteration); and (2) asphalt-surfaced pavements (longitudinal cracking, transverse cracking, alligator/block cracking).

Salt Lake City and the University of Utah recently developed an automatic pavement evaluation system based upon a digital still camera system for data collection [Jitprasithsiti and Lee, 1996; Lee et al., 1996]. The camera is mounted to a van perpendicular to the pavement surface to cover a pavement area of 2.13 m (7ft) by 1.52m (5ft).

Image processing software was developed to determine crack index for evaluation of pavement surface condition. The program also connected to the Mapinfo GIS (Geographic Information System). Based on crack index readings, the program recommends the most appropriate maintenance strategies and displays those strategies on a digital map. The GIS can retrieve attribute data from the pavement database and automatically generate custom maps to meet specific needs.

The University of New Mexico developed a simple pavement distress survey system, based upon an 8-mm camcorder, an inexpensive image-digitizing board, and a personal microcomputer [Chua and Xu, 1994]. An image-processing algorithm was developed to identify longitudinal, transverse, diagonal, alligator, and map cracking.

In addition to the above systems, other manufacturers, transportation agencies and researchers are involved in the development of automated pavement evaluation systems, including : EKTRON, Bedford, Massachusetts; VideoComp, Idaho; MHM Associates, South Bend, Indiana; KLD Associates, Huntington Station, New York; the Iowa DOT [Jones, 1992]; a cooperative research program between the Kansas DOT, Kansas State University, and The University of Kansas [Gattani et al., 1994]; the Texas DOT and Texas A&M University [Acosta et al., 1994; Bell, 1995; Lau, 1995; Ritchie, 1990]. However, most of these systems remain under development and subject to various limitations in several aspects, though each has the obvious goal of developing a fully automated and accurate pavement evaluation system without need of human intervention.

2.3 Video Image Interpretation

As described in the previous section, the most common technique for automatic pavement evaluation is image collection by video camera. Generally, the collected video images can be analyzed either by video logging or digital image processing, or through a combination of both.

2.3.1 Video Logging

Video logging techniques involve the in-office manual interpretation of pavement images. The steps for video logging pavement evaluation include image acquisition, preprocessing, image display, interpretation, and distress recording. The pavement images are usually obtained by survey vehicle. Once the images are obtained, preprocessing is may required. The images are then displayed and interpreted by trained raters, who record distress information in recording form or in distress recording programs. The interpretation is usually performed on still-frame images. When the first frame is completed, a second frame is selected. The frame selection can be performed by human or computer. The analysis is continued until all frames are completed.

Many automatic survey systems use this technique to interpret pavement images. Usually, the inspected distress information is recorded using specially designed distress recording programs. For reference, consider the PASCO-developed Pavement Distress Analysis System (PADIS) program for distress interpretation used to analyze collected pavement images. The software combines film-video and/or laser disk images with a personal computer. Image interpretation is accomplished by displaying the road surface one frame at a time and using the screen pointer (cursor) to designate and record distress. Once the image screen has appeared, the operator identifies the first distress in the frame and assigns a severity level. The location of the distress is recorded using the mouse and the grid and the information is saved. Then, using same procedure, the next distress is recorded [PASCO, 1996; Solminihac and Roper, 1991].

The Pavedex office videolog workstation includes a computer, 20" monitor, and a video subsystem. A trained analyst evaluates pavement images by observing "still-frame" video images and inputting detected distress via the keyboard. The distress is input by classification, severity, and extent and the computer assigns the precise location of each noted distress by reading the decorder. Once the evaluation is completed, the videotape is advanced to next video frame and the process is repeated [Pavedex, 1997].

Video logging methods provide several advantages with respect to traditional rating methods [Hanley et al., 1992]. First, the rating is done in an office environment under nearly ideal working conditions. The raters are not exposed to varying traffic and weather conditions. Second, each frame rated is a permanent record and can be rerated or, if necessary, rated by many raters. Third, this takes the inspector off the road and reduces traffic interruption, both of which are important on high volume highways [Smith et al., 1996].

However, since human factors are involved in this method, subjectivity is still present in identifying distress types, severities, and quantities. Also, resolution is decreased because the observer is viewing a two-dimensional video image [Smith et al., 1996].

2.3.2 Digital Imaging Processing

The digital image analysis concept is receiving increased attention because of its potential to provide accurate pavement condition data. For the greater part, current pavement image interpretation research has concentrated upon the technical development of digital image processing.

The term digital image processing generally refers to processing of a two-dimensional picture using a digital computer [Jain, 1989]. Digital images are represented by a two-dimensional array of small areas or "pixels" using 24-bit color video graphics adapters (VGA). This typical display presents $(2^8)^3$ possible colors (i.e., about 16.7 million colors) [Landphair and Larsen, 1996]. Expressed in gray scale, 8 bits per pixel are common, permitting 2^8 or 256 gray tones.

Most image processing for pavement analysis uses gray scale rather than color, as shown in the histogram in Figure 2.1. Based upon visual shadowing, pavement cracks thus can be detected. Given that a pixel value of 0 is black and 255 is white, cracked or damaged regions in an image have low pixel values, due to shadowing that is much darker than the surrounding pavement [Ritchie, 1990]. As shown in Fig 2.2, digital image processing steps include data acquisition, digitization, restoration, enhancement, segmentation, and feature extraction and cluster classification [Ritchie, 1990]. The latter two, image segmentation and feature extraction and cluster classification, are the most important processing steps.

Image segmentation is the process of separating potential regions of interest or objects (i.e., distress areas) from their background. The result of segmentation is usually a binary image in which pixels with the value 1 indicate distress areas and pixels with the value 0 are background areas. Edge detection and thresholding are the two principal segmentation approaches. An edge is defined as the boundary between two regions with relatively distinct gray-scale characteristics. Edge-detection techniques segment objects by outlining their boundaries using gray-scale discontinuity information [Koutsopoulos et al., 1993]. This technique can be useful for the identification and quantification of low-severity-level cracking [Li et al., 1991].

Thresholding is a popular method for segmenting gray-scale images. A large number of thresholding algorithms have been proposed for the selection of optimum values [Sahoo et al., 1988]. Major techniques include: 1)histogram thresholding, 2) an entropy-based approach, 3) a relaxation method, and 4) a regression method. Thresholding by regression analysis has been applied widely to pavement analysis, since it provides a simple and efficient computational approach [Chua and Xu, 1994; Georgopoulos et al. 1995; Jitprasithsiri and Lee, 1996; Koutsopoulos and Sanhouri, 1991].

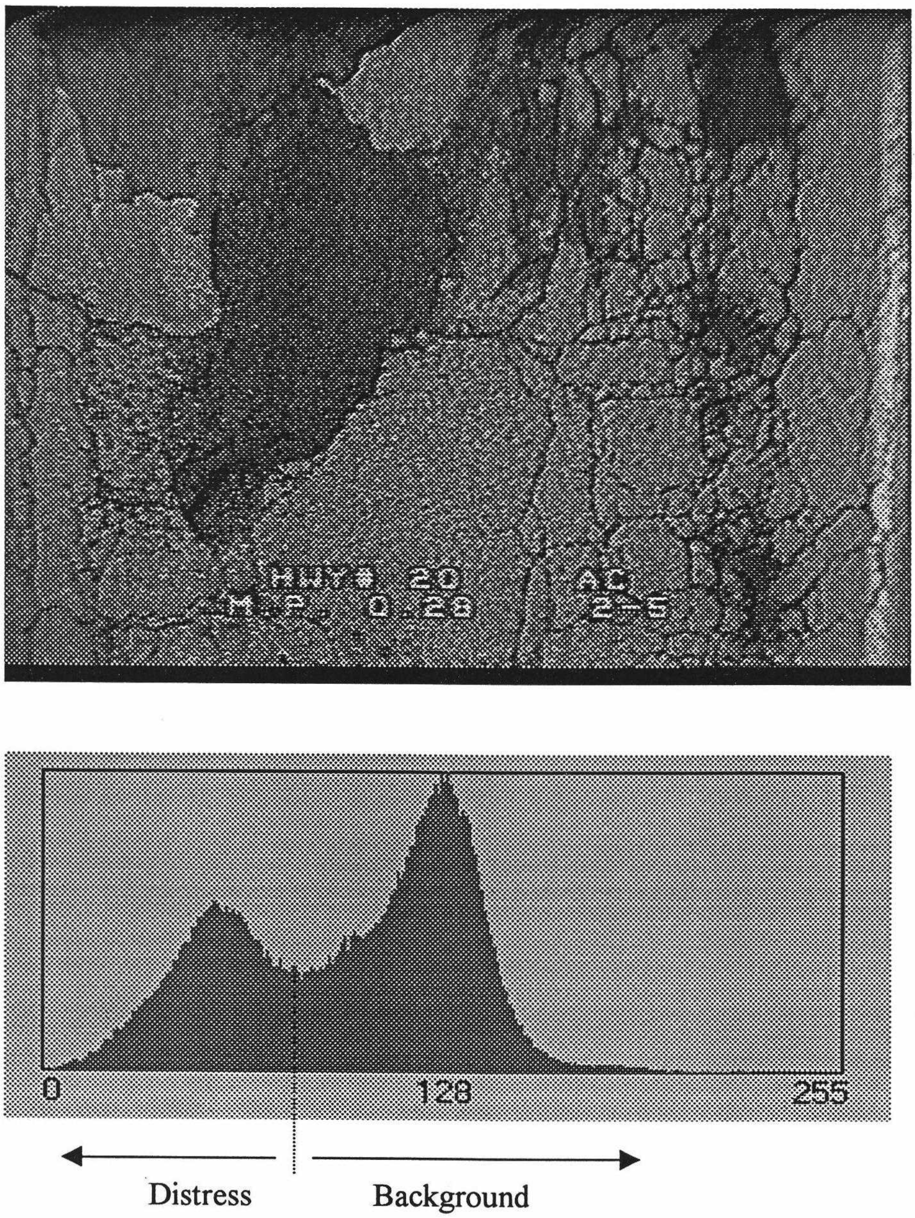

Figure 2.1 Gray-Scale Pavement Image and Histogram.

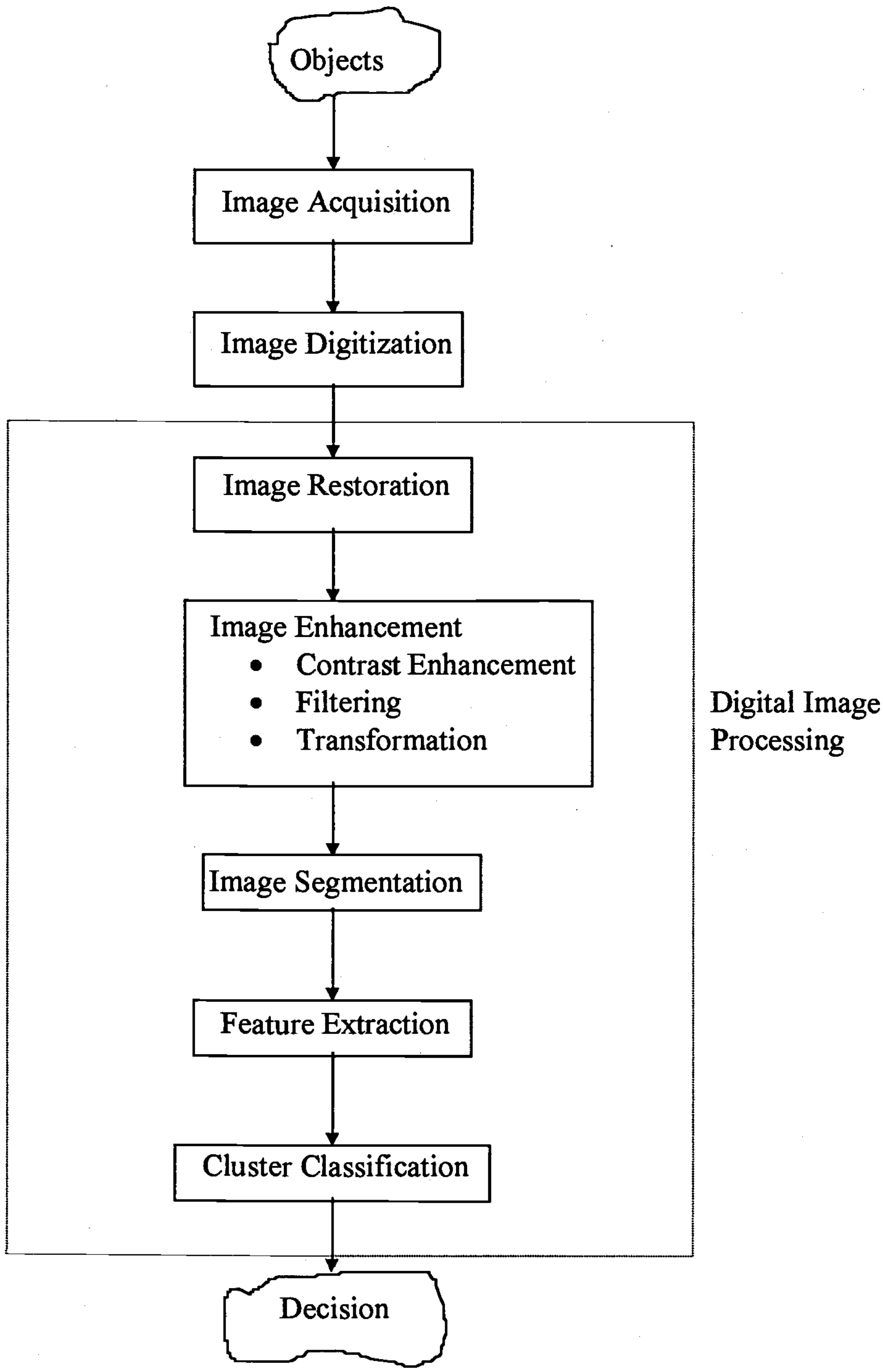

Figure 2.2 Steps for Digital Image Processing [Ritchie, 1990].

The entropy-based approach is also used in pavement image segmentation [Chou and Liau, 1996; Chou et al. 1995]. The entropy of an image is the statistical value of the distributed probability of image gray levels (from 0 to 255). Using this technique, the threshold value is the value to satisfy the maximum sum of object entropy and background entropy. Koutsopoulos et al. [1993] compared four thresholding techniques for pavement image analysis; the Otsu, the Kittler, relaxation, and regression methods. Detail descriptions of these algorithms can be obtained in several references [Abutaleb, 1988; Chou and Liau, 1996; Jitprasithsiri et al., 1996; Kapur et al., 1985; Kittler et al., 1985; Koutsopoulos et al., 1993; Li et al., 1991; Otsu, 1979; Sahoo at al., 1988].

If the segmentation process is accomplished properly, the object within the image should be interpreted by application of a pattern recognition process. The first step is feature extraction. Once an object within the image is found, its geometric and statistical properties, such as area, radius of gyration, aspect ratio, and variance of gray-level values, may be calculated. The features extracted can be then be grouped into three categories based upon position, shape, and size [Fundakowski, 1991].

In cluster classification, applying appropriate guidelines to the information extracted, the object can be classified and identified. The classification goal is to categorize the regions of interest detected in the pavement images, determining their type and severity and quantifying their extent. There are numerous approaches that include the application of statistical methods, including syntactic or structural graph-oriented methods, decision trees incorporating fuzzy logic, pattern associations using neural networks, binary decision trees, and many variants and hybrids of these methods and those discussed above [NCHRP, 1991]. Statistical approaches constitute the most common methods used in the classification of pavement images [Acosta at al., 1994].

Acosta et al. [1995] extracted 19 features from pavement images using developed decision trees to classify 32 distress types for 3 pavement types. Ritchie et al. [1991], Chou et al. [1995] and Chou and Liau [1996] used neural networks to determine the type, severity, and extent of distress from pavement images. Ritchie et al. [1991] divided the image into regions and classified the content of each region, using neural network models as a potential for distress classification of pavement images. Chou et al. [1995] used moment invariants for feature extraction of pavement images, following which a backpropagation neural network was used to classify the type of distress in relation to the moment invariants.

Koutsopoulos and El Sanhouri [1991] applied minimum distance classifiers and a hierarchical classification method based on a decision tree, in which density, angle, inertia ratio, and aspect ratio were the classes for each tree node. Koutsopoulos and Downey [1993] proposed a primitive-based classification method. Similar to the Ritchie approach, images were subdivided into regions that were grouped into primitive classes based upon the physical properties of pixels within each region. Then, at the global level, classification was performed.

Grivas et al. [1994] suggested a mathematical morphology (MM) assessment, analyzing pavement textures on the basis of the geometric features of textural particles such as size, orientation, shape, and overlap among others. By measurement of particle distributions, it was possible to obtain such feature information as area, dimensions, and type of distress.

2.3.3 Human and Computer Image Processing Interactions

The two approaches are used for video-image interpretation are human video-image processing (video logging) and computer video-image processing (digital-image processing). These approaches have been summarized by the author in Figure 2.3. The basic concepts of each process method are similar. However, in video logging, the user selects a frame to evaluate and record distress types, severity, and amounts. Video logging can be accomplished using a distress recording program. In digital image processing, the computer is used to select a frame and to evaluate the selected frame. Several researchers have investigated the use of image processing and pattern recognition techniques to achieve automated pavement distress rating. However, most of automated systems require human intervention to some degree during the image interpretation process, since it has been difficult to achieve a fully automated interpretation process [Smith, 1996].

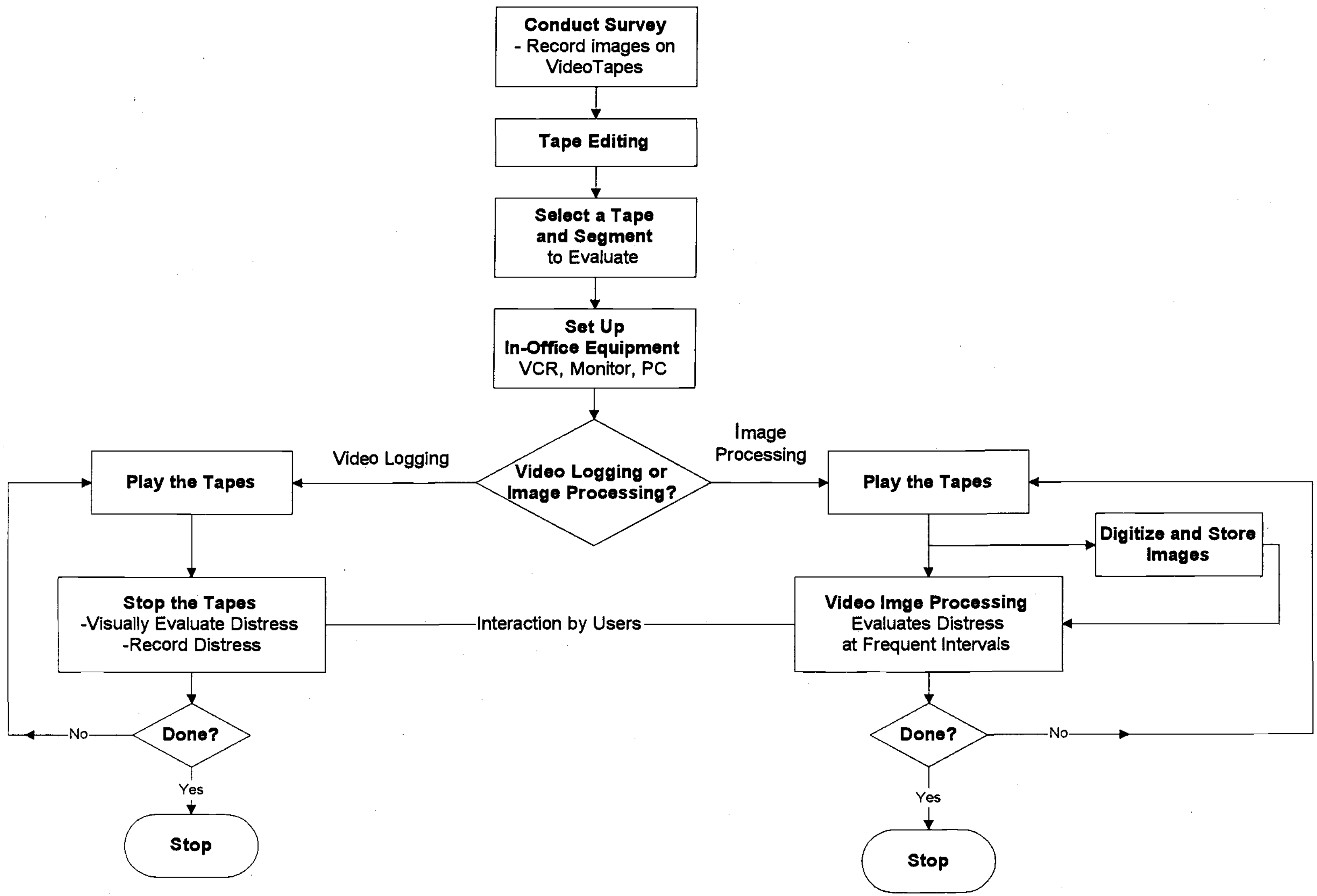

Figure 2.3 Concept Diagram for Video Image Processing.

The two evaluation approaches are interconnected through users or operators, as shown in Figure 2.4. Operators or observers can intervene at any point during the evaluation process. Some vendors collect the data and run the video through automated interpretation, then use trained observers to manually edit the analytical results. These observers make changes at those points it is apparent that the automated interpretation is in error [Smith et al., 1996]. The computer program may not analyze distress correctly in situations such as shadowy images or texture-related distress. Thus, if users do not approve the computer analysis, they can overwrite the evaluation with their own evaluation (Figure 2.4).

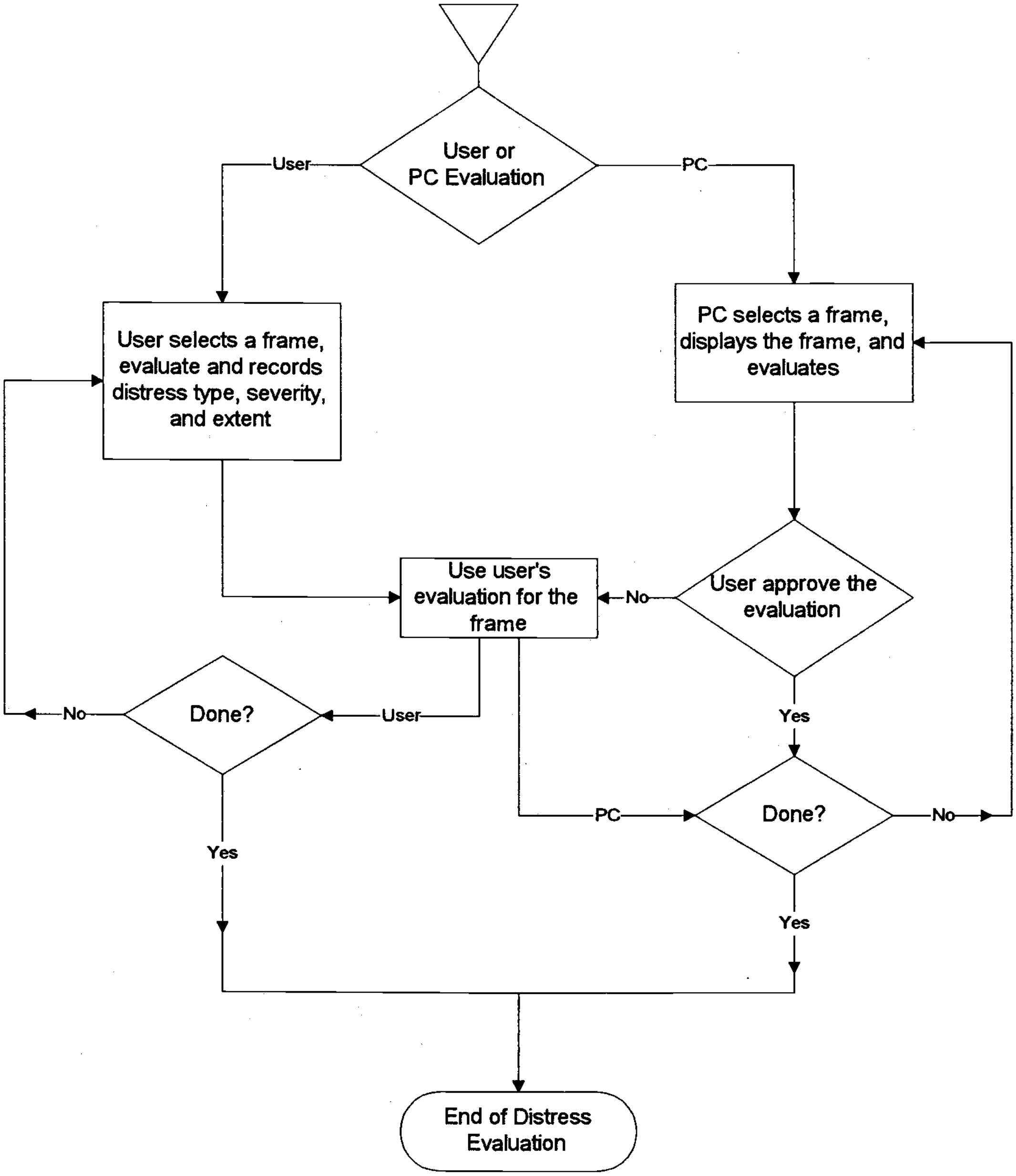

Figure 2.4 Flow Diagram for Distress Evaluation.

3. DEVELOPMENT OF A VIDEO-IMAGING SYSTEM FOR PAVEMENT EVALUATION

The requirements and procedures for the development of a video-imaging system are presented in this chapter.

3.1 Elements of a Pavement-Imaging System

An automated pavement imaging system consists of a number of elements. As shown in Figure 3.1, the activities in a pavement-imaging system include data acquisition, data storage, image processing, reporting condition data, and using data for various applications. For most actions, various combinations of hardware, software, and procedural elements can be used and not all system structures require each of the activities indicated in Figure 3.1 [Haas and McNeil, 1990].

Pavement-imaging begins with data acquisition using various types of image sensors [Ritchie et al., 1991] and supplemental devices, including a camera lens, lighting devices, an on-board monitor, a power generator and converter, a distance measuring instrument, and a character generator among others. These devices are optional, depending upon system characteristics. Once the data are acquired in a field, the image data are saved to proper storage devices and digitized as necessary.

The image data are processed by computer, human interpreter, or a combination of both as described in Chapter 2. The results of image processing may be presented by various types of output devices. Finally, the output results are reported for specific use.

The activities or elements of a pavement imaging system are conducted in different places by various approaches. In real-time or on-board processing, almost all actions are conducted in the survey vehicle. For the in-office processing approach, a number of these elements are conducted in the office.

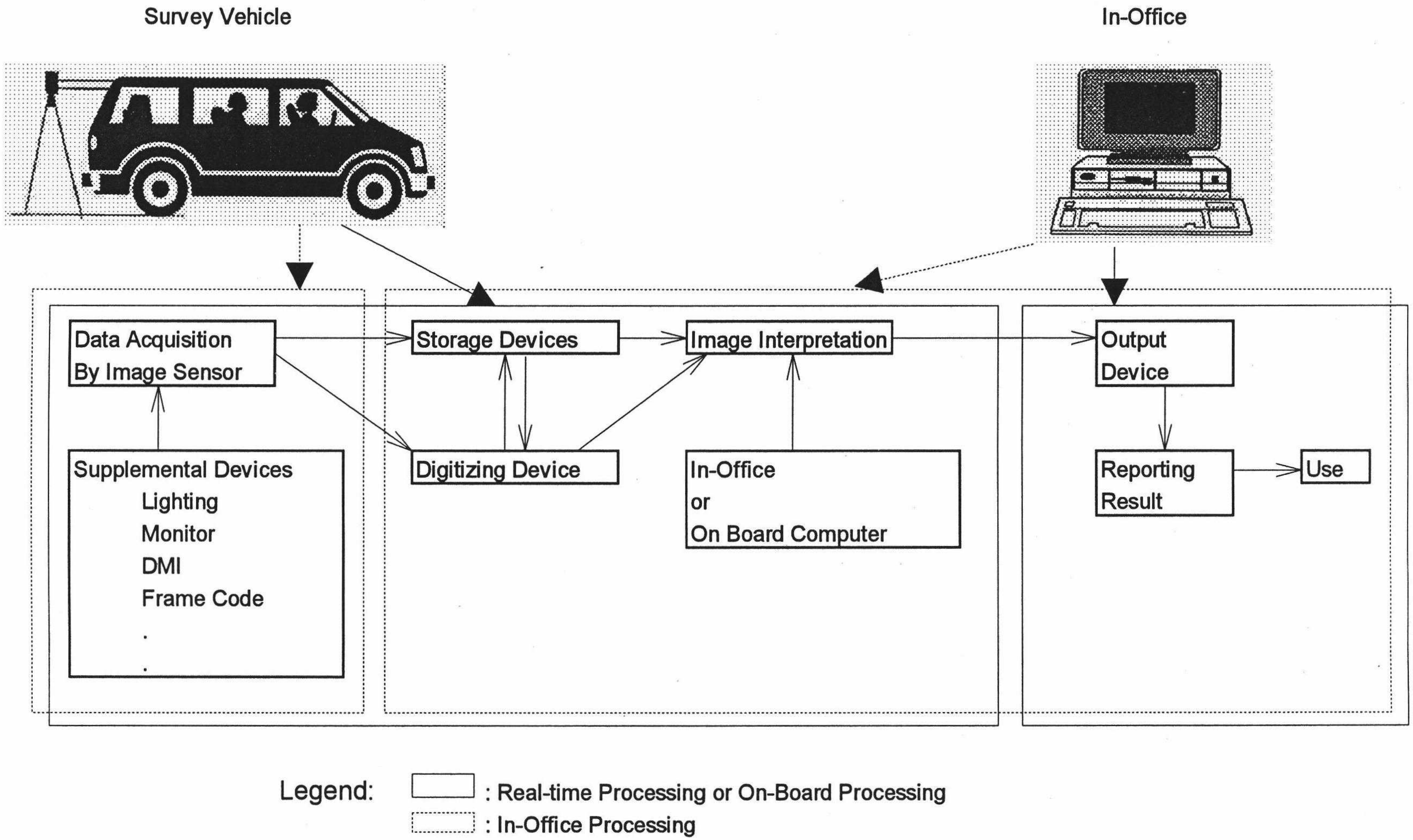

Figure 3.1 Elements of a Pavement Imaging system.

3.2 Processing Procedure

To develop a pavement-imaging system, the choice of a processing procedure is the initial and most fundamental decision affecting all hardware and software system elements. The procedures include real-time processing, on-board processing, and in-office processing, three approaches that are compared in Table 3.1 [Haas and McNeil, 1990].

Table 3.1. Processing Procedure Comparison.

Processing Procedures	Real-time Processing	On-Board Processing	In-Office Processing
Description	Processing of sensor data at almost same time usually on the survey vehicle	Processing of image data on the survey vehicle	Data collection in the field Processing of image data in the office later
Advantages	• Immediate analysis of the image data • Immediate verification for the analysis • Immediate modification of bad data in the field	• Fast analysis and verification for the collected image data • Quick access for analysis	• Minimum hardware is required • Flexible for sampling and processing • In-office equipment can be used for other purposes during off time
Disadvantages	• Special hardware is required • Little flexibility of sampling and processing	• High cost hardware is required • Little flexibility of sampling and processing	• Delayed analysis • Additional cost when bad data are incurred
Requirements	Special computer and processing system	Minimum two computers on board for data collecting and analyzing	Least hardware
System cost	High	High/Medium	Low

Real-time processing is the processing of sensor data almost simultaneous to data acquisition, with processing usually conducted on-board the survey vehicle. This approach permits almost immediate access to the image data analysis as well as verification of the analytical results. However, special hardware and processing systems are required. On-board procedures are the processing of image data on a survey vehicle, providing rapid analytical results from image data. The drawback to both of these approaches is the high cost of both the hardware and processing system.

Using in-office processing, image data are collected in the field. Once the data are acquired, they are processed in an office setting, providing a flexible sampling and processing procedure that requires only minimum hardware resulting in a lower cost system. However, using this approach the analysis of results can be delayed. In addition, when bad data are incurred, additional costs are involved, since prompt modification of bad data is difficult during the time of in-field surveys. For the present investigation, in-office processing was used for system development, since this approach minimized system development costs while providing the flexibility to absorb technological advances. This was the purpose of the present investigation, providing sufficient reason for the selection of this approach.

3.3 Selection of the Video Image-Collection System

Selection of the equipment required to complete an in-vehicle image-collection system is described in this section.

3.3.1 Video Camera

The camera is the basic tool for recording images and the three types of cameras most often considered for pavement data collection include the film camera, the video camera, and the digital camera [Landphair and Larsen, 1996]. For the present investigation, a video camera was selected as the image sensor. The video camera is both simple and popular, providing reasonable picture quality when played back directly from the recorded cassette. Video cameras are also usually less expensive than other cameras.

There are numerous choices in video camera markets. For this investigation, a Burle TC392 high resolution CCD DSP (1/3") color camera was selected. Several features made it the camera of choice. The unit weight of the camera is 0.4 kg (0.9 lbs.) plus lens weight, making it ideal for mounting on a structure extended from the front of a vehicle. It is operated on 12 Volts allowing a direct connection to vehicle battery power. It may also be "genlocked," meaning that it can run with both composite color video and black-burst for external synchronization operations. This enables superimposition of mileage and other highway information over the picture.

The camera has a variable shutter speed that is operated in the auto-shutter mode, allowing automatic changes in shutter speed to control incoming light levels. It can be set at various ranges of electronic shutter speeds to produce a stop-action effect when viewing moving images, greatly increasing the camera's dynamic resolution [Burle Tech. Inc., 1996]. The shutter speed can be set to 1/60, 1/200, 1/2000, 1/20,000, or 1/90,000 and for the present investigation, the camera was operated in the 1/90,000 mode since it was required to capture high speed motion. The camera provides active picture elements of 755H × 494V with 450 lines of horizontal resolution. A wide angle 3.5–8 mm zoom lens was used to allow for covering the width of a lane.

3.3.2 Survey Vehicle and Equipment

Following several trials, an arrangement was made with the Oregon Department of Transportation (ODOT) to use their video log truck as the research survey vehicle. The vehicle is a 1990 GMC Suburban truck, originally designed for state roadway video logging. The vehicle carries several equipment items, including a color camera (Panasonic 300CLE), a video recorder deck (3/4") (Sony VO9800), a distance measuring instrument (DMI, K-5000 Nu-Metrics), a 13-inch video monitor (Sony PVM 1341), a character generator, a keyboard for character input, and a 2,000 Watt power inverter.

The Panasonic camera was installed to take pictures through the windshield of vehicle during roadway video logging. However, since the camera is too heavy and its physical shape is not suitable for camera mounting, it was not used for this research investigation and the Burle camera described in the previous section was selected. The Sony tape deck recorded roadway images in 3/ 4" videotapes with 330 lines of horizontal resolution. The DMI indicated driving distance information on its display panel with a claimed accuracy of ±1 foot per mile [Nu-Metrics, 1996]. However, the experience of ODOT users indicated errors that were larger than the claimed accuracy of ±1 foot per mile. This error needed to be corrected in the field work. The 13-inch monitor displayed camera pictures with 450 lines of horizontal resolution. In turn, the character generator permitted superimposition of DMI and other highway information on the video picture by means of an external video signal. The power inverter was necessary to convert from 12 VDC vehicle battery power to the 120 VAC volts AC which is required to operate the video electronics.

After several meetings with ODOT, it was decided to use their video logging vehicle for this study without major modifications of their current equipment structure. Therefore, the Burle camera was connected directly to the vehicle battery and then linked to other vehicle equipment. Equipment in addition to that listed above was not installed, since the purpose of this investigation was to develop a low cost video imaging system. Figures 3.2 and 3.3 show the exterior and interior of the survey vehicle used in the study.

Figure 3.2 Survey Vehicle and Camera Mounting Devices.

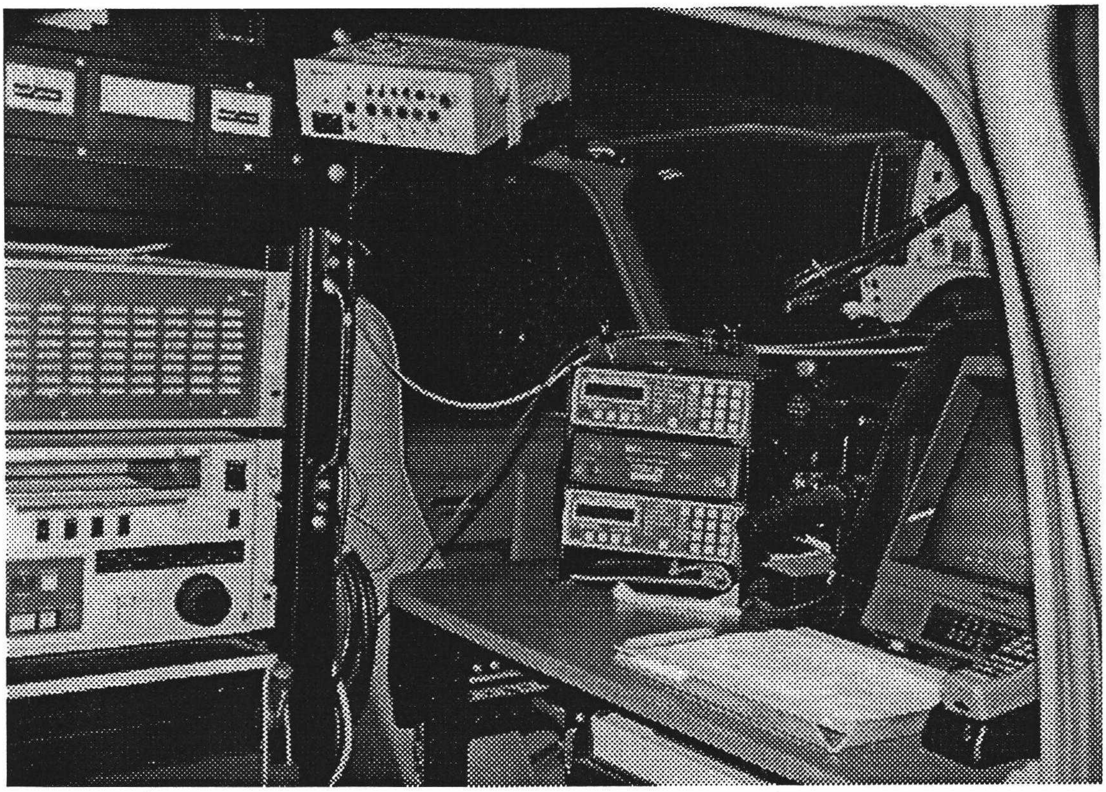

Figure 3.3 Inside of Survey Vehicle.

3.3.3 Survey Vehicle Camera Mounting and Lighting

Camera mounting devices were designed with assistance from the Oregon State University (OSU) Communication Media Center. To mount the video recording camera, four steel mounting bars were installed on the survey vehicle. As shown in Figure 3.4, of a total of four steel mounting bars, two were connected to the light bar of the vehicle and the remaining two were connected to the front bumper. This device was mounted at the front and on the top of the vehicle without visual obstruction for the driver. The camera was thus located at 11 feet above the road surface and 7 feet ahead of the front bumper. The mounting structure was designed to permit adjustment of the camera angle as needed. Finally, the camera was connected by cable to the equipment inside the survey vehicle.

For night surveys, or to reduce shadow effects during daylight surveys, a lighting system was designed, necessitating modification of the previously insufficient vehicular power source. Sufficient lighting was expected to require at least 5,000 Watts light intensity for daytime use and 2,000 Watts light intensity for night surveys. In comparison, the GERPHO device uses a lighting intensity of five 1,000 Watt instruments [Hudson et al., 1987]. Guralnick et al. [1996] designed a prototype of a road inspection vehicle with lighting intensity totaling 4,100 Watts. This high light-intensity requirement would have necessitated installation of an additional electric generator, a type of modification that could not be considered at this stage of the present investigation. Thus, four weak-intensity lights, consisting of four 50 Watt halogen lamps totaling 200 Watts were mounted as shown in Figure 3.4 and then tested. This lighting intensity was expected to be insufficient for purposes of the present investigation. However, the lighting system was tested as an experiment for consideration of future system development.

3.3.4 Image Data Recording and Storage

For data recording and storage, two types of image data formats, digital and analog, were considered. Pavement image data can be stored in digital format, which would have been convenient for digital image processing.

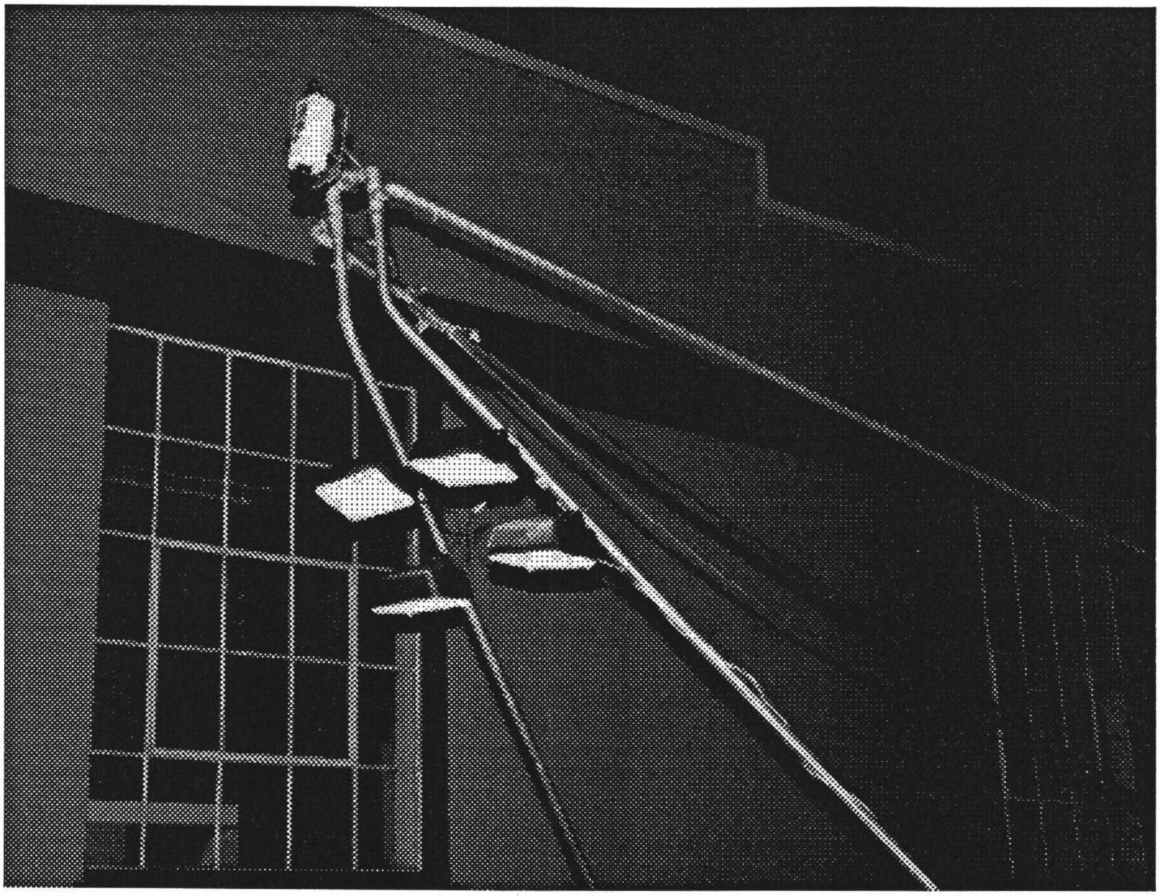

Figure 3.4 Camera Mounting and Lighting.

However, digital images usually require enormous amounts of storage space. As noted in section 3.3.2, the pavement images were recorded and stored on videotape as 3/4" analog signals, and, subsequently converted to 1/2" videotape. Using videotape allowed storage of more information without use of a dedicated image storage device. Stored analog data could then be played back for either visual inspection or digitization.

However, the greatest limitation of videotape is low image resolution. An average 1/2" VHS videotape for home use provides only 230 to 260 lines of horizontal resolution, which is a considerable drop from the original image resolution (i.e., Video Camera at 450 lines, 3/4" videotape at 330 lines). However, even in view of low-image resolution, videotape provides reasonable picture quality for the nature of the present research undertaking. Videotape is old technology, but continues to remain the most popular image data-storage technique. Many automatic distress evaluation systems continue to save images on videotape. Therefore, in this research, video image data were stored on videotape and selected images are subsequently digitized and saved on the computer hard drive as necessary.

3.3.5 System Organization for Video-Image Collection

Based on the selected elements, the image-collection system was organized as shown in Figure 3.5.

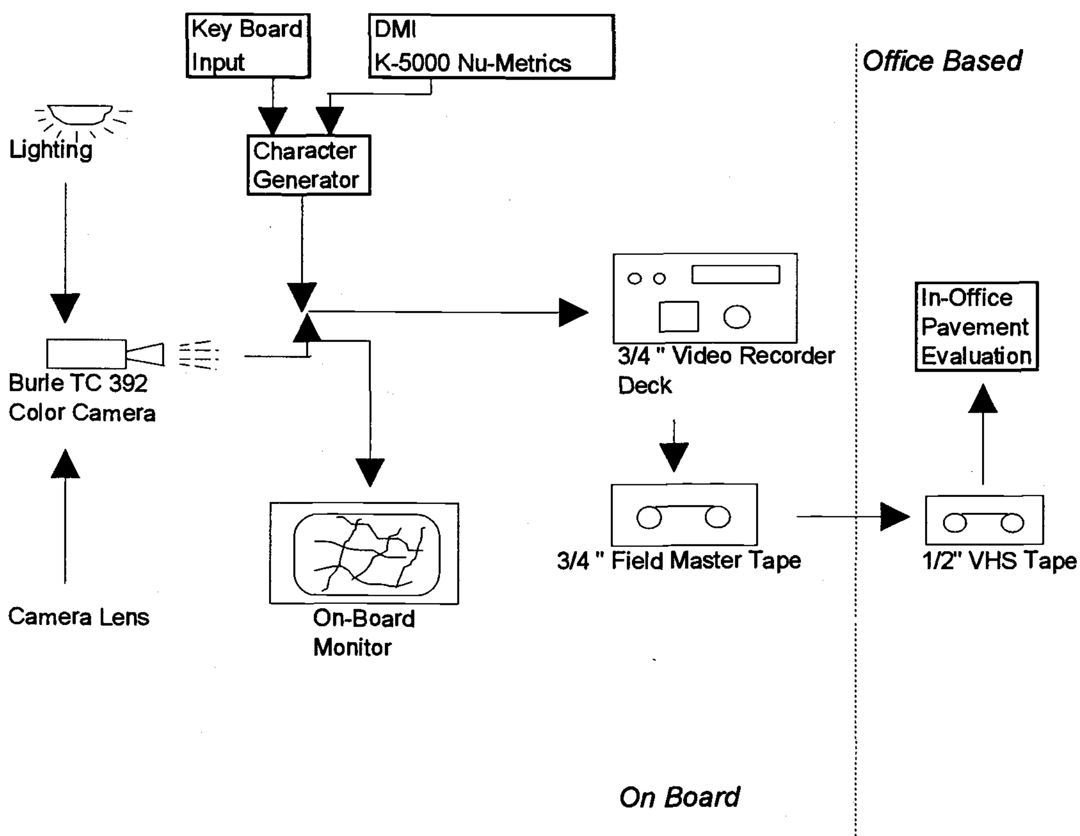

Figure 3.5 System Architecture for Video Image Collection.

3.4 In-Office System

The in-office system was designed to provide a desktop image-retrieval system for collected video data. The several devices, as assembled, are described in the diagram shown in Figure 3.6.

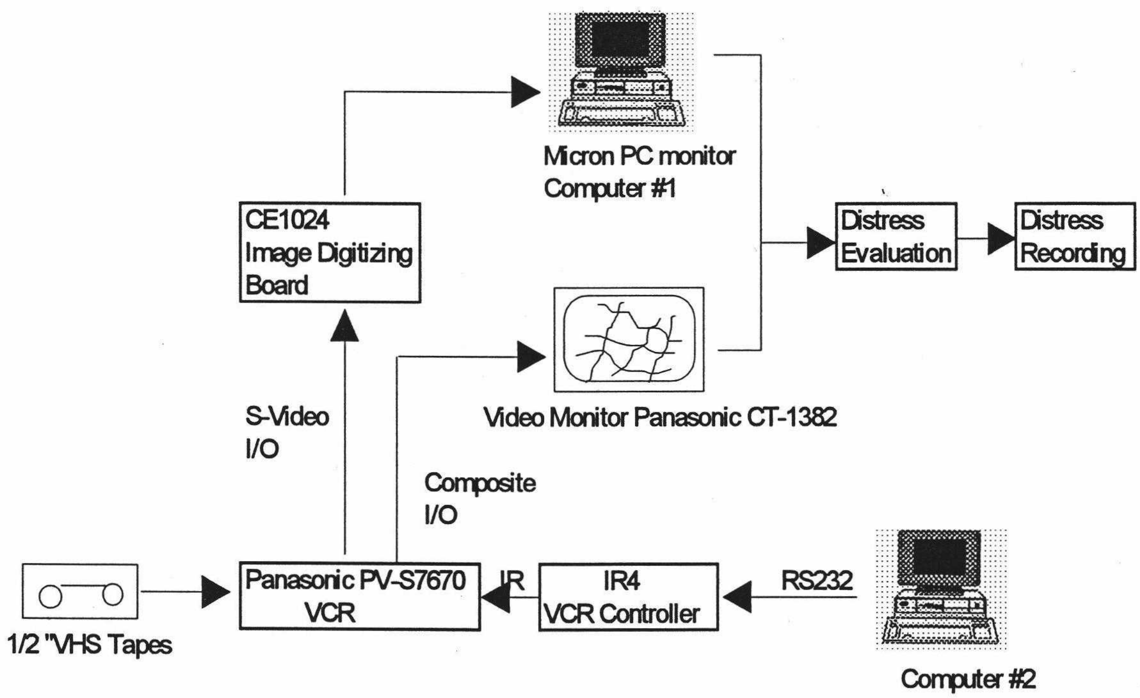

Figure 3.6 Diagram of In-Office System.

Videotapes (3/4") taken from field video surveys were converted to a 1/2" VHS videotape format for processing in-office using an IR4 infrared controller (Akman, Inc.) with the VHS tape player. The controller was designed for use with all types of infrared input devices (e.g., the VCR, CD players, or light switches). The IR4 controller captures infrared codes from remote IR units and stores them directly into the computer, to which it was connected through an RS-232 interface. Editing software provided with the IR controller allows the user to modify and control the program [Akman, 1995].

For a videotape player, the Panasonic PV-S7670, a home-use type, 4-head VCR was selected following several trials. Video tapes could be displayed on two different monitors: the 14" Panasonic CT-1382 video monitor and the Micron 17" PC monitor. The video monitor displayed analog color images, connected by composite input/output to the VCR. The PC monitor displayed digital gray-scale images, connected by S-Video input/output to the VCR. These two types of displays were thus complementary, serving to supplement the weak points each would have displayed had they been operated individually. This approach enhanced system capability to display distress detection. For example, some cracks may be less clearly displayed in analog images, whereas they will be clearly displayed in digital images. Also, shadow effects are hard to distinguish in digital images, whereas they may be seen easily analog images.

The video images shown by the PC monitor were displayed in digital format using an image-digitizing board. A high-speed analog-to-digital converter, known as a frame grabber or image-capturing board, digitized the data and stored them in a buffer memory. Video digitizing provided a convenient low-cost alternative, but it also exhibited generally poor spatial resolutions and often unrepeatable radiometric or gray-scale resolutions [Clarke, 1996].

Image-processing cards are available in a wide range of prices and capabilities. For the present investigation, the ComputerEyes/1024 manufactured by Digital Vision Inc. was used. This frame grabber provides inexpensive acquisition of real-world images in full color or black-and-white from any standard video source [Digital Vision Inc., 1995]. The images can be displayed by computer monitor or can be saved in computer hard drives, and then edited by image-processing software for further analysis. Also, images can be saved in a moving file format that may useful for future information retrieval.

3.5 System Operation and Distress Evaluation

The proposed system was operated to conduct distress evaluations of video images. The operation process is shown in Figure 3.7. Video logging was performed by examining two screens. As shown, once the in-office system was set up, appropriate pavement sections were selected. The corresponding milepoints for required management sections were searched by VCR operation. The video survey began at corresponding mileposts using the VCR controller. The most useful VCR functions for this video survey were variable slow speed, pause, and frame advance. Using combined function operations, it was possible to capture distress objects and to determine distress types.

Operators were also able to determine the severity of the distress by placing a cursor, which corresponds to 3/4 " width, on images of 640 × 480 pixels. A grid equivalent to one-foot square was then used to overlay the screen to aid in estimating distress extents. It was possible to operate the VCR forward and reverse as additional inspection was required for selected management sections. This process was continued until the end of each management section.

The proposed system can be used for variable types of management systems and distress definitions. However, for specific uses of different systems, the requirements of system operation may be different. For the present investigation, two different PMSs were used for evaluation, as described in Chapter 5.

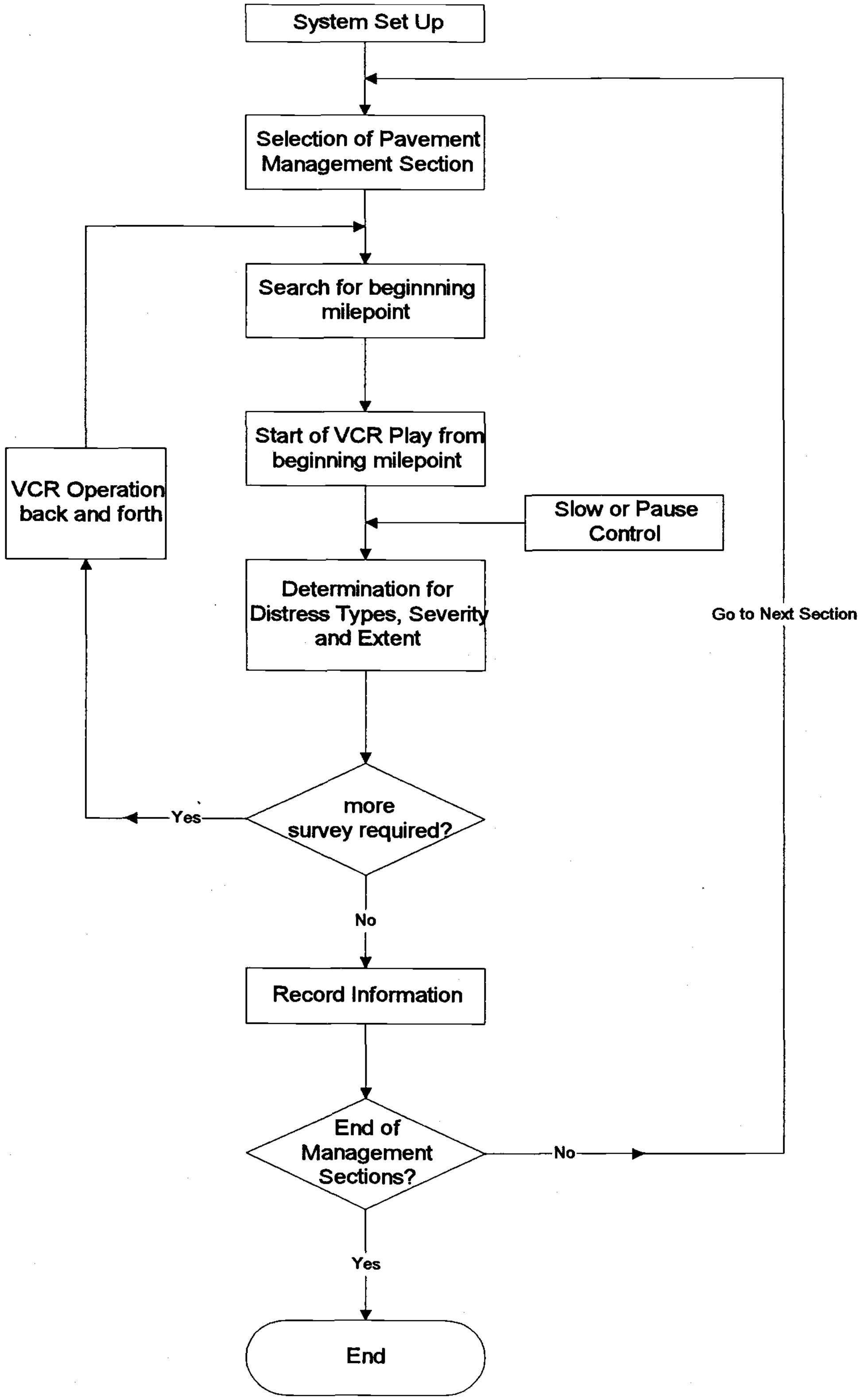

Figure 3.7 System Operation Process.

4. FIELD VIDEO TEST IMPLEMENTATION

4.1 Test Overview

A field test was performed in March, 1997 using the ODOT video-log vehicle. There were several variables to be considered for data collection. As shown in Table 4.1, these variables included test area, pavement types, driving speeds, camera angles, lighting, survey times, and pavement conditions. The test area includes sections of interstate highway, state highway, and urban street. Each test area exhibits different traffic volume, construction and maintenance history, functional definition, and management philosophy.

Table 4.1 Variables Considered in Test Plan.

Variables for Test	A	B	C
Test Area	Interstate Highway (I-5)	State Highway (HW34, 20, 99W)	Urban Street (Corvallis, Albany)
Pavement Type	Asphalt, PCC	Asphalt, PCC	Asphalt, PCC
Driving Speed (mph)	High: 65 mph, Speed Limit Low: 50	High: 55 Low: 40	Speed limit (25,35)
Camera Angle	Perpendicular, 30 degree angle	Perpendicular, 30 degree angle	Perpendicular, 30 degree angle
Lighting	Yes, No	Yes, No	Yes, No
Survey time	Day, Night	Day, Night	Day, Night
Pavement Condition	Dry, Wet	Dry, Wet	Dry, Wet

Pavement type was considered as a test variable, since video images show different characteristics by pavement type. In general, asphalt-surfaced pavements are more challenging than concrete pavements for reason of unclear contrasts between distressed areas and their background. Also, on PCC pavements, surface tining posed a substantial problem to video imaging. [Fundakowski et al., 1991].

Driving speed is an important issue with many of the automatic pavement evaluation systems. Obviously, video images taken from slow moving vehicles show better picture quality than images taken from fast moving vehicles. However, in real situations, the survey vehicle must be operated without interrupting the traffic flow. In tests for the present investigation, the vehicle speed was set at either (1) high speed, at the speed limit of the specific highway, or at (2) low speed, from 15 mph to the highway speed limit.

The camera angle was another important variable. Many developed systems established camera angles as normal to the road surface or as an angle, or as a combination of both using multiple cameras. The issue "which angle is best?" was not thoroughly examined during previous research projects. Both cases (normal and angled) provided considerable distortion of the images.

Pavement images can be affected significantly by lighting conditions. Even during same-day surveys, images can be affected by sunlight directions. Thus, controlled artificial lighting appeared to be useful to minimize the number of missed distress detections [El-Korchi et al., 1991]. A lighting system was thus designed as an experimental part of the present study as also described in section 3.3.3.

Pavement condition was also an important variable. Most previous investigations have focused on the analysis of dry pavement. However, wet ground conditions without standing water on the pavement surface on a cloudy day would be an ideal situation for video image collection. In this situation, the noise and shadow effect in the image can be almost wholly removed. Chou and Liau [1996] reported the case of pictures taken when it stopped raining and the ground was wet, but without water ponding, providing the best results for image analysis. They claimed that, in this case, the whole distress picture remains in the binary image, but the image had almost no noise.

After several discussions with ODOT, a loop-type test was selected to maintain efficiency and to collect the appropriate amount of pavement information. A test route was selected, as shown in Figure 4.1, to cover various pavement features. This route included:

Corvallis ⟶ HW34 ⟶ I5 to North (Exit 228-238) ⟶
I5 to South ⟶ Exit234 ⟶ Albany ⟶ HW20 ⟶ Granger Ave. ⟶
HW99W ⟶ Corvallis ⟶ Walnut PCC ⟶ Walnut AC ⟶
Harrison ⟶ Monroe.

The total length of the test loop was 43.48 miles. It was planned to perform the test on the outside lane or the truck lane only, since it was the most severely distressed.

As shown in Table 4.2, this loop included 11 large sections containing either asphalt concrete pavement, jointed concrete pavement, or continuous reinforced concrete pavements. In total, 15 runs of the loop were planned to cover various test variables. A detailed description of the 15 test loops is given in Table 4.3.

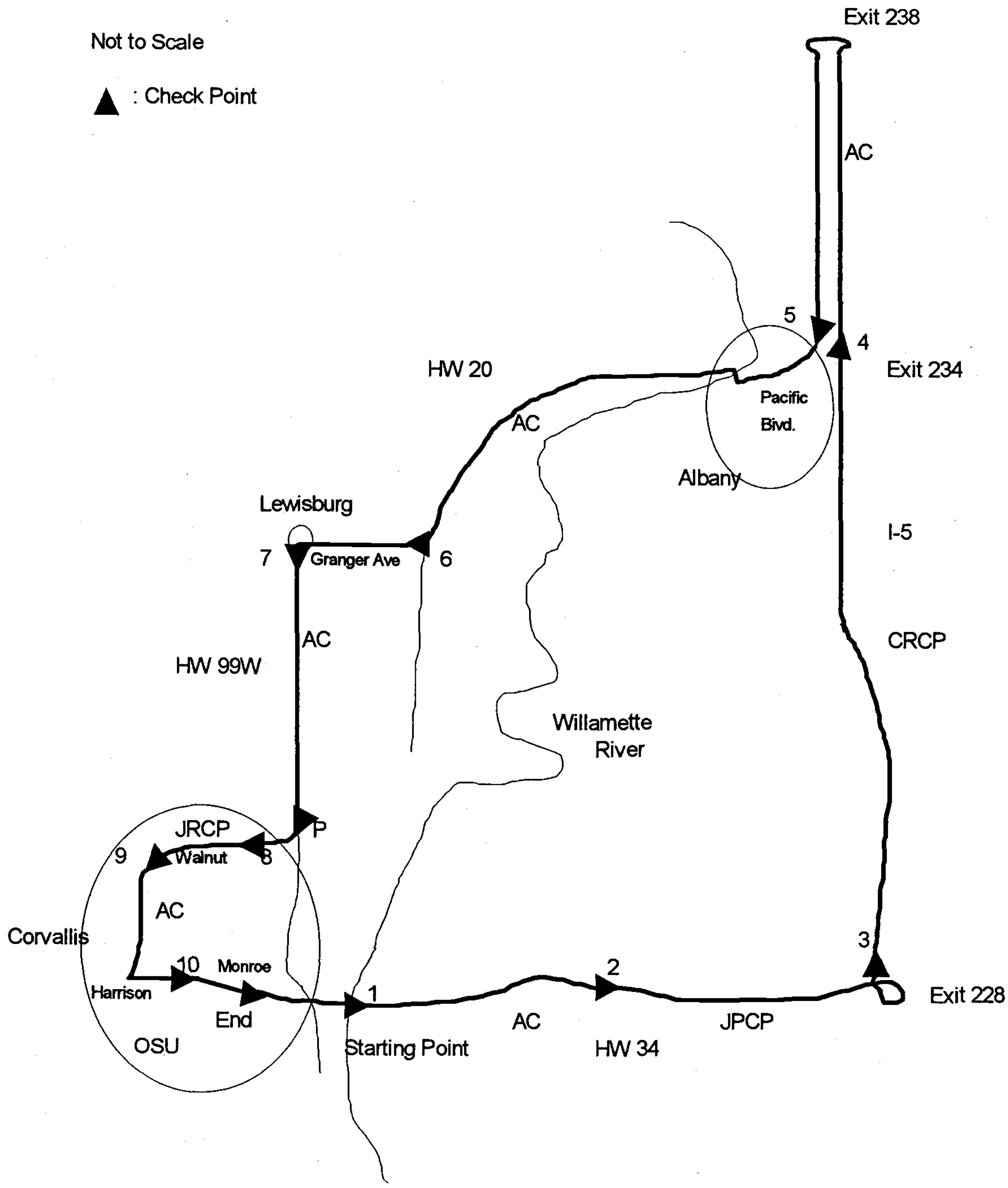

Figure 4.1 Loop Test Route.

Table 4.2 Test Sections.

Section Number	Road Name	Description	Pavement Type	Length in Video tapes (miles)	Real Mile Points	Note
1	HW34	East bound From end of bridge to end of AC section	AC	6.20	0.1 - 6.3 (East)	
2	HW34	East bound From beginning of PCC section to I-5 exit 228	JPCP	4.08	6.3 - 10.0 (East)	Exit area is not included
3	I-5	North bound From to end of PCC section	CRCP	6.38	228.3 - 234.7 (North)	
4	I-5	North bound and exit 238, and then south bound From beginning of AC section to exit 234	AC	8.34	234.7 - 238.5 (North) 238.2 - 234.1 (South)	Exit area is not included
5-1	HW99E	Pacific Blvd.	AC	2.09		Albany
5-2	HW20	West bound From exit 234 to Granger Ave.	AC	5.48		
6	Granger Ave.	West bound From HW 20 to HW 99W	AC	2.38	N/A	

Table 4.2 Test Sections (Continued).

Section Number	Road Name	Description	Pavement Type	Length in Video tapes (miles)	Real Mile Points	Note
7	HW 99W	South bound From Granger Ave. to Walnut Blvd, Corvallis	AC	2.46	78.9 - 81.4 (South)	
8	Walnut Blvd.	West bound PCC Section of Walnut Blvd	JRCP	0.89	N/A	Corvallis
9	Walnut Blvd. Harrison St.	AC section of Walnut - Harrison to 29th St.	AC	4.27	N/A	Corvallis
10	Monroe St.	East bound Anold Wy - Monroe to 9th St.	AC	0.91	N/A	Corvallis
Total				43.48		

Table 4.3 Loop Test.

Loop Number	Vehicle Speed	Camera Angle	Lighting	Day, Night	Pavement Condition	Test Date
1	High	Perpendicular	No	Day	Dry	3/13
2	Low	Perpendicular	No	Day	Dry	3/13
3	High	Perpendicular	Yes	Day	Dry	3/24
4	Low	Perpendicular	Yes	Day	Dry	N/A
5	High	30 degree Angle	No	Day	Dry	3/13
6	Low	30 degree Angle	No	Day	Dry	3/13
7	High	30 degree Angle	Yes	Day	Dry	3/24
8	Low	30 degree Angle	Yes	Day	Dry	N/A
9	High	Perpendicular	Yes	Night	Dry	3/24
10	Low	Perpendicular	Yes	Night	Dry	3/24
11	High	30 degree Angle	Yes	Night	Dry	3/24
12	Low	30 degree Angle	Yes	Night	Dry	3/25
13	High	30 degree Angle	No	Day	Wet	3/13
14	High	30 degree Angle	Yes	Night	Wet	N/A
15	High	30 degree Angle	Yes	Day	Wet	N/A

Note: High Speed
- I-5: 65mph
- HW: 55mph
- Street: speed limit

Low Speed
- I-5: 50mph
- HW: 40mph
- Street: speed limit

4.2. Test Implementation

Before the field test was conducted, a pilot test run was performed using the survey vehicle and equipment. The purpose of the pilot test was to resolve the following issues:

- compatibility of mounting device with the van equipment,
- compatibility of camera connection with existing equipment,
- available image size and resolution,
- camera shutter speed,
- vehicle speed,
- camera angle, and
- camera vibration during driving.

The pilot tests were performed on two days (March 4 and March 12, 1997). It was determined that the mounting devices had strength sufficient to support the video camera. The camera allowed adjustment of image size to extend coverage to 13 feet width. However, large-sized images show large image distortions. Therefore, to minimize distortion and to maximize coverage, a 10-foot width was selected as the most suitable image size using a single camera, covering almost one lane width, including the both wheel paths.

To minimize blurring during high speed running, the camera was set at its maximum shutter speed (1/90,000-sec). Since the camera was operated in an auto-shutter mode, when the camera detected high-speed motions, it kicks the shutter speed up to the full level automatically. During the pilot tests, it was demonstrated that the maximum shutter speed setting was sufficient to prevent blurring even at high speeds. The survey vehicle could drive up to 65 mph and continue to generate acceptable picture quality. Vibration was not a serious problem during testing, since the camera had a vibration damping function. Also, two types of camera angles were tested: perpendicular and 30 degrees from perpendicular.

Field testing was conducted over three days (March 13, 24, and 25, 1977). Loop number 13 was the first run on March 13. During the early morning run, it was assumed that the pavement would be in a wet condition, since it had rained heavily during the previous night. Thus, the first run was designated as high speed, angled camera, without lighting, and wet condition. For the following run, tests of loops number 5 and 6 were performed in the morning. The weather condition was partly cloudy, resulting in the frequent occurrence of the shadow. The test of loops number 1 and 2 were conducted on the same day during the afternoon. However, a light rain had fallen prior to the afternoon testing.

The lighting system was installed on the survey vehicle on March 23. With the lighting system, night runs of loops number 9, 10, and 11 were performed during the night of March 24. Also, on the same day, day runs with lighting were performed (numbers 3 and 7). The weather was also partly cloudy with slight rain during testing. Finally, the testing of loop number 12 was conducted during the following night.

During the test, it was determined not to run certain of the test loops. Since the lighting system intensity was fairly weak, no substantial differences in video imaging resulted between daytime surveys either with or without lighting. Therefore, loops 4 and 8 were not tested. Also, since it was hard to control ideal wet pavement conditions, loops 14 and 15 were not tested.

As a result of field testing, 22 videotapes (11 tapes of each 3/4" master and 1/2" VHS) were produced. For each test loop, one master tape was produced. The recorded 3/4" master tapes were edited in the ODOT video lab where the masters were converted to 1/2" VHS for processing in-office.

The tapes were displayed by VCR on the TV and computer monitors. In Figure 4.2, a typical display is shown. The screen displays information as it was created by the character generator and DMI. The image contains information about road name, location (milepost), pavement type, loop (circuit) number, and section number.

In general, the daytime surveys provided acceptable results to allow performance of the image-interpretation process. The quality of images was sufficiently clear to detect cracks. However, as was expected, the night survey results were not successful. Since the light source was not sufficiently intense, there was considerable blurring in the images. Thus, it was decided that the videotapes from the night surveys could not be used for further image processing. Therefore, seven of the eleven videotapes were used for video image interpretation, including: loop numbers 1, 2, 3, 5, 6, 7, and 13.

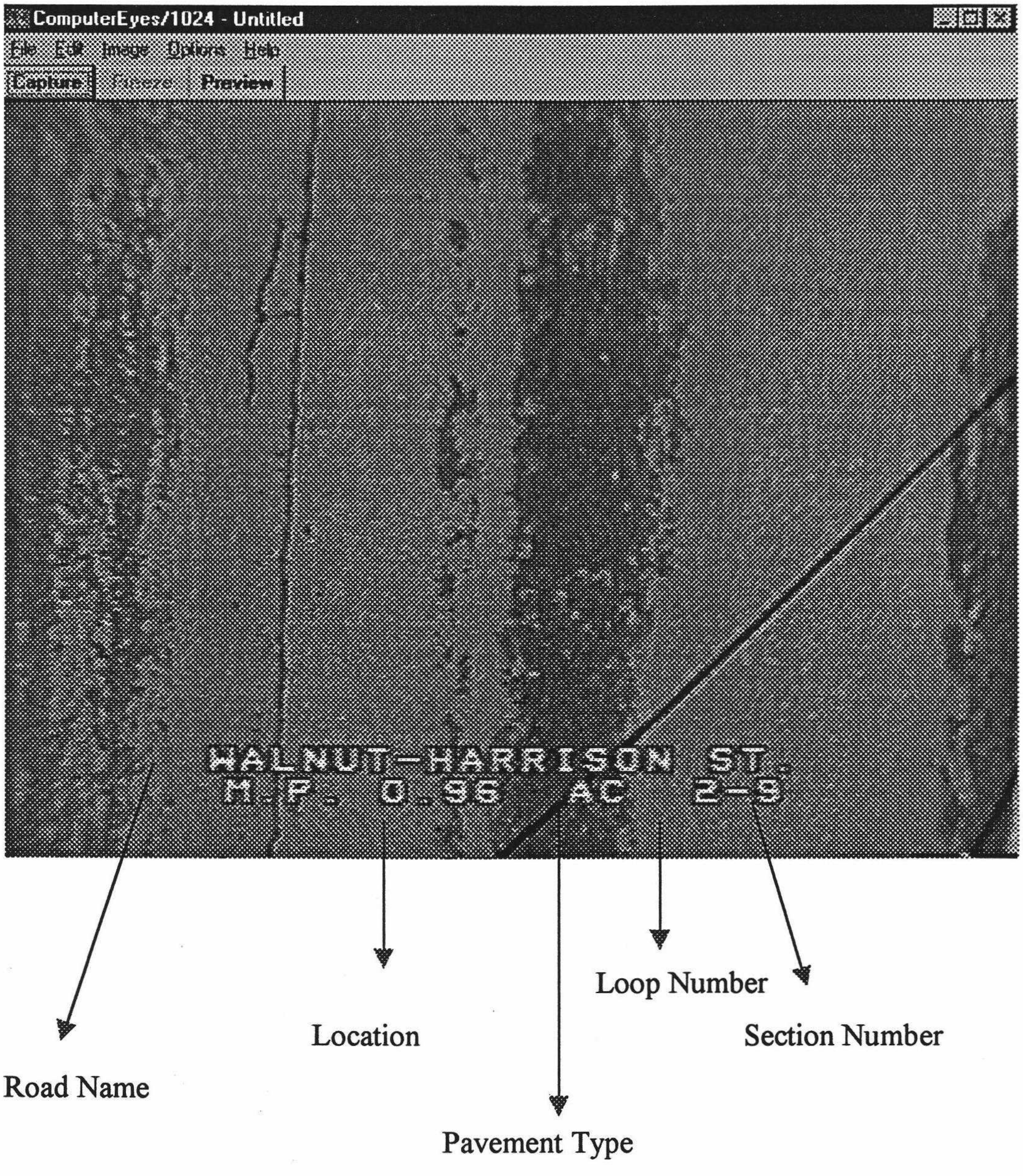

Figure 4.2 Screen Display for a Pavement Video Image.

5. SYSTEM EVALUATION PROCESS

5.1 Evaluation Process Overview

In order to evaluate the performance of the proposed video imaging system, a systematic validation process is needed. The validation process includes video-image inspection, manual field distress inspection, digital image analysis, and performance evaluation. The validation process is described in Figure 5.1.

As described in Chapter 4, field video testing was completed for 11 large test sections that included different pavement types in the various test areas. For system evaluation, samples from each of 11 large test sections were selected as representative areas for a detailed distress inspection. As shown in Table 5.1, 107 pavement sections of 0.1 mile each (total: 10.7 miles) were selected from the video-test loop of 43.48 miles. This selection included 79 sections of asphalt concrete (AC), 18 sections of jointed concrete pavement, and 10 sections of continuous reinforced concrete pavement (CRCP). To select the inspection sections, the issues described below were considered:

- representative distress types and severity for overall test sections,
- safe pavement shoulder space for walking surveys,
- no maintenance work since video image collection, and
- availability of mileposts to match video distance information.

For the field surveys, the pavement sections were sectionalized into sections of one-tenth mile in length, using a 100-foot tape as a measure from selected highway mileposts. For subsequent video inspection, it was necessary to convert the video mileage distance information to real mileage information. This was performed by calculating distance information using a Global Positioning System (GPS) technique, as explained in the following section.

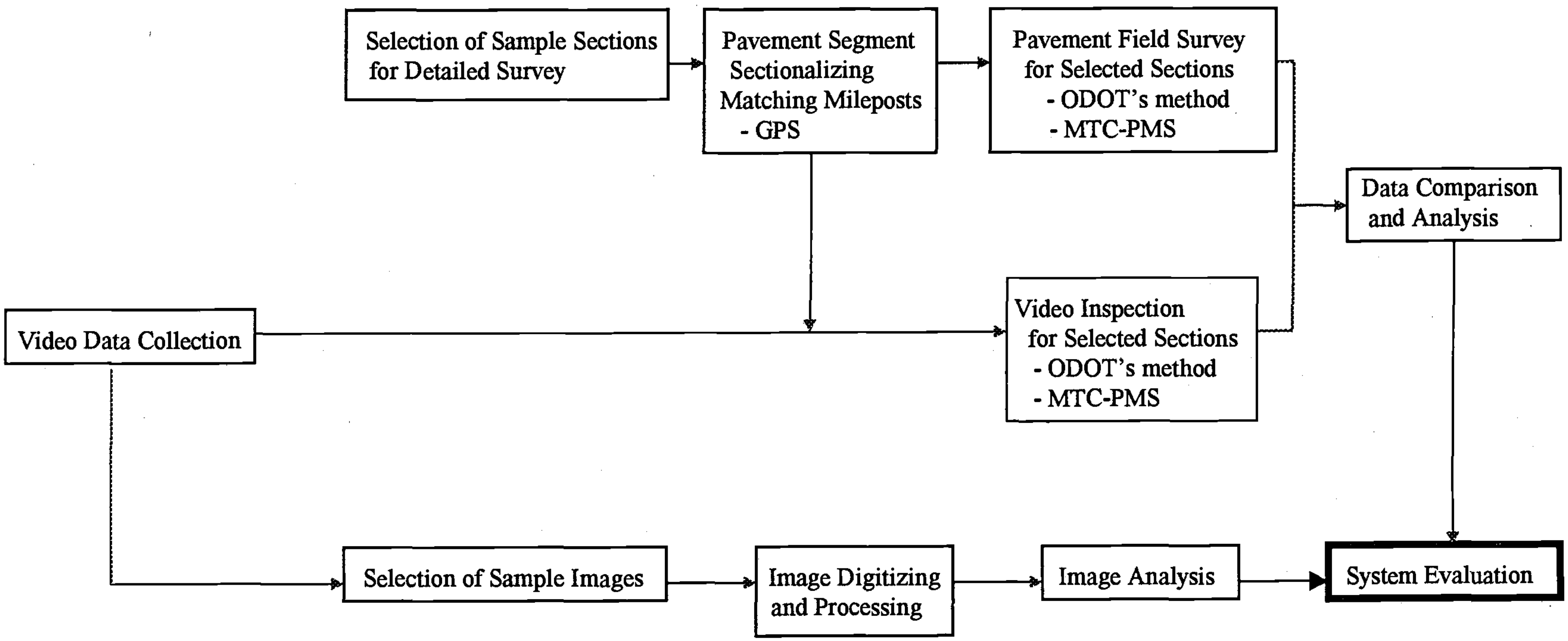

Figure 5.1 System Evaluation Process.

Table 5.1 Video and Field Inspection Plan.

Road Name	Pavement Type	Length in Video Tape (miles)	Sample Sections		Inspection Plan					
					ODOT			MTC-PMS		
			# of sections (Miles)	Mile Post	Field		Video	Field		Video
					#1	#2		#1	#2	
HW34	AC	6.2	10(1)	3.0-4.0	K	ODOT	K			
HW34	JPCP	4.08	10(1)	6.5 - 7.5	K	ODOT	K			
I-5	CRCP	6.38	10(1)	228.7-229.7	K	ODOT	K			
I-5	AC	8.34	10(1)	234.8-235.5, 237-237.3	K	ODOT	K			
HW99E	AC	2.4	10(1)	0.4 - 1.4	K	ODOT*	K	K	F	K
HW20	AC	5.57	10(1)	10.0 - 9.0	K	ODOT*	K	K	F	K
Granger Av.	AC	2.38	10(1)	0.5 - 1.5	K	ODOT*	K	K	F	K
HW99W	AC	2.46	10(1)	79.0 - 80.0	K	ODOT*	K	K	F	K
Walnut	JRCP	0.89	8(0.8)	0.0 - 0.8	K	ODOT*	K	K	F	K
Walnut-Har.	AC	4.27	10(1)	0.0 - 1.0	K	ODOT*	K	K	F	K
Monroe	AC	0.91	9(0.91)	0.0 - 0.91	K	ODOT*	K	K	F	K
Total:		43.48 miles	107 sections (10.71 miles)							

K: Arthur ODOT: ODOT's Survey Crew
F: Dr. Fautina Apostolova, Visiting Scholar to OSU
* : Survey was performed, but data is not available.
[shaded]: Survey was not performed.

Detailed field and video-distress inspections were conducted for each of the selected sample sections, using the ODOT and MTC-PMS distress-survey techniques. Video data collected through application of the proposed video-imaging system were received video-distress inspection for selected sections. An in-office video inspection was performed by the author using the developed in-office system. The ODOT approach was applied to all of the 107 selected pavement sections. However, due to limited resources the MTC-PMS technique was not applied to either the Interstate Highway 5 (I-5) sections or the State Highway 34 (HW34) sections. Also, because that the MTC evaluation technique is usually applied to the streets of cities and counties [Sachs and Smith, 1994], it was not applied to I-5 or HW34 sections.

The author, the ODOT distress-survey team, and another surveyor conducted a field-distress survey for the selected pavement sections. Two different surveys were performed independently of the field-distress surveys. The first field survey was performed by the author and is indicated as Field #1 in Table 5.1. The ODOT survey crews performed those field surveys indicated as Field #2 in Table 5.1. For the sections of highways I-5 and 34, field surveys were performed as a part of the ODOT annual pavement condition survey. The remaining highway sections were surveyed by ODOT crews on September 5, 1997. However, the inspection data for these latter sections were not processed as the data file was lost due to a technical problem. For reason of limited resources and the technical nature of the problem, this data could not be recovered. Thus, the ODOT survey data for these sections were not included in the data analysis. For the MTC-PMS approach, a second field survey was performed by another surveyor[1] on September 12, 1997. The collected field and video data were processed in-office for the system performance evaluation. The performance results generated by proposed video-image system were compared to a distress inventory for the same pavement sections generated by means of a visual field inspection for the two approaches.

From the videotapes, digital images were acquired and then examined by means of image analysis. Since there were seven different test videotapes to process, the images in

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[1] Performed by Dr. Fantina Apostolova, visiting scholar to OSU.

the same locations for each test loop video were digitized using the ComputerEyes1024 video-capturing card.

A total of 324 of pavement digital images from 50 locations were collected and analyzed. The PicCrack pavement analysis program, developed at the University of Utah, was used for image analysis [Jitprasithsiri, 1996].

Using the pavement distress data collected through video and field inspection, condition index values were calculated. The condition index values are a function of the distress type, severity, and quantity present in the pavement surface. In the ODOT method, the overall index and other indices related to distress types (e.g., the rut index, the fatigue index, the raveling index, the patching index, and the non-load crack index) were computed for each 0.1 mile pavement segment. The calculated index values were then compared for analysis. However, the rut index was not considered for analysis, since video images pose restrictive limitations upon the evaluation of depth-related types of distress. For the MTC-PMS method, a pavement condition index (PCI) was used to represent pavement condition. PCI values between the video and field surveys for each 0.1 mile section were then compared. The PCI deduct-value measurements for each distress category were compared for system performance evaluation. However, though depth-related distress was recorded during the survey, this stress type was not accounted for in the calculation.

5.2. GPS Work for Mileage Conversion

The acquisition of accurate distance information is an important issue for video logging, since the location information for both the video inspection data and the field survey data must be matched. Thus, the correct placement of video images in real fields must be assured. Even if pavement management activities are performed for sections not for the video frames, for future management activities, the reasonable accuracy of distance information must be provided. For the present investigation, DMI information was inscribed upon the video images. However, the distance information within the video data did not necessarily match with real milepost information. Therefore, the video-distance information was converted to real mileage information after conduct of the video survey.

Global positioning system (GPS) technique was used to measure distances from video checkpoints to the nearest mileposts, since the GPS provides an accurate and simple approach to the acquisition of information for the linear features of roadways. The GPS is a method of positioning points based upon data collected from orbiting satellites [Simmons, 1996]. The GPS device named GeoExplorer II was used to measure distances for seven video checkpoints. This operation was initiated with opening a file for a starting point in the roadway. When activated, the GeoExplorer II began tracking visible satellites to calculate location information at regular time intervals during movement (i.e., either walking or driving), by storing data in the opened file [GeoExplorer II, 1996]. When the end points were reached, the file was closed and the location information was saved. Figure 5.2 shows the GPS device and the GPS work for highway location positioning.

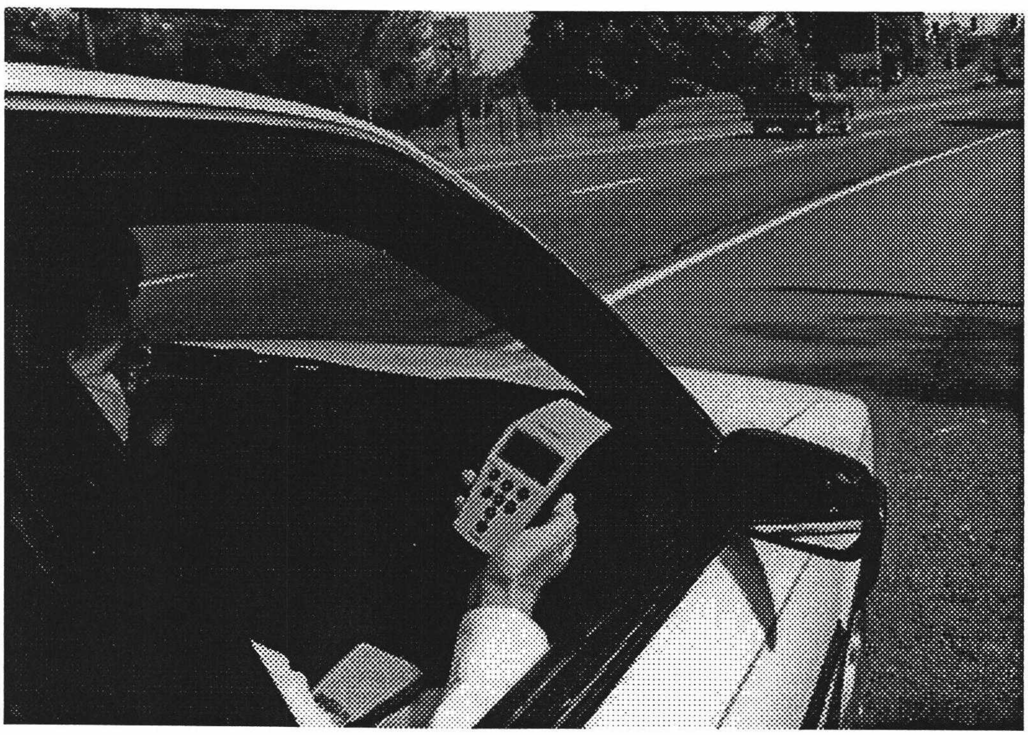


Figure 5.2 The GPS Device for Highway Location Positioning.

The location information files were then processed in the lab to determine distance calculations, using "Pathfinder" software as follows:

1) The saved files in GeoExplorer II were transferred to the lab computer and then displayed as position point tracks represented by longitude and latitude coordinates (Figure 5.3).
2) Point path distances were calculated using the "Pathfinder" *measure* command.
3) The calculated distance information was used to convert video mileage distance information to real mileage information.

The calculated mileage conversion chart is shown in Table 5.2.

It is obvious that the GPS technique provides a sophisticated tool to automate pavement surveys, promptly providing location information that is reliably precise. In this study, GPS data were not processed in real-time. However, with the introduction of the real-time kinematic GPS survey, a practical application for this type of system has become possible [Simmons, 1996]. Using real-time GPS processing techniques, exact distance and location data can be acquired as the location data are displayed in video images in real time.

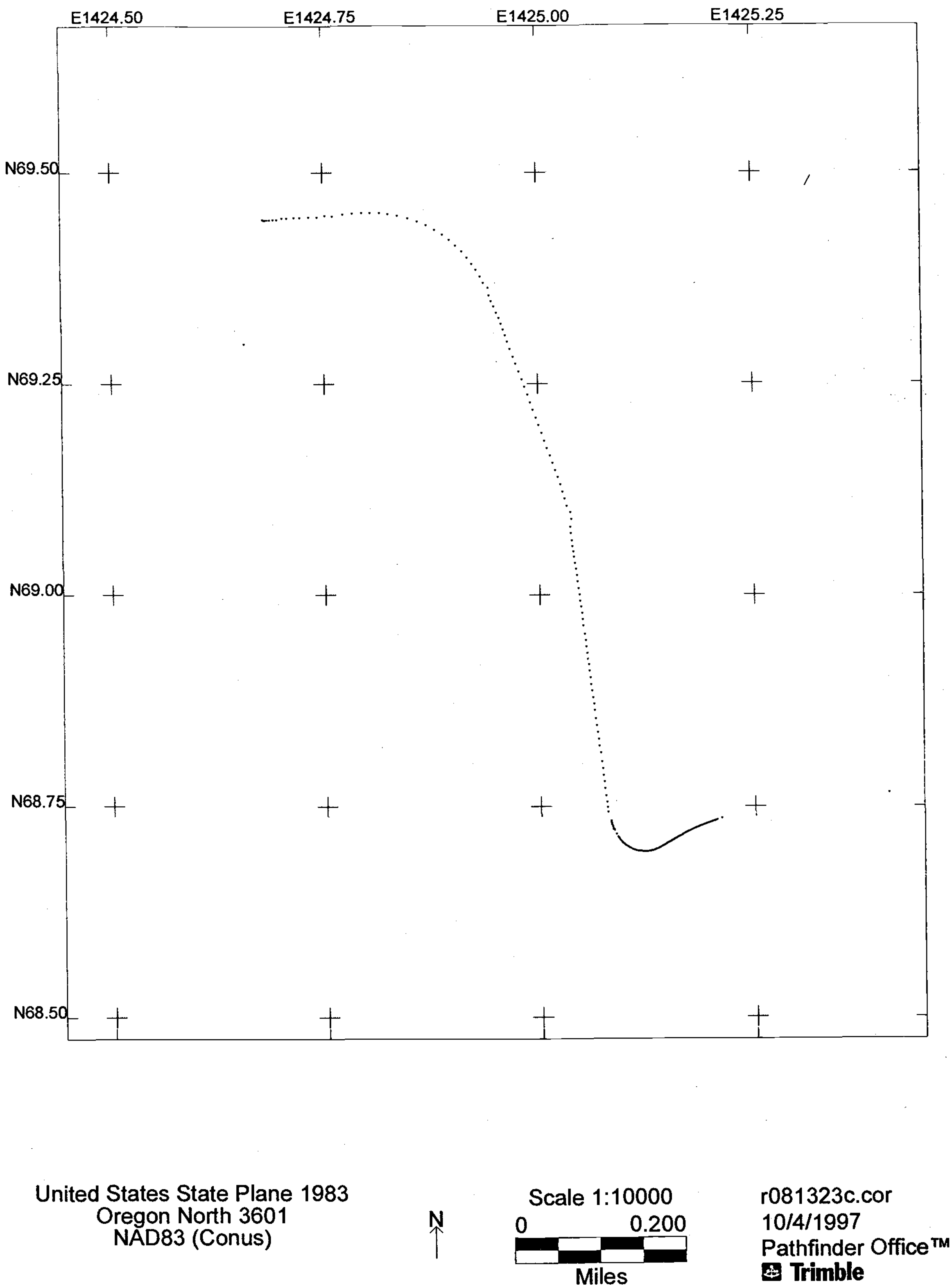


Figure 5.3 A Display of Point Path by GPS.

Table 5.2 Mileage Conversion Chart.

	Video Mileage	Real Mileage		Video Mileage	Real Mileage
Section 1	0.00	0.20	Section 5-1	0.20	0.40
HW 34 AC	2.80	3.00	HW 99E	0.30	0.50
	2.90	3.10		0.40	0.60
	3.00	3.20		0.50	0.70
	3.10	3.30		0.60	0.80
	3.20	3.40		0.70	0.90
	3.30	3.50		0.80	1.00
	3.40	3.60		0.90	1.10
	3.50	3.70		1.00	1.20
	3.60	3.80		1.10	1.30
	3.70	3.90		1.20	1.40
	3.80	4.00			
Section 2	0.05	6.50	Section 5-2	3.12	10.00
HW34 PCC	0.15	6.60	HW20	3.22	9.90
	0.25	6.70		3.32	9.80
	0.35	6.80		3.42	9.70
	0.45	6.90		3.52	9.60
	0.55	7.00		3.62	9.50
	0.65	7.10		3.72	9.40
	0.75	7.20		3.82	9.30
	0.85	7.30		3.92	9.20
	0.95	7.40		4.02	9.10
	1.05	7.50		4.12	9.00
Section 3	0.38	228.70	Section 6	0.50	0.50
I-5 PCC	0.48	228.80	Granger Av.	0.60	0.60
	0.58	228.90		0.70	0.70
	0.68	229.00		0.80	0.80
	0.78	229.10		0.90	0.90
	0.88	229.20		1.00	1.00
	0.98	229.30		1.10	1.10
	1.08	229.40		1.20	1.20
	1.18	229.50		1.30	1.30
	1.28	229.60		1.40	1.40
	1.38	229.70		1.50	1.50
Section 4	0.09	234.80	Section 7	0.00	78.95
I-5 AC	0.19	234.90	99W	0.05	79.00
	0.29	235.00		0.15	79.10
	0.39	235.10		0.25	79.20
	0.49	235.20		0.35	79.30
	0.59	235.30		0.45	79.40
	0.69	235.40		0.55	79.50
	0.79	235.50		0.65	79.60
	2.29	237.00		0.75	79.70
	2.39	237.10		0.85	79.80
	2.49	237.20		0.95	79.90
	2.59	237.30		1.05	80.00
				2.05	81.00

* For Corvallis streets, same mileage is used for video and real field mileage

5.3 Video and Field Pavement Inspection

5.3.1 Distress Survey Evaluation Methods

A variety of distress evaluation processes are used by transportation agencies. The proposed system can be used in varying types of management systems and distress definitions. However, for the present investigation two types of distress evaluation processes were selected: the ODOT approach and the MTC-PMS. The ODOT system is used to rate state jurisdiction highways, which are mainly included in the video test loop. The MTC-PMS is one of the most widely used system in the nation's northwestern area. The MTC-PMS users are nearly 200 agencies, which are almost two-thirds of the region's cities and counties [Cheng and Marcus, 1996]. The two approaches provide a contrast in survey methodology. The ODOT system is based on 100% pavement-section surveys, whereas the MTC-PMS is performed sampling surveys (i.e., more than 10 % sampling for section areas) [Smith, 1986].

More detailed descriptions of the two approaches are presented in Appendix A. The MTC-PMS definition of distress types and severity and the strategic highway research program (SHRP) distress manual used in the ODOT approach are also described in Appendix A.

5.3.2 Video Inspection System Operation

The operation procedures are developed for video distress inspection. It requires either one or two operators for operation. The procedures are different with different distress survey methods and different pavement types. Two distress survey methods and three pavement types were considered: ODOT and MTC-PMS for asphalt concrete (AC), jointed portland cement concrete (PCC), and continuous PCC. For distress inspection, survey forms were prepared for each case. More detailed operation procedures for video inspection are described in Appendix B.

However, during the video inspections, it was decided that the depth-related distresses are not detected, since the video inspection shows limitations to the detection of depth related distress such as rutting and faulting. Texture related distress (such as weathering and raveling) was another limitations for the video inspection. However, the texture related distress was tried to detect as an experimental for this investigation.

5.3.2.1 ODOT Method

The ODOT approach was required to inspect all of the section areas. For AC pavements, distress inspection was performed in imaginary small segments of 0.01 miles in length (52.8 feet) using the second decimal number of DMI codes. The inspection process was repeated ten times until the end of each section was reached.

For jointed-concrete pavements, the inspection process was conducted slab-by-slab throughout the section. For continuous reinforced concrete pavements, the process used for the evaluation of asphalt pavements was applied. The inspections were performed based on segments of 0.01 miles in length.

5.3.2.2 MTC-PMS

Since the MTC-PMS is a sampling approach, a frame-by-frame inspection was applied for the evaluation of AC pavements. Pavement condition was evaluated by observing still-frame video images and recording distress areas on a recording form. Two still-frames were randomly selected from every second decimal number of DMI codes, thus there were 20 video frames per section (i.e., 28.4% sampling). For jointed concrete pavements, slab-by-slab inspection was conducted based upon two inspection units of 10 slabs each (i.e., approximately 60% sampling). For the present investigation, continuous reinforced concrete pavement sections were not evaluated using MTC, since these section types were not included in the sample sections. However, a suggested processing method is described in Appendix B.

5.3.2.3 System Operation

All video surveys for the present study were performed by the author alone. In this case, the VCR was remotely controlled. However, it is desirable to operate the system using two operators: one to control the VCR using an IR4 controller and the connected computer, and the second to observe two screens and record distress information.

5.3.3 Field Distress Inspection Implementation

For the ODOT survey, the field inspection was performed by a walking survey using a distress-recording form. The author's field survey was conducted during the last week of July and first two weeks of August, 1997. However, the ODOT field inspection was performed via a "windshield" survey conducted from a slow-moving vehicle operating on the adjacent shoulder. This survey was conducted during July and August of 1997.

For the MTC-PMS, a walking survey was performed. For the AC sections, two of 100 foot length inspection units were inspected, which is 38% sampling. For the jointed PCC sections, inspection is performed in two inspection units of 10 slabs each, or approximately 60% sampling. The second field survey was performed by another Oregon State University (OSU) surveyor on September 12, 1997. However, during the second field survey, it was found that some of the pavement sections had been repaired since the first field survey.

5.4 Digitized Image Analysis

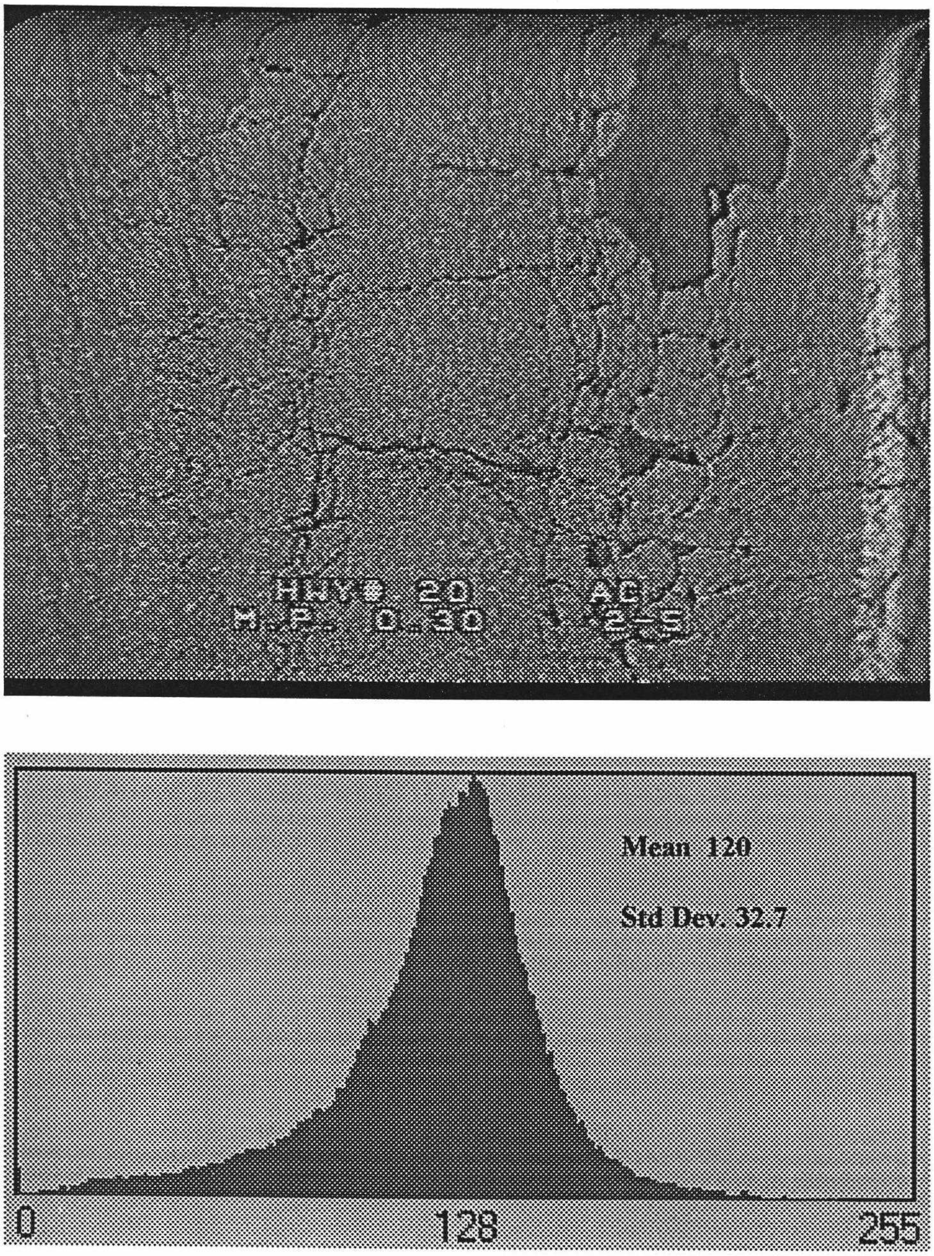
To examine the characteristics of video images and to test repeatability for the different video loop tests, the video images were digitized and analyzed. The collected images were then analyzed by "PicCrack," a pavement-image-analysis program developed at the University of Utah.

5.4.1 Image Digitizing and Initial Processing

Video still images were selected and digitized for further analysis. Since it is required to capture the same locations on each test loop, distinguishable image spots are selected while playing the video. Thirty spots for AC pavement and twenty spots for concrete pavements (10 for jointed concrete and 10 for continuous reinforced concrete) were selected for analysis. However, images in the same locations did not necessarily display the same perfect location. This was because the survey vehicle driver could not drive in same tracks over seven different test loops. Moreover, in technical terms it is almost impossible to capture the same location images by VCR operations. However, it was observed that the images in the same locations were in reasonably close proximity to one another.

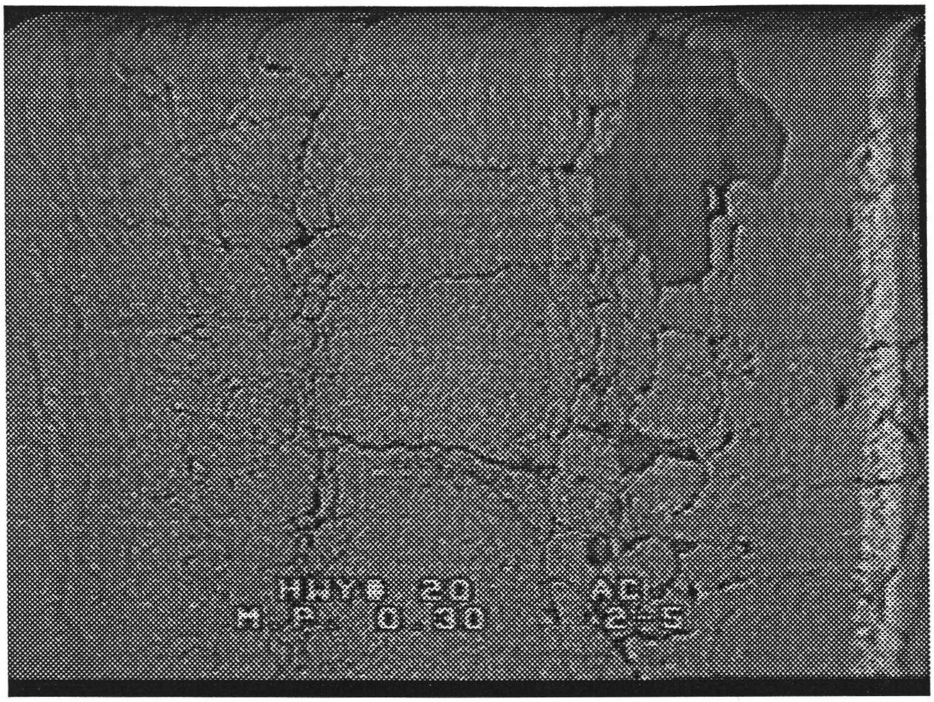
The images were digitized as 256 gray-scale images using the ComputerEyes 1024 video frame grabber, then captured and saved in the Joint Photographic Experts Group (JPEG) image file format. This was because JPEG image files allow for dramatic reduction in the amount of disk space required for storage [Digital Vision, 1995].

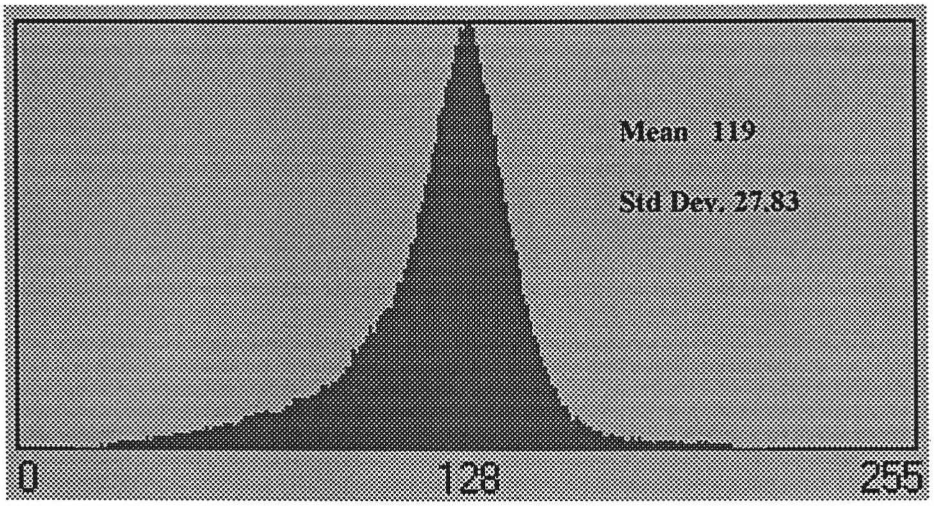
An image enhancement process was applied to digitized images to improve their appearance for visual and mechanized analysis. Following several trials, smooth edge filtering using ProImage version 1.0 software was applied to the images. This smooth filtering was applied to reduce background noise and to smooth blocky image data [Avery and Berlin, 1992]. In Figure 5.4, images and histograms are compared between the originally captured images and filtered images. As shown, filtered images showed a reduction in excessive crack edge effect without degradation of crack sharpness. The image histograms show there were no significantly large differences between the two images. However, the histogram standard deviation for filtered images was less than for the original images, implying some degree of noise reduction and smoothing.



(a)

Figure 5.4 Comparison for Original Captured Image and Filtering Applied Image.
(a) Original Image, (b) Filtering Applied Image





(b)

Figure 5.4 Comparison for Original Captured Image and Filtering Applied Image.
(Continued)

5.4.2 Image Analysis

For image analysis, the "PicCrack" image analysis program, as developed based on the Digital Still Camera System, was used. This system digitally records and compresses color images on a memory card, and also plays back images on a monitor. The picture taken by the digital camera is saved in a digital image file as a 256 RGB true color image [Jitprasithsiri et al., 1996].

The program crack analysis module consists of several steps, as shown in Figure 5.5. The 640×480 pixel color image was converted to a 256 gray-scale image and a median filtering technique was applied. A binary image was obtained using thresholding by regression analysis technique. Each pavement image was then divided into 15×11 square tiles. By counting the number of cracked tiles, a unified crack index (UCI) was calculated, defined further as the ratio of crack area to total pavement area, expressed as a percentage [Jitprasithsiri et al., 1996].

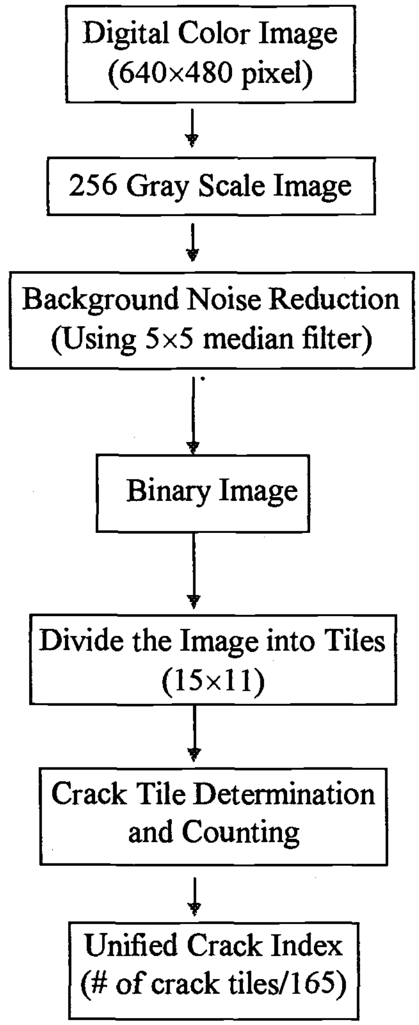


Figure 5.5 Crack Analysis Module of PicCrack Program.

6. VIDEO AND FIELD EVALUATION, DIGITIZED IMAGE DATA

6.1 Video and Field Evaluation Data by ODOT Approach

The inspected data from the application of the ODOT approach for video and field inspections were processed in the ODOT lab for pavement condition evaluation. Table 6.1 provides a description of the ODOT evaluation for each large pavement section inspected. For AC sections, five types of index values for each pavement sections are displayed: an overall index, a fatigue index, a patching index, a raveling index, and a non-load crack index. The rut index was also evaluated, but was not considered during the study, since video inspection poses limitations to the detection of depth-related distress.

All indices ranged from zero to 100 with larger values indicating better pavement condition. The overall index represents the overall condition of the pavement section, categorized as good, fair, poor, or etc. The fatigue index was calculated from the fatigue cracks that were produced principally by repetitive traffic loading. The patching index and raveling index were calculated, respectively, by patching and raveling distress. The non-load crack index is a result of combined calculations for non-load related cracks, including transverse, longitudinal, and block cracks.

For Portland cement concrete (PCC) pavement sections, three types of index values are shown in the table: an overall index, a fatigue index, and a patching index. For the jointed PCC calculation, the fatigue index is calculated from a combination of corner cracks, corner breaks, transverse cracking, longitudinal cracking, and "punchout." The overall index calculation includes all index values and joint conditions (i.e., transverse joints, lane joints, and shoulder joints).

For CRCP calculations, the fatigue index was calculated from a combination of transverse cracking, longitudinal cracking, and punchout. Again, the overall index calculation represents a combination of all index values and joint conditions.

Table 6.1 Pavement Condition Evaluation by ODOT Approach.

HW34 AC

Section ID	Distress Survey	Overall Index	Fatigue Index	Patching Index	Raveling Index	Non-Load Crack Index
1	Field #1	100	100	100	100	100
	Field #2	100	100	100	100	100
	Video	100	100	100	100	100
2	Field #1	100	100	100	100	100
	Field #2	100	100	100	100	100
	Video	100	100	100	100	100
3	Field #1	95.3	100	100	95.3	100
	Field #2	100	100	100	100	100
	Video	100	100	100	100	100
4	Field #1	100	100	100	100	100
	Field #2	100	100	100	100	100
	Video	100	100	100	100	100
5	Field #1	95	100	100	100	95
	Field #2	100	100	100	100	100
	Video	100	100	100	100	100
6	Field #1	12.7	26.3	55.1	100	87.8
	Field #2	14	22.8	61.4	100	100
	Video	24.7	32.7	77	100	98.2
7	Field #1	17.4	18.4	100	100	95
	Field #2	24.6	25.9	100	100	100
	Video	23.3	23.3	100	100	100
8	Field #1	100	100	100	100	100
	Field #2	100	100	100	100	100
	Video	100	100	100	100	100
9	Field #1	100	100	100	100	100
	Field #2	100	100	100	100	100
	Video	100	100	100	100	100
10	Field #1	100	100	100	100	100
	Field #2	100	100	100	100	100
	Video	100	100	100	100	100

Table 6.1 Pavement Condition Evaluation by ODOT Approach (Continued).

HW34 JPCC

Section ID	Distress Survey	Overall Index	Fatigue Index	Patching Index
1	Field #1	100	100	100
	Field #2	100	100	100
	Video	94	100	100
2	Field #1	94	100	100
	Field #2	100	100	100
	Video	94	100	100
3	Field #1	100	100	100
	Field #2	100	100	100
	Video	85	90.4	100
4	Field #1	100	100	100
	Field #2	65.4	100	65.4
	Video	94	100	100
5	Field #1	96	100	100
	Field #2	100	100	100
	Video	100	100	100
6	Field #1	100	100	100
	Field #2	100	100	100
	Video	100	100	100
7	Field #1	100	100	100
	Field #2	100	100	100
	Video	100	100	100
8	Field #1	94	100	100
	Field #2	100	100	100
	Video	94	100	100
9	Field #1	100	100	100
	Field #2	100	100	100
	Video	100	100	100
10	Field #1	100	100	100
	Field #2	100	100	100
	Video	100	100	100

Table 6.1 Pavement Condition Evaluation by ODOT Approach (Continued).

I-5 CRCP

Section ID	Distress Survey	Overall Index	Fatigue Index	Patching Index
1	Field #1	100	100	100
	Field #2	100	100	100
	Video	100	100	100
2	Field #1	100	100	100
	Field #2	100	100	100
	Video	100	100	100
3	Field #1	92.2	100	100
	Field #2	100	100	100
	Video	96.7	96.7	100
4	Field #1	96	100	100
	Field #2	100	100	100
	Video	100	100	100
5	Field #1	91.5	95.3	100
	Field #2	100	100	100
	Video	95.5	95.5	100
6	Field #1	100	100	100
	Field #2	100	100	100
	Video	95.5	96.4	100
7	Field #1	96	100	100
	Field #2	100	100	100
	Video	100	100	100
8	Field #1	100	100	100
	Field #2	100	100	100
	Video	100	100	100
9	Field #1	100	100	100
	Field #2	100	100	100
	Video	97	97	100
10	Field #1	100	100	100
	Field #2	100	100	100
	Video	100	100	100

Table 6.1 Pavement Condition Evaluation by ODOT Approach (Continued).

I-5 AC

Section ID	Distress Survey	Overall Index	Fatigue Index	Patching Index	Raveling Index	Non-Load Crack Index
1	Field #1	14.5	51	47.6	100	59.8
	Field #2	38.5	100	46.6	100	82.6
	Video	17	52.9	48.6	100	66
2	Field #1	16.3	54.7	47.6	100	62.7
	Field #2	19.3	48.2	46.6	100	85.8
	Video	18.7	57.1	48	100	68.2
3	Field #1	21.9	57.8	48.4	100	78.5
	Field #2	17	43.8	47.1	100	82.2
	Video	19.6	57.8	47.8	100	71
4	Field #1	17.1	48.7	48.4	100	72.7
	Field #2	40.4	100	47.1	100	85.8
	Video	18.4	48.8	48	100	78.7
5	Field #1	20.1	53.4	48.4	100	77.8
	Field #2	36.1	100	44	100	78.2
	Video	22.5	55.5	49	100	82.8
6	Field #1	18.2	52.8	49.3	100	70
	Field #2	14.1	47.5	38.2	100	77.5
	Video	18.7	54.4	49.3	95.3	73.1
7	Field #1	33.3	100	48.4	100	68.9
	Field #2	20.3	55.7	44	100	72.2
	Video	34.2	100	47.7	100	71.8
8	Field #1	33.1	100	48.4	100	68.4
	Field #2	31.7	100	44	100	72.2
	Video	32.7	100	48	100	68
9	Field #1	17	54.4	48.4	100	64.7
	Field #2	11.9	36.6	44.2	100	73.2
	Video	15.3	55.1	47.9	100	57.9
10	Field #1	30.8	100	48.4	100	63.6
	Field #2	15.4	47.1	47	100	69.5
	Video	30.6	100	48.5	100	63

Table 6.1 Pavement Condition Evaluation by ODOT Approach (Continued).

99E

Section ID	Distress Survey	Overall Index	Fatigue Index	Patching Index	Raveling Index	Non-Load Crack Index
5	Field #1	4	14.3	30.9	95.3	100
	Video	3	11.6	28.5	100	95
6	Field #1	4.7	17.3	36.9	100	73.1
	Video	8.1	25.9	37.9	100	83
7	Field #1	11.7	35.9	45.9	92.3	77.4
	Video	14.8	37.4	51.1	100	77.4
8	Field #1	22.4	41.1	71	100	76.9
	Video	27.1	46.1	71	100	82.8
9	Field #1	34.1	43.3	100	92.3	85.3
	Video	36.7	43.5	100	100	84.4
10	Field #1	32.6	41.6	100	100	78.3
	Video	31.3	43.1	100	100	72.7
11	Field #1	27.6	41.8	100	95.3	69.3
	Video	31.8	44.7	100	100	71.7
12	Field #1	34.8	42.7	100	100	81.5
	Video	37.4	48	100	100	77.9
13	Field #1	16.9	45.8	55.1	100	67
	Video	18.8	47.4	55.1	100	72.1
14	Field #1	95	100	100	100	100
	Video	58.1	100	58.1	100	100

HW20

Section ID	Distress Survey	Overall Index	Fatigue Index	Patching Index	Raveling Index	Non-Load Crack Index
100	Field #1	66	100	100	82.8	75.5
	Video	39.3	57.8	100	100	71.6
99	Field #1	34.7	48.9	100	93.9	85.5
	Video	36.6	49.7	66.7	100	81.8
98	Field #1	41	49.2	100	100	90.4
	Video	41.6	49.7	100	93.3	89.8
97	Field #1	16.5	45	49.9	89.5	85.6
	Video	19.1	49.1	48.4	92.8	86.9
96	Field #1	24.2	55.5	53.2	81.7	95
	Video	27.3	54.4	62.6	89.5	95
95	Field #1	27.6	55.5	60.6	86.4	100
	Video	53.2	100	59.9	83.9	100
94	Field #1	13.2	36	46.8	91.4	82
	Video	16.9	43.4	51.7	93.9	80.1
93	Field #1	38.4	46	100	92.3	83.3
	Video	38.2	45.6	100	100	83.7
92	Field #1	25.6	49.5	65.3	92.8	75.5
	Video	27.3	50	100	100	77.5
91	Field #1	37	49	100	100	79.7
	Video	33.2	46.4	100	87.8	77.4

Table 6.1 Pavement Condition Evaluation by ODOT Approach (Continued).

Granger Av.

Section ID	Distress Survey	Overall Index	Fatigue Index	Patching Index	Raveling Index	Non-Load Crack Index
6	Field #1	90.2	100	100	100	95
	Video	95	100	100	100	95
7	Field #1	69.4	100	77	100	95
	Video	93.2	100	100	100	93.2
8	Field #1	88.3	100	100	100	92.9
	Video	91.1	100	100	100	91.1
9	Field #1	95	100	100	100	100
	Video	100	100	100	100	100
10	Field #1	90.2	100	100	100	95
	Video	94.1	100	100	100	94.1
11	Field #1	55.4	100	62.8	100	92.9
	Video	58.2	100	63.5	100	91.6
12	Field #1	53.2	100	62.8	100	89.9
	Video	57.1	100	63.5	100	89.9
13	Field #1	93.2	100	100	100	98.1
	Video	98.2	100	100	100	98.2
14	Field #1	87.3	100	100	100	91.9
	Video	85.8	100	100	100	85.8
15	Field #1	62.3	100	100	92.3	71.1
	Video	86.6	100	100	100	86.6

HW 99W

Section ID	Distress Survey	Overall Index	Fatigue Index	Patching Index	Raveling Index	Non-Load Crack Index
1	Field #1	21	25.2	100	100	83.2
	Video	26.4	34.1	100	100	77.5
2	Field #1	34.3	36	100	95.3	100
	Video	47.6	47.6	100	100	100
3	Field #1	9.7	11.3	100	100	85.8
	Video	16.8	19.2	100	100	87.9
4	Field #1	14.6	16.2	100	100	89.9
	Video	27.3	31.8	100	100	85.7
5	Field #1	8	17.9	55.1	89.8	89.9
	Video	30.3	31.9	100	100	95
6	Field #1	21.2	23.5	100	100	89.9
	Video	8.3	15.6	61.5	100	85.8
7	Field #1	34.2	35.3	100	100	96.8
	Video	26.4	29.3	100	100	89.9
8	Field #1	41.6	45	100	100	92.5
	Video	40.8	44.1	100	100	92.5
9	Field #1	50	55.5	100	100	89.9
	Video	52.3	56.5	100	100	92.5
10	Field #1	53.8	54.4	100	100	99
	Video	57.1	57.8	100	100	99

Table 6.1 Pavement Condition Evaluation by ODOT Approach (Continued).

Walnut JRCP

Section ID	Distress Survey	Overall Index	Fatigue Index	Patching Index
1	Field #1	40	42.6	100
	Video	45	47.9	100
2	Field #1	60.3	64.1	100
	Video	60.3	64.1	100
3	Field #1	38.7	59.2	65.4
	Video	28	42.3	66.2
4	Field #1	36	39.9	100
	Video	41.7	44.3	100
5	Field #1	45.9	53	100
	Video	43.3	46.1	100
6	Field #1	72.3	72.3	100
	Video	59.6	59.6	100
7	Field #1	45.3	50.1	100
	Video	36.9	39.3	100
8	Field #1	38.3	38.3	100
	Video	16.2	16.2	100

Walnut-Harrison

Section ID	Distress Survey	Overall Index	Fatigue Index	Patching Index	Raveling Index	Non-Load Crack Index
1	Field #1	79.6	100	100	100	79.6
	Video	74.5	100	100	100	74.5
2	Field #1	43.2	52.9	100	100	81.6
	Video	44.3	57.8	100	100	76.6
3	Field #1	43.3	56.5	100	100	76.6
	Video	43	56.5	100	100	76.1
4	Field #1	78.2	100	100	100	78.2
	Video	78.3	100	100	100	78.3
5	Field #1	51.8	100	61.7	100	83.9
	Video	28.4	52.9	63.2	100	85
6	Field #1	46.1	100	55.1	100	83.6
	Video	42.9	100	53.2	100	80.5
7	Field #1	48.2	100	60.9	94.6	83.8
	Video	47.4	100	59.2	95.8	83.5
8	Field #1	84.9	100	100	100	84.9
	Video	84.9	100	100	100	84.9
9	Field #1	63	100	74.3	100	84.8
	Video	84.1	100	100	100	84.1
10	Field #1	57.2	100	69.8	100	81.9
	Video	85.1	100	100	100	85.1

Table 6.1 Pavement Condition Evaluation by ODOT Approach (Continued).

Monroe

Section ID	Distress Survey	Overall Index	Fatigue Index	Patching Index	Raveling Index	Non-Load Crack Index
1	Field #1	87	100	100	100	87
	Video	88.1	100	100	100	88.1
2	Field #1	84.4	100	100	100	84.4
	Video	84.2	100	100	100	84.2
3	Field #1	84.1	100	100	100	84.1
	Video	83.7	100	100	97.9	85.5
4	Field #1	44.7	100	56.5	100	79
	Video	47.5	100	55.1	100	86.3
5	Field #1	81.9	100	100	94.6	86.6
	Video	71	100	100	94.6	75.1
6	Field #1	25.2	100	28	100	90
	Video	80.7	100	100	91.4	88.4
7	Field #1	25	100	29.3	100	89.9
	Video	71.9	100	100	75.6	95
8	Field #1	90.2	100	100	100	95
	Video	100	100	100	100	100
9	Field #1	41	100	46.4	100	93.2
	Video	41.6	100	45.4	100	91.7

6.2 Video and Field Evaluation Data by MTC-PMS

The inspected data from the MTC approach for video and field inspections were processed for a second pavement condition evaluation, using the new MTC-PMS software Version 7.0 for Windows for processing. This new software contains some decided innovations, blending together the toolbars, screens, tabs, drop-down menus, and combo boxes [Cheng, 1997]. This provides for fast and convenient data entry and data processing.

The results of condition evaluation by MTC-PMS for each large pavement section are described in Table 6.2, with section PCI and total PCI deduct values for each distress type. The section PCI range from zero to 100 with larger value indicating better pavement condition. The PCI was calculated for individual inspection units within the management section, which were combined to determine the management section PCI.

The first step for PCI calculation was determination of a deduct value for each distress type and severity. The deduct value was determined from deduct curves developed by MTC. The total deduct values in Table 6.2 indicate calculated PCI deduct values for each distress type. However, for PCI calculation, it was necessary to adjust the total deduct value to a corrected deduct value by application of the appropriate deduct correction curve [Smith, 1987].

Table 6.2 Pavement Condition Evaluation by MTC-PMS.

HW99E

Section ID	Distress Survey	Section PCI	Total Deduct Value					
			Alligator Cracking	Block Cracking	Distortions	Linear Cracking	Patching Util. Cuts	Weathering Ravelling
	Field #1	33	94.53		18.57		51	
5	Field #2	39	89.38				83.15	6.6
	Video	50	119.22		2	4.7	32.55	
	Field #1	48	70.2	3.79		15.17	36.2	3.4
6	Field #2	50	79.38				56.62	5
	Video	71	32.44	2.22		27.03	13.31	
	Field #1	53	66.8	3.79		15.65	19.7	3.4
7	Field #2	80*				16.8		10
	Video	64	65.9			18.88		
	Field #1	60	37			20.56	2.01	3.4
8	Field #2	41	64.58			31		8
	Video	71	30.6	1.57		17.27		
	Field #1	43	74.55			4.82	19.03	8
9	Field #2	51	70.72			6.98		13.2
	Video	64	38.62	0.15		21.78		
	Field #1	61	52.84	1.7		18.73		5
10	Field #2	62	37					12.6
	Video	58	39.24	0.87		44.51		
	Field #1	58	38.75	10.36		12.64		9.6
11	Field #2	44	76					11
	Video	67	8.82	0.01		31.98		
	Field #1	53	64.73	2.39		19.59		
12	Field #2	38	115.2			4.32		11.8
	Video	56	21.23	0.57		64.96		
	Field #1	56	61.27	6.57	5.68	11.91		
13	Field #2	45	72.26	0.18		6.9		11
	Video	72	20.18	1.2		42.89		
	Field #1	100						
14	Field #2	95						5
	Video	93				10.03		
	Field #1		560.67	28.6	24.25	119.07	129.94	32.8
Total	Field #2		604.52	0.18		66	139.77	94.2
	Video		376.25	6.59	2	279.33	89.17	

* : Maintenance works since first field survey

Table 6.2 Pavement Condition Evaluation by MTC-PMS (Continued).

HW20

Section ID	Distress Survey	Section PCI	Total Deduct Value					
			Alligator Cracking	Block Cracking	Distortions	Linear Cracking	Patching Util. Cuts	Weathering Ravelling
100	Field #1	66	16.23	11.5		35.15		
	Field #2	62	63.8	6.2		14.03		
	Video	77		0		30.45		
99	Field #1	76	24.12	3		8.5		
	Field #2	66	33.71	9.09		0.02		
	Video	78		7.52		25.05		
98	Field #1	65	42	8.37		18.01		2.4
	Field #2	68	22.44	13.87		16.61		
	Video	82				21.16		
97	Field #1	62	55.98	2.18		14.42		3.4
	Field #2	83				2.01		13.8
	Video	70	46.23	0.06		25.79	1.26	3.5
96	Field #1	69			23.95	20.42		18.4
	Field #2	73				24.99	0	11
	Video	85	15.17			20.2		3.6
95	Field #1	74	19.55		4.4	13.59		9
	Field #2	73				24.97	18	6.6
	Video	88				19.44		
94	Field #1	62	44.43			13.59		8.5
	Field #2	49	60.32			2.04	13.5	6.6
	Video	70	23.58	1.89		28.34		
93	Field #1	59	59.96			9.71		9.5
	Field #2	75	35.98			0		8.5
	Video	78	7.49			21.29		
92	Field #1	70	48.5	0	2.6	7.52		5.8
	Field #2	53	46.8	6.2		9.51		
	Video	85		0.99		23.75		2.47
91	Field #1	58	70.53	4.01		10.4		
	Field #2	51	57.11	2.01		16.98		
	Video	68	9.64	3.6		39.81		
Total	Field #1		381.3	29.06	30.95	151.31		57
	Field #2		320.16	37.37		111.16	31.5	46.5
	Video		102.11	14.06		255.28	1.26	9.57

Table 6.2 Pavement Condition Evaluation by MTC-PMS (Continued).

Granger Av.

Section ID	Distress Survey	Section PCI	Total Deduct Value					
			Alligator Cracking	Block Cracking	Distortions	Linear Cracking	Patching Util. Cuts	Weathering Ravelling
6	Field #1	91			3.81			6.6
	Field #2	88			4.4	3.59		4.33
	Video	86			4.29	7.14		7.51
7	Field #1	91			0.34	2.8		6.6
	Field #2	82			2.6	11.91		4.17
	Video	85		1.41	9	14.15		3.26
8	Field #1	93				0		6.6
	Field #2	92			4.4			3.85
	Video	90		5.02	5.27	6.08		3.26
9	Field #1	93						6.6
	Field #2	90			6.6			3.85
	Video	73			34.01	21.02		3.37
10	Field #1	91			2.6	3.59		6.6
	Field #2	95						5
	Video	86		0	6.28	10.57		5.94
11	Field #1	90			5.62			8
	Field #2	95						5
	Video	80			23.67	34.18		3.37
12	Field #1	90				1.19		7.3
	Field #2	88				4.32	6.69	5
	Video	83			9.67	19.93	6.24	4.42
13	Field #1	91		0.04		0.18		6.6
	Field #2	91				3.59		5
	Video	89				16.14	4.82	3.5
14	Field #1	92						8
	Field #2	94				0.18		5
	Video	89			1.33	12		6.28
15	Field #1	88			0.98	3.28		7.3
	Field #2	84			2.6	7.59		5
	Video	88				7.14		6.49
Total	Field #1			0.04	13.35	11.04		70.2
	Field #2				20.6	31.18	6.69	46.2
	Video			6.43	93.52	148.35	11.06	47.4

Table 6.2 Pavement Condition Evaluation by MTC-PMS (Continued).

HW99W

Section ID	Distress Survey	Section PCI	Total Deduct Value					
			Alligator Cracking	Block Cracking	Distortions	Linear Cracking	Patching Util. Cuts	Weathering Ravelling
1	Field #1	40	102.19			6.46		
	Field #2	74*				9.13	21.5*	4.33
	Video	49	111.88			19.24		
2	Field #1	59	72.47			4.32		3.7
	Field #2	78*	14.88	0.18		2.01	1.41*	14.32
	Video	63	94.86			10.69		
3	Field #1	30	85.08			14.85		
	Field #2	66*				0.73	27.6*	4.17
	Video	28	112.48			12.83		
4	Field #1		103.21			1.34		3.4
	Field #2	68*				0.02	26.28*	4.5
	Video	44	124.66			12		
5	Field #1	24	106.62					2
	Field #2	68*				0.02	25.4*	4.67
	Video	51	119.39			13.18		
6	Field #1	23	101.79			4.32		
	Field #2	59*	31.97	0.18		10.79	23.48*	4.67
	Video	36	110.12	0		11.75		
7	Field #1	56	89.51	0		4.32		5.16
	Field #2	70*	14.88	3.79		4.32	20*	4.67
	Video	72	81.75			0.73		
8	Field #1	40	79.56					3.4
	Field #2	45	59.32			2.98		4
	Video	70	85.79			4.18		
9	Field #1	84				12.67		8.1
	Field #2	84	21.8			0		6.12
	Video	91	12.95			4.85		
10	Field #1	86		0.18		10.46		9.5
	Field #2	80	18.3			6.33		5.64
	Video	93		0		8.13		2.26
Total	Field #1		740.43	0.18		58.74		35.26
	Field #2		161.07	4.15		36.33	145.67*	57.09
	Video		853.88	0		97.58		2.26

* : Maintenance works since first field survey

Table 6.2 Pavement Condition Evaluation by MTC-PMS (Continued).

Walnut (JRCP)

Section ID	Distress Survey	Section PCI	Total Deduct Value					
			Corner Break	Shattered Slab	Linear Cracking	Patching Util. Cut	Scaling Crazing	Spalling
1	Field #1	79			18			13
	Field #2	81			15			12
	Video	82			16			12
2	Field #1	81			16			12
	Field #2	80			16			12
	Video	80			16			12
3	Field #1	86			13	0		1
	Field #2	77			29			1
	Video	87			15	0		4
4	Field #1	76	9		11			15
	Field #2	79			16			12
	Video	80	5		11			14
5	Field #1	80			18			20
	Field #2	80			18			12
	Video	82			18			10
6	Field #1	88			13			
	Field #2	94			6			
	Video	92			6			2
7	Field #1	77			29			
	Field #2	79			27			
	Video	83			20			
8	Field #1	73		6	38			3
	Field #2	77		16	16			
	Video	75	5	11	28			1
Total	Field #1		9	6	156	0		64
	Field #2			16	143			49
	Video		10	11	130	0		55

Table 6.2 Pavement Condition Evaluation by MTC-PMS (Continued).

Walnut - Harrison

Section ID	Distress Survey	Section PCI	Total Deduct Value					
			Alligator Cracking	Block Cracking	Distortions	Linear Cracking	Patching Util. Cuts	Weathering Ravelling
1	Field #1	86		0.58		11.12		
	Field #2	85		0		17.24		
	Video	78		3.88		25.44		
2	Field #1	83	15.07	0		10.14		
	Field #2	87				14.92		
	Video	83	24.87	0		18.09		
3	Field #1	78	13.98			22.72		
	Field #2	78		0	0.98	26.93		2.01
	Video	80		0.85		29.13		
4	Field #1	86				16.13		
	Field #2	79			0.6	25.77		
	Video	82	6.73	0		23.01		
5	Field #1	86		0.4	0.61	17.28		1.18
	Field #2	91	6.92	0		7.81		
	Video	86				18.98	3.04	
6	Field #1	88		0.2		12.82		3.7
	Field #2	86				18.15		
	Video	87				20.93		
7	Field #1	71			3.81	29.4	16	10.01
	Field #2	82				23.12		
	Video	79		0	7.58	27.07		
8	Field #1	81		0		18.25		
	Field #2	82		0		21.19		
	Video	75		0		30.99		
9	Field #1	78				25.82		3.4
	Field #2	81				21.3		
	Video	81				27.9		
10	Field #1	86			0.6	12.82		5
	Field #2	89				11.64		0.58
	Video	85		0		20.91		
Total	Field #1		29.05	1.18	5.02	176.5	16	19.59
	Field #2		6.92		1.58	188.07		2.59
	Video		24.88	4.73	7.58	242.45	3.04	

Table 6.2 Pavement Condition Evaluation by MTC-PMS (Continued).

Monroe

Section ID	Distress Survey	Section PCI	Total Deduct Value					
			Alligator Cracking	Block Cracking	Distortions	Linear Cracking	Patching Util. Cuts	Weathering Ravelling
1	Field #1	94				5.18		
	Field #2	87				12.64		
	Video	89		1.41		12.33		2.63
2	Field #1	87		0		11.91		
	Field #2	88				11.45		
	Video	87		0		14.68		
3	Field #1	92		0		6.94		
	Field #2	91				9.28		
	Video	94			0.6	4.64		2
4	Field #1	94		0		8.05		
	Field #2	85			5.3	8.14	2.01	
	Video	90				15.93		
5	Field #1	85				16.92		
	Field #2	95				4.55		
	Video	90				17.15		
6	Field #1	81			4.4	1.19	25.4	
	Field #2	92				7.16		
	Video	89			0.68	10.84		3.24
7	Field #1	73			8	1.34	27.6	11
	Field #2	86						13.8
	Video	95		0.95		4.18		2
8	Field #1	89						11
	Field #2	86						13.8
	Video	96				2.57		2.98
9	Field #1	71	31.57					
	Field #2	67*					33*	
	Video	74	42.1			6.5		2.57
Total	Field #1		31.57		12.4	51.53	53	22
	Field #2				5.3	53.22	35.01	27.6
	Video		42.1	2.36	1.28	88.82		15.42

* : Maintenance works since first field survey

6.3 Image Analysis Data

Digitized images were analyzed using the "PicCrack" image-analysis program [Jitprasithsiri et al., 1996]. UCI values were computed for each image frame and the values for each digital image are described In Table 6.3. Images with low UCI values indicate better pavement conditions. However, as indicated in Table 6.3, some images were not included in the analysis. Since image blurring occasionally occurred during field testing, the blurred images were not analyzed. In addition, some images were not included in the analysis because it was technically hard to determine images in the same locations. The shadow-affected images are also indicated in Table 6.3. The amounts of shadow affections are different for each image. However, if considerable amount of shadow is observed, it is marked as * in the table, which is used for further analysis.

Table 6.3 Crack Index Values for Images.

(AC Pavements)

Pavement Type	Road Name	Video Mile Post	Test Loop 1	2	3	5	6	7	13
AC	HW34	0.00	60.61	30.30	32.12	26.06	24.24	26.67	B
		0.02	56.36	16.97	20.61	22.42	22.42	28.48	B
		0.03	64.85	25.45	30.30	24.24	20.00	49.09	B
		0.05	75.15	27.27	34.55	30.30	27.27	40.00	B
		0.06	80.00	39.39	30.91	40.61	36.97	35.76	B
		0.06	84.64	52.73	16.97	48.48	15.76	18.18	B
		3.37	76.36	51.52	72.73	30.91	36.36*	64.85	47.88
		3.41	94.55	97.58	79.39	55.15	X	X	54.55
		3.42	92.12	93.33	85.45	58.79	X	X	56.36
		6.07	B	90.91	70.30	75.76	34.55	81.21	19.39
AC	I-5	0.06	50.91	65.45*	43.64	34.55*	31.52*	41.21	64.24
		0.08	32.12	47.88*	24.24	35.15*	33.94*	B	60.00
		0.19	43.64	40.61*	21.21	33.33*	32.73*	B	45.45
		0.24	35.15	41.82*	16.36	24.85*	35.15*	B	B
		0.32	23.64	47.88*	29.09	34.55*	33.33*	B	41.21
AC	99E	0.27	88.48	47.88	60.00	58.79	53.33	70.30	49.09
		0.28	78.18	76.97	67.88	83.03	74.55	41.82	88.48
		0.30	83.03	50.30	57.58	57.58	42.42	64.85	41.21
		0.47	93.94	56.36	60.00	67.88	53.33	32.73*	69.09
		1.47	43.03*	30.91	52.73*	33.94	28.48	36.36*	44.85
AC	Walnut - H	0.07	58.79*	39.39	44.85*	33.94	38.79	36.36*	26.06
		0.13	47.27*	23.64	B	29.09	34.55	29.7*	B
		0.49	55.76*	32.73	44.85*	33.33	38.18	38.18*	B
		0.51	67.27*	36.97	41.82*	27.27	24.85	32.73*	B
		0.62	52.73*	30.91	44.85*	28.48	35.15	30.91*	23.03
AC	Monroe	0.08	34.55	36.36	40.61	31.52	25.45	41.21	23.64
		0.20	37.58	36.97	39.39	27.88	37.58	52.12	18.79
		0.26	27.27	28.48	18.18	27.27	23.64	23.03	13.33
		0.84	57.58*	83.64*	67.88*	82.42*	50.30	35.76	28.48
		0.86	36.97*	70.30*	64.85*	83.03*	47.27	33.33	12.12

Legend: B; Image Bluring
X; Images are not avalable
*; Shadow effects on images

Table 6.3 Crack Index Values for Images (Continued).

(PCC Pavements)

Pavement Type	Road Name	Video Mile Post	Test Loop 1	2	3	5	6	7	13
Jointed PC	HW34	0.00	53.33	34.55	24.24	35.15	38.18	28.48	X
		0.03	26.06	35.15	30.91	37.58	40.61	26.06	30.91
		0.05	37.58	44.24	30.30	42.42	44.24	40.61	42.42
		0.06	36.97	37.58	31.52	35.15	43.64	33.94	36.97
		0.21	36.97	36.36	26.06	31.52	41.21	37.58	33.94
	Walnut	0.01	37.58*	36.36	B	29.09	15.15	B	B
		0.15	36.36*	21.82	B	30.30	27.27	28.48*	B
		0.72	30.91*	23.03	36.97*	26.06	20.00	28.48*	15.76
		0.75	42.42*	36.26	49.70*	36.97	33.33	49.7*	31.52
		0.85	42.42*	35.76	40*	33.94	27.88	27.27*	34.55
CRCP	I-5	0.07	29.70	40.06*	27.27	45.45*	38.79	18.18	20.00
		0.09	21.82	44.24*	21.21	42.42*	21.82	15.76	14.55
		0.10	26.67	47.88*	24.24	43.03*	24.85	13.13	15.76
		0.27	15.15	42.42*	13.94	41.21*	35.76	10.91	12.12
		0.65	24.85	43.03*	21.21	38.18*	29.89	15.76	9.69
		0.87	30.30	54.55*	18.79	47.88*	35.15	25.45	15.15
		0.98	30.91	49.09*	20.61	38.79*	30.30	12.12	10.91
		1.00	29.09	48.48*	24.24	38.79*	28.48	22.42	10.30
		1.02	24.85	40.61*	23.64	40.61*	16.97	18.18	12.12
		1.04	36.36	48.48*	24.24	47.27*	10.30	16.36	22.42

Legend: B; Image Bluming
X; Images are not avalable
*; Shadow effects on images

7. ANALYSIS AND DISCUSSION

7.1 Statistical Comparisons of Data Sets

The data presented in Chapter 6 require analysis by several statistical approaches to evaluate the performance of the proposed system. The following description outlines the concepts and benefits of various statistical methods.

To determine the accuracy of the system performance, a *two-sided paired t-test* can be used. This testing is required to determine how close an observation matches an accepted reference value or an assumed true value. To compare two databases, visual field surveys are assumed as true values or reference values. As such, the observed data from video logging can be compared to data from the visual field inspection. The theoretical sampling distribution of the differences between two sets of measurement can be assumed to be a t-distribution [Hoggs and Tanis, 1993].

If there is no difference between two data evaluations, the population of differences would be centered at zero. So, the hypothesis test can be processed about the mean differences, between ratings for each pavement section evaluation. The hypothesis test is stated as follows:

$$H_o: \mu_d = 0$$
$$H_a: \mu_d \neq 0 \qquad \text{(Eq. 7.1)}$$

Where H_o and H_a represent the null and alternative hypotheses, respectively, and μ_d is the mean of the differences between ratings for each pavement section evaluation. The t-statistic is used to decide whether to reject or not reject the null hypothesis. The p-value obtained from the t-statistic or attained significance level is the smallest level of significance α for which the observed data indicate that the null hypothesis should be rejected [Wackerly et al., 1996]. The level of significance for α is generally set at 0.05.

A common method of studying a linear relationship between two data sets is *linear regression analysis*. This method allows one to analyze the data sets using the "least squares" approach to fit a line through a set of observations. This tool is very useful in analyzing the relationship between two data sets. It determines how a single dependent variable is affected by the values of independent variables. The most common form of the simple linear regression model is represented as follows:

$$y = \beta_0 + \beta_1 x \quad \text{(Eq. 7.2)}$$

Where y and x are dependent variable and independent variable respectively, and β_0 and β_1 are unknown parameters expressed by intercept and slope of the linear model. The slope parameter (β_1) measures the amount of change in the mean response associated with a single unit of the explanatory variable [Ramsey and Schafer, 1997].

Several values can be used to determine how well the two data sets match. One of the commonly used measures is the R-square value. An R-square value of 1 means that the values are matched perfectly. A value of zero means no linear relationships between two sets of data. Another simple expression for comparing two variables is the *coefficient of correlation* ρ. This correlation indicates the linear relationship between two data sets that are scaled to be independent of the unit of measurement. The ρ satisfies the inequality $-1 \leq \rho \leq 1$. Thus -1 or +1 implies a perfect correlation; a zero, however, implies no correlation [Wackerly et al., 1996].

The *analysis of variance (ANOVA)* method is performed to test the hypothesis that means from two or more samples are equal. This technique expands on the tests for two means such as the t-test. The ANOVA method is adopted for repeatability testing in this study. Repeatability testing determines if differences between multiple ratings at given locations are significant. There are seven data sets (videotapes) to be compared. The UCI values that are calculated from PicCrack program are compared for testing.

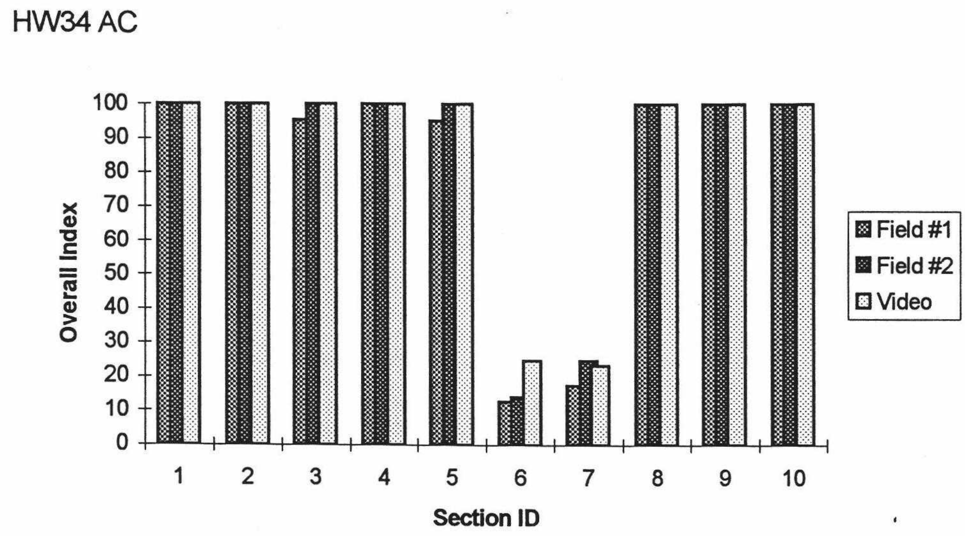
The *Variable comparison* test determines the levels of significance of variables. Variables considered include vehicle speed (high vs. low), camera angle (perpendicular vs. angle), and pavement condition (dry vs. wet), etc. This test is performed using a statistical modeling technique. The details for developing and evaluating the model are described in section 7.5.

7.2 Evaluation by ODOT Approach

Using the ODOT approach, video and field inspections were applied for a selected group of the107 sections. However, the field inspection by ODOT crews was only processed on I-5 and HW34 sections as explained in Chapter 5. Overall evaluations for the selected I-5 and HW34 pavement sections are displayed in Figure 7.1. Figure 7.1 shows that the shape of the overall index distribution for each AC section maintains a similar distribution for field and video evaluations. Figure 7.1 also shows that the concrete pavement sections are in very good condition, indicating that many of the index values are rated at 100.

To evaluate the video system performance using the ODOT approach, however, it is required to analyze the results using statistical approaches. To ascertain the accuracy of the test results, a two-sided paired t-test is applied. This approach tests the null hypothesis, that the mean differences between each overall index data set are not significantly different (i.e., the mean differences equal zero). From the observed level of significance (the p-value), the null hypothesis should be rejected or accepted at a certain level of significance. The smaller the p-value becomes, the more compelling the evidence that the null hypothesis should be rejected [Wackerly et al., 1996].

The results of the paired t-test are summarized in Table 7.1. The p-values from the t-test for three categories of comparison (video vs. field #1, video vs. field #2, and field #1 vs. field #2) are listed for overall sections and for each large section. The small p-values are represented in bold style (level of significance set at 0.05). However, the primary focus of this study is given to the comparison between the data analysis of video inspections and the data analysis of other independent field inspections (represented by field #2).



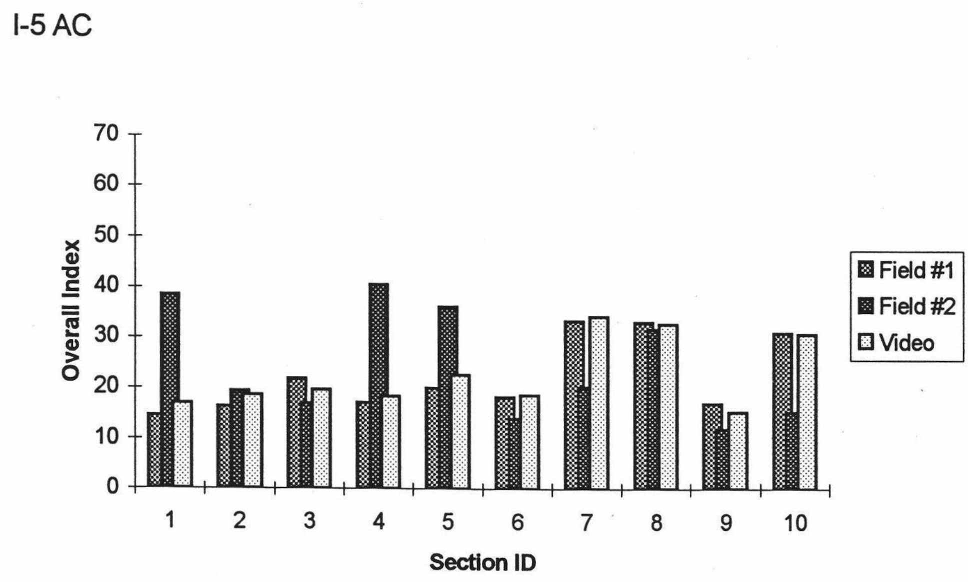
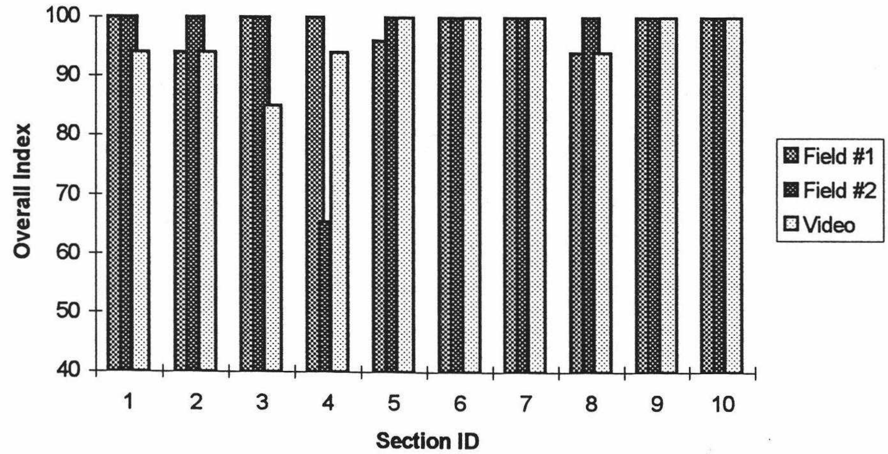


Figure 7.1 Overall Pavement Condition, ODOT Approach for I-5 and HW34.

HW34 JPC



I-5 CRCP

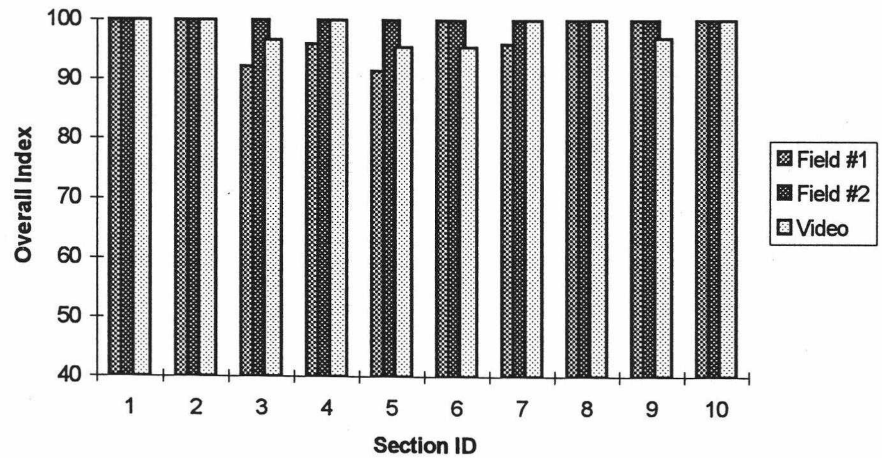


Figure 7.1 Overall Pavement Condition, ODOT Approach for I-5 and HW34 (Continued).

Table 7.1 Paired t-test for HW34 and I-5 Sections.

		Video- Field#1	Video- Field#2	Field#1-Field#2
AC	HW34	0.06104	0.41174	0.06495
	I-5 AC	0.34116	0.69326	0.62929
PCC	HW34 JPC	0.20908	0.90470	0.62976
	I-5 CRCP	0.39005	**0.04077**	0.05196
Overall		0.46834	0.61980	0.43479

Table 7.1 shows that the p-values of most sections are higher than the significance level $\alpha=0.05$. For an overall index evaluation of AC sections, the p-values of most sections are also higher than the significance level of $\alpha=0.05$. The high p-values mean that the null hypotheses is substantiated rather than the alternative hypotheses, indicating that the mean differences between each overall index data is not significantly different. Thus, for the AC sections of HW34 and I-5, the 2-sided paired t-test indicates that there are no significant differences between the overall condition indices between evaluations of field and video inspections or field #1 and field #2 inspections.

Most of the PCC sections also show higher p-values than the 0.05 significance level. This indicates that the mean differences between each overall index data are not significantly different. However, the test for I-5 CRCP sections by video vs. field#2 comparison shows a low p-value of 0.04077. This low p-value indicates strongly that the overall index values between two measurements are significantly different. More analysis of this section shows that the means for the overall index are 98.47 for video inspection and 100 for the field#2 inspection. The mean difference is 1.53 and the 95 % confidence interval (CI) is 1.53 ± 1.45. However, for concrete sections, since most of sections are in very good condition, it is difficult to expect any significant results from the statistical analysis.

To examine the relationships between evaluations, correlation coefficients (ρ) are calculated (See Table 7.2). High correlation coefficients are represented in bold. For overall sections, the ρ values are very high, close to 1, which indicate strong relationships between evaluations. In addition, the ρ values for HW34 AC sections also show high ρ values. The I-5 AC sections, however, show generally low ρ values except the video vs. field #1 comparison. For PCC sections, the ρ values do not provide any meaningful statistical results.

Table 7.2 Correlation Coefficient (ρ) for HW34 and I-5 Sections.

		Video- Field#1	Video- Field#2	Field#1-Field#2
AC	HW34	**0.99756**	**0.99651**	**0.99755**
	I-5 AC	**0.97291**	-0.02854	-0.16503
PCC	HW34 JPC	0.08252	0.15030	-0.21350
	I-5 CRCP	0.42814	****	****
Overall		**0.99374**	**0.97047**	**0.96670**

In Figure 7.2, a regression analysis of the index values for overall area is shown. In Figure 7.3, regression analysis of the overall index values for AC and PCC sections of HW34 and I-5 sections are described. The condition evaluations of ODOT's field inspections (field #2) and in-office video evaluation (video) are compared using regression analysis, since the primary concern for this study is to compare the two inspections.

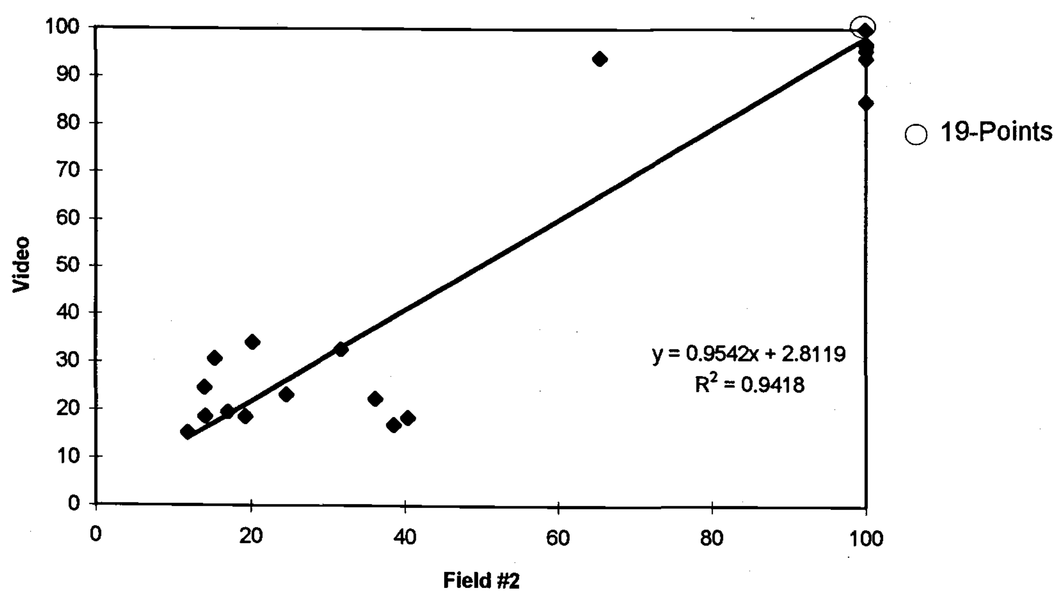
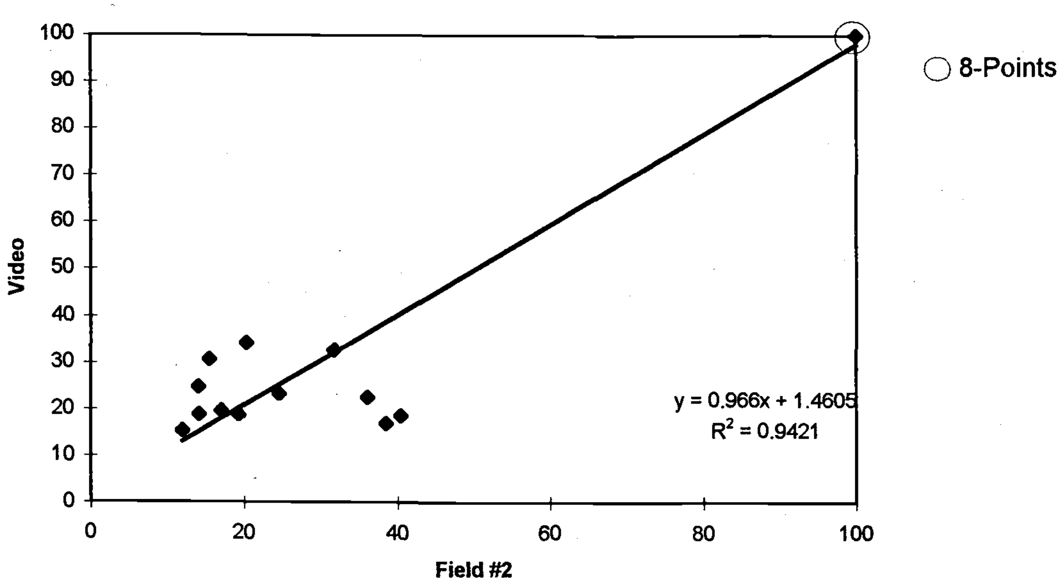


Figure 7.2 Regression Analysis of Overall Index for HW34 and I-5.

AC



PCC

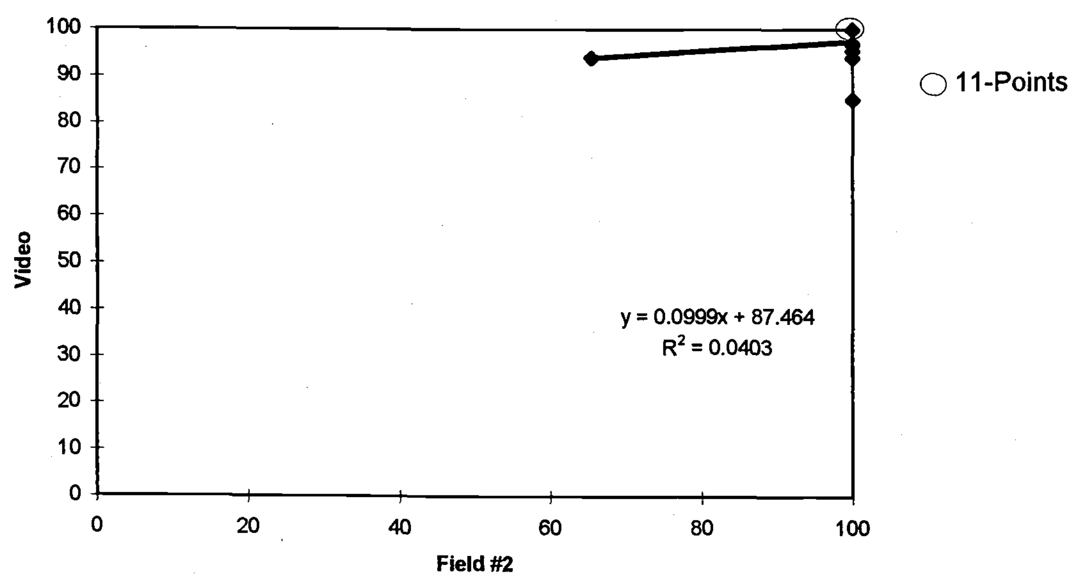


Figure 7.3 Regression Analysis of Overall Index for AC Pavement and PCC Pavement.

From Figure 7.2, it can be observed that a very good relationship exists between the wo inspections, as the R^2 is 0.9418 (same comparison by ρ shows 0.97047). From Figure 7.3, it can be observed that the AC sections are highly correlated ($R^2 = 0.9421$). However, the PCC sections show poor relationship ($R^2 = 0.0403$). This poor relationship may be attributed to the very good condition of the PCC sections (most of section's index value is 100). Thus, in general, the AC sections of HW34 and I-5 show very promising results from the comparison of video inspections and field #2 inspections. However, for the PCC sections, it is difficult to draw any significant conclusions from the data analysis.

The ODOT approach evaluates the overall condition index and other distress related index values. In Figures 7.4 - 7.6, the regression analysis between the video and field #2 on HW34 and I-5 AC sections (20 sections) for the fatigue index, the patching index, and the non-load crack index are shown.

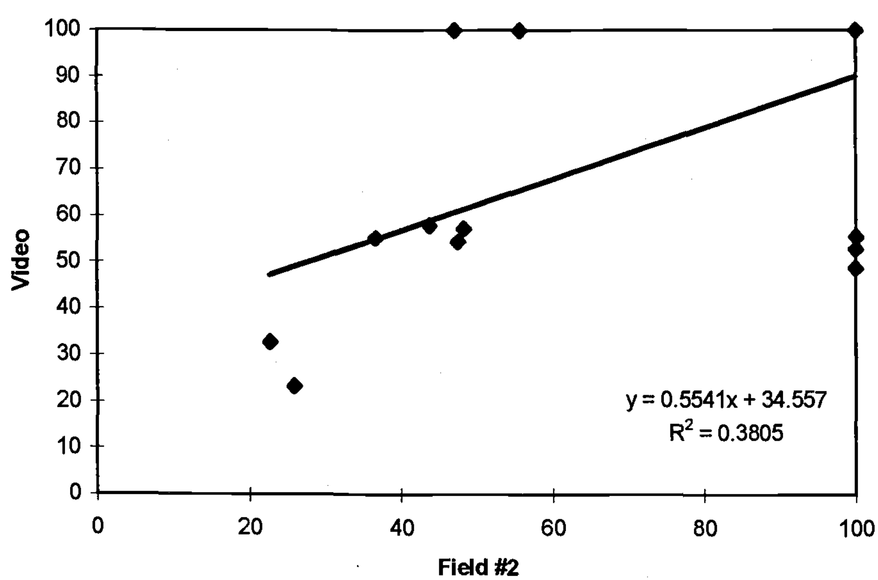


Figure 7.4. Regression Analysis of the Fatigue Index.

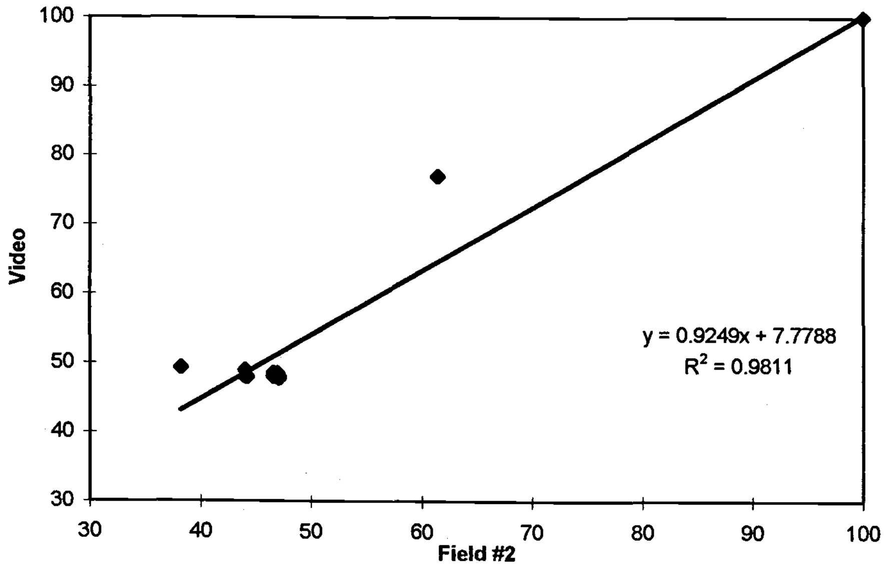


Figure 7.5. Regression Analysis of the Patching Index.

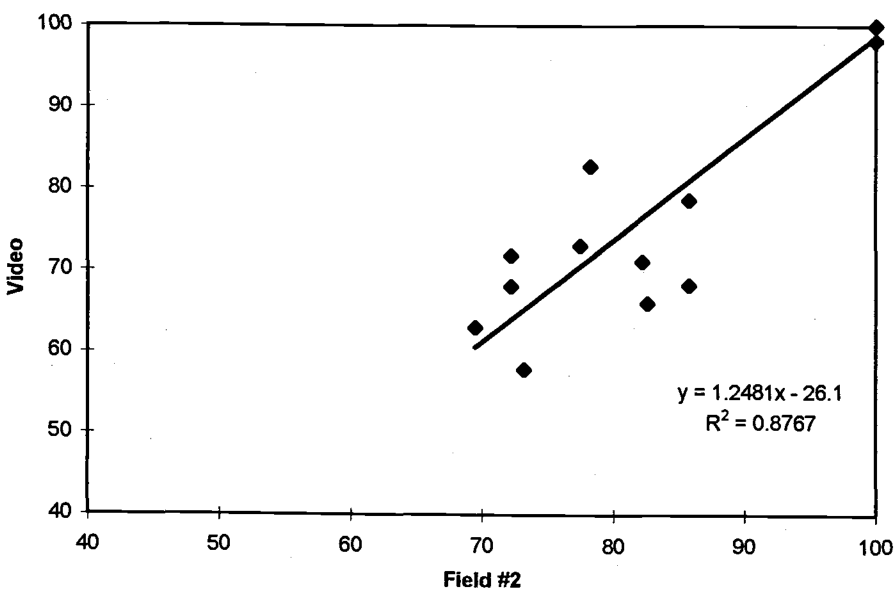


Figure 7.6. Regression Analysis of the Non-Load Crack Index.

As seen in Figure 7.4, the regression analysis for the fatigue index does not show a good relationship between the observations of video and field #2 ($R^2 = 0.3805$). Five observations are detected as outliers (values that are outside the normal expected range)as identified in the Figure. The outliers usually occur when one inspection evaluated the section as a non-fatigue distressed section, while the other inspection observed fatigue cracks to some extent. However, in the index calculation of the ODOT approach, the deduct coefficients for the fatigue index are very high when compared to other types of distresses. This means that the fatigue index is very sensitive, even to small amounts of extent measurements.

As observed in Figure 7.5, the regression analysis of the patching index shows very good matching results between the observations of video and field #2 ($R^2 = 0.9811$). The patching distress in the Figure is usually observed in I-5 sections. The patching in these sections was observed as stretched blocks on both wheel paths, each 3-4 feet wide. Because of this unique patching distress, it was easy to detect the distress type and extent during the video inspection.

The regression analysis of the non-load crack index also shows good matching results between the observations of video and field #2, as shown in Figure 7.6 ($R^2 = 0.8767$). The non-load crack index is a combined calculation of transverse, longitudinal, and block cracks. These types of distress are considered the most recognizable distresses from video logging. As expected, these types of distress are well detected from video inspections of the AC sample sections.

For analysis of the remaining sections (including 67 sections, except HW34 and I-5 sections), the data from field #1 and video inspections are statistically compared. In Figure 7.7, the overall condition evaluations for the remaining 67 sections by field #1 and video inspections are presented. Figure 7.7 shows that the overall indices between the two evaluations contain very similar distributions, save for several outliers. In Figure 7.8, the regression analysis for the 67 sections are presented; and, although some significant outliers are observed, most of the observations show a good relationship ($R^2 = 0.7405$).

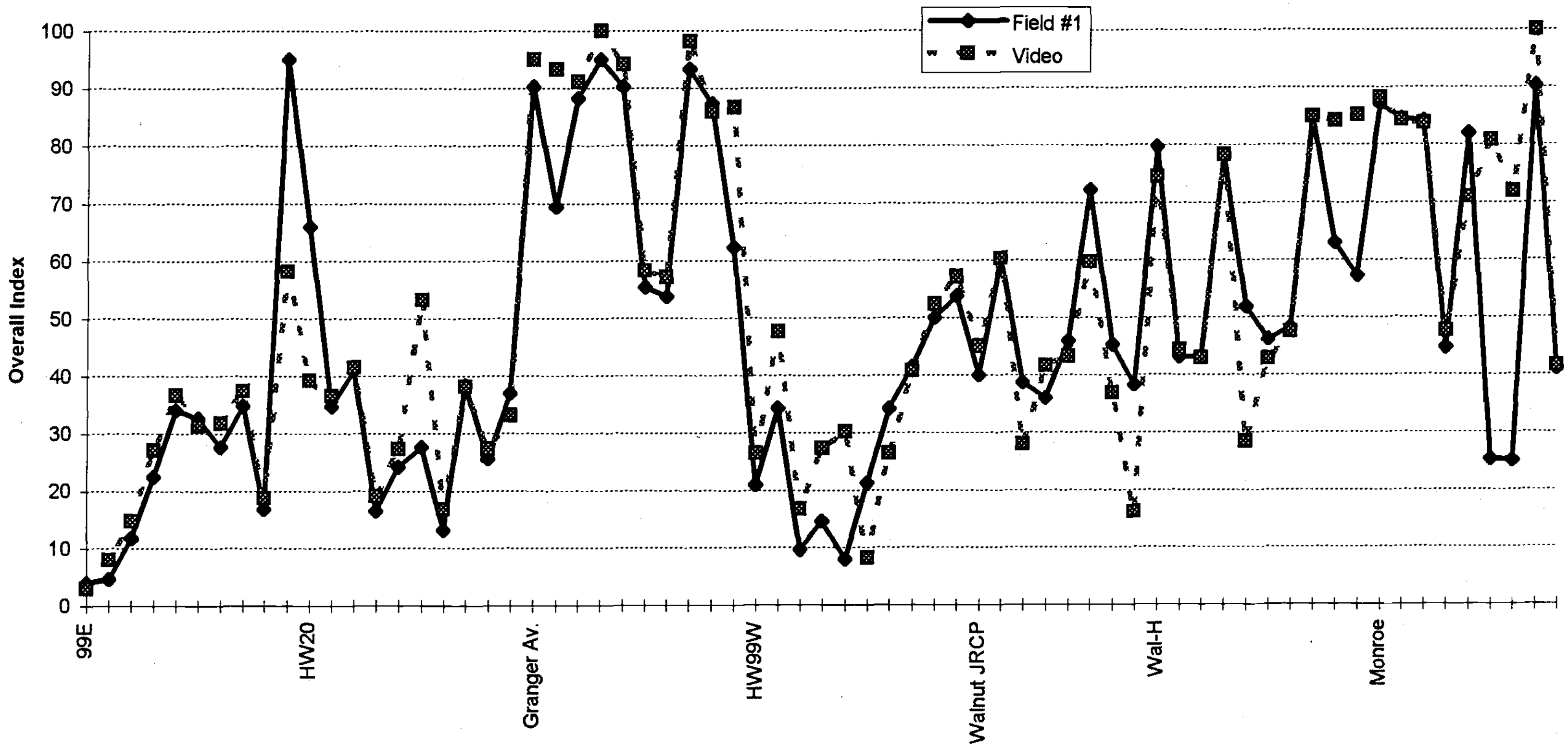


Figure 7.7 Overall Condition Evaluation for Other 67 Sections.

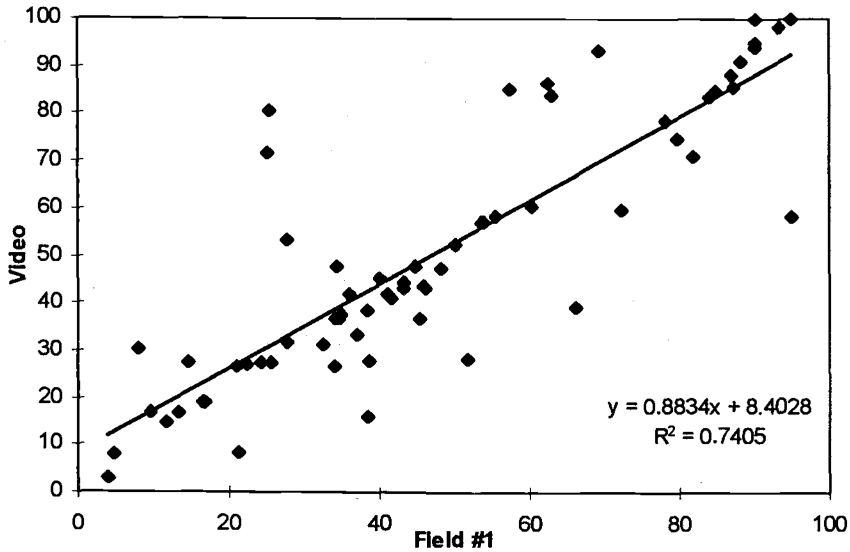


Figure 7.8. Regression Analysis for Other 67 Sections.

In Table 7.3, p-values from the paired t-test and the correlation coefficient (ρ) for 67 sections are presented. The p-values from the paired t-test indicate that most of the p-values are higher than the significance level of $\alpha = 0.05$. It indicates that the mean differences between field and video inspections are not significantly different for the majority of the 67 road sections. However, the p-value for Granger Avenue is calculated at 0.02771, which is lower than significance level. It means the mean difference is expected between field and video inspections for this section.

Table 7.3. P-Values from Paired t-test and Correlation Coefficient.

Road Name	Paired t-test P-value	Correlation Coefficient
Overall	0.10662	**0.86053**
99E	0.68345	**0.93025**
HW20	0.83489	0.57182
Granger Av.	**0.02771**	**0.84442**
HW99W	0.20192	**0.79435**
Wal	0.13337	**0.77085**
Wal-H	0.70464	**0.76949**
Monroe	0.16774	0.57345

In Table 7.3 (column 3), correlation coefficients are also listed. Generally, the coefficients show relatively high values, indicating strong relationships between video and field inspections. However, the analysis for the 67 sections implies lack of independence, since the author was the only inspector to perform field and video inspections. Independent surveys were not available due to the technical problems from ODOT field inspections.

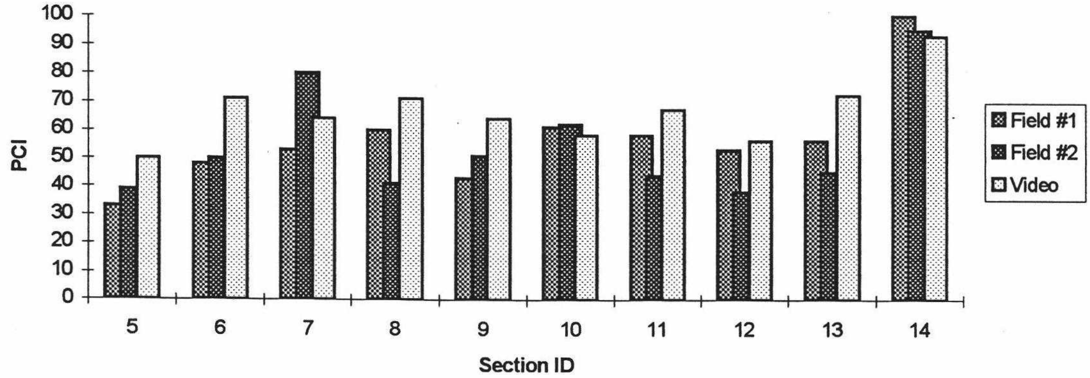
7.3 Evaluation by MTC-PMS

The overall condition evaluation by MTC-PMS for each large section is described below in Figure 7.9. The data field #1 and field #2 are the result of inspection by author and an other independent surveyor, respectively. As shown in Figure 7.9, the overall shape of the PCI distribution for each area is generally well matched for each inspection outcome. However, it is observed that the PCI values for video inspection show generally higher values than the two field inspections. Also, for HW 99W sections, it is observed that there are significant differences between the results of the field #2 survey and the results of the other two inspections. The PCI values for HW 99W sections by the field #2 inspection show high PCI values; this is due to extensive patching work in this area since the field #1survey.

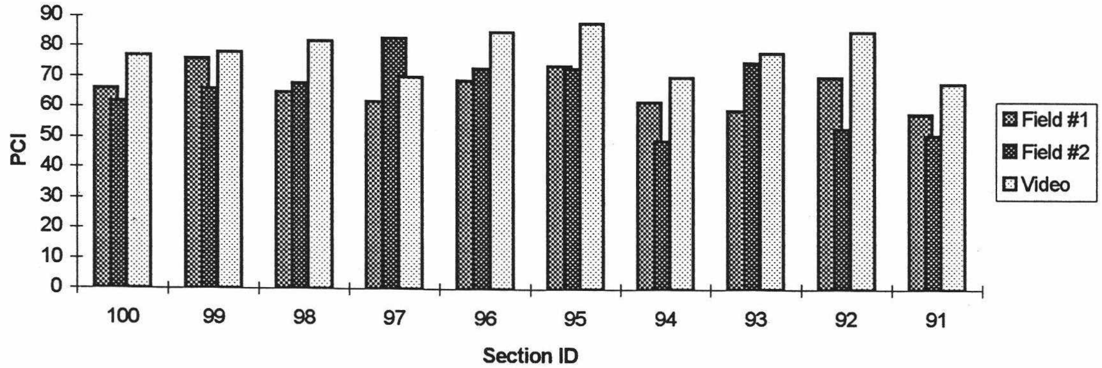
To evaluate the system performance using MTC-PMS, the results are analyzed using certain statistical approaches. To evaluate the accuracy of the test results, the two-sided paired test is applied for the 67 pavement sections. In this test, patching work-applied sections in HW 99W are not included in analysis of field #2 data.

The results of paired t-test are summarized in Table 7.4. The small p-values are represented in bold-italic (level of significance = 0.05). As seen in Table 7.4, for overall sections, t-test of video vs. field #1 and video vs. field #2 show very small overall p-values. These p-values imply there is strong evidence for rejecting the null hypothesis from the field and video evaluation comparison. It means there is strong evidence that the PCI of the video inspection was higher than the PCI of field inspection #1 and field inspection of #2 (for field #1, paired t-statistic = 4.3459 with 66 degree of freedom (d.f.); 2-sided p-value = 0.00005; for field #2, paired t-statistic = 3.0401 with 60 d.f.; 2-sided p-value = 0.0035).

HW99E AC



HW20 AC



Granger Av. AC

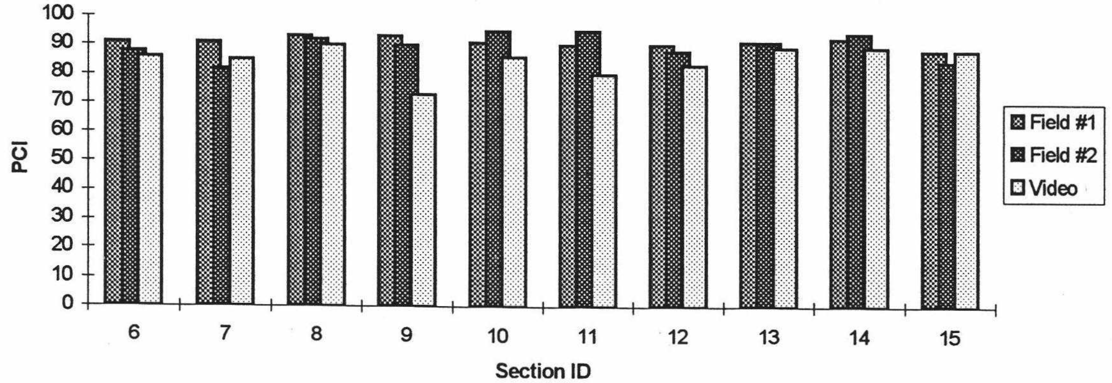
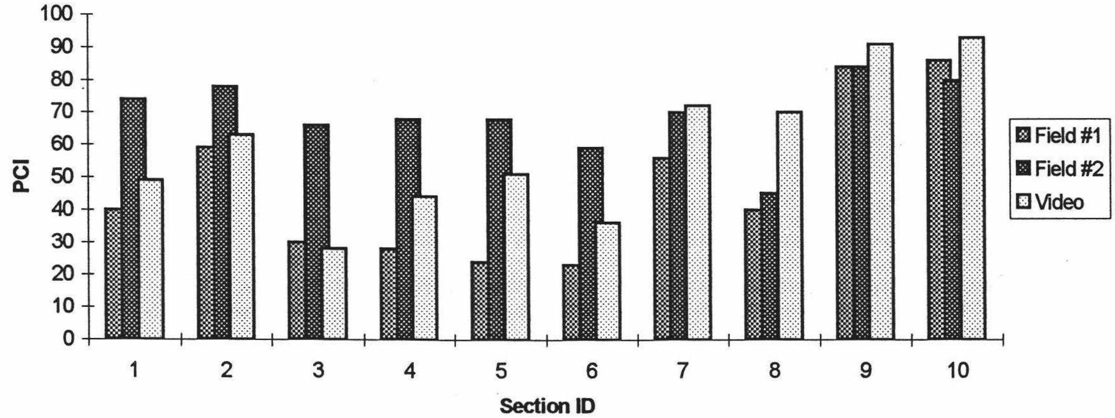
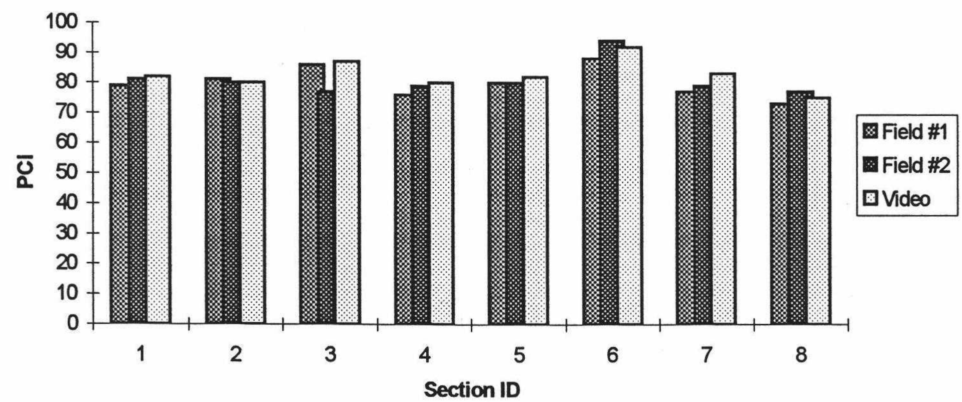


Figure 7.9 PCI Comparison for Video and Field Evaluation by MTC-PMS.

HW99W AC



Walnut JRCP



Walnut-Harrison AC

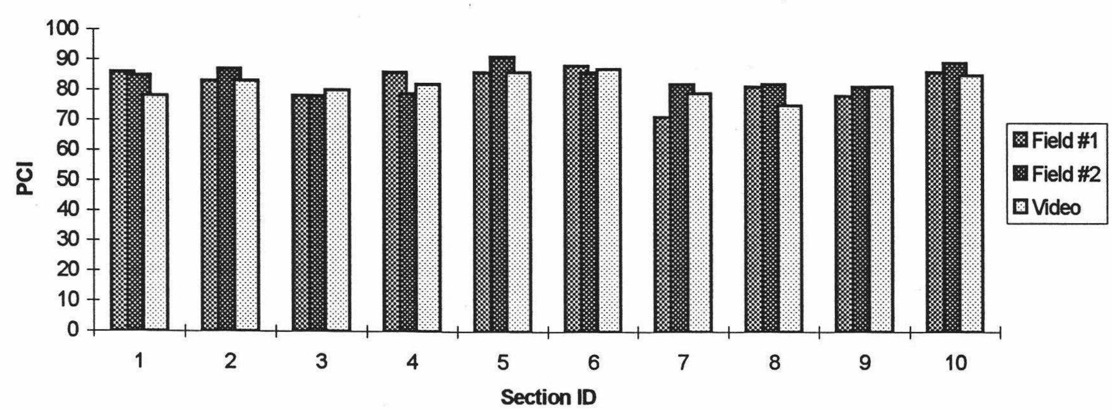


Figure 7.9 PCI Comparison for Video and Field Evaluation by MTC-PMS (Continued).

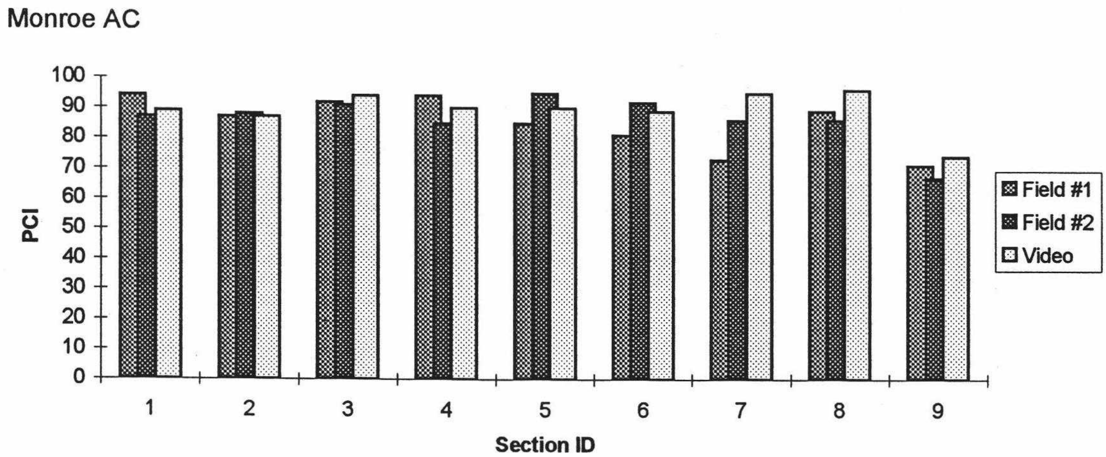


Figure 7.9 PCI Comparison for Video and Field Evaluation by MTC-PMS (Continued).

Table 7.4 Paired T-test for MTC Evaluation.

		Video - Field #1	Video - Field #2	Field #1- Field #2
Overall		***0.00005***	***0.00350***	0.89414
Road Name	HW99E	***0.01047***	***0.03115***	0.65834
	HW20	***0.00004***	***0.00710***	0.84035
	Granger Av.	***0.00753***	***0.04839***	0.42057
	HW99W	***0.00300***	0.09843	0.49827
	Walnut	***0.01028***	0.24300	0.60332
	Wal-Har.	0.64155	0.06781	0.29034
	Monroe	0.15325	0.12593	0.66536

The overall PCI mean of the field #1 was smaller than the overall PCI mean of video by 5.06. A 95% confidence interval on the mean difference is calculated as 5.06 ± 2.28 (from 2.78 to 7.34). Also, the overall PCI mean of field #2 was smaller than the overall PCI mean of video by 4.31. A 95 % confidence interval on the PCI mean difference is estimated as 4.31 ± 2.78 (from 1.53 to 7.09). Thus, from the paired t-test, it is estimated that the overall PCI values for video inspection is higher than overall PCI values for field inspections. Many reasons can be included for these high PCI values for video inspection. In particular, the video inspection has some general limitations for detecting some types of distress, such as raveling. Also, video limited the determination of the amount of distress extent, since the MTC evaluation is processed on video frame by frame.

The p-values from the paired t-test for each road section are also shown in Table 7.4 above. The table shows that some sections have significant evidence of PCI differences between video and field evaluation (small p-values), while other sections show no significant differences. Focusing on the t-test of video vs. field #2 inspections, the p-values for HW99E, HW20, and Granger Avenue sections are lower than the significance level of $\alpha = 0.05$, while p-values for the other sections are higher than the significance level. However, the t-test for field #1 and field #2 shows no significant differences between the two inspections.

In Table 7.5, the correlation coefficients (ρ) for overall sections and each road section are described. The ρ values for overall sections show generally good relationships between inspections. For ρ values on individual road sections, they also show relatively good relationships. However, some road sections (such as Granger Avenue and HW20) show poor relationships.

Table 7.5 Correlation Coefficient (ρ) for MTC Evaluation.

		Video - Field #1	Video - Field #2	Field #1- Field #2
Overall		**0.88321**	**0.74956**	**0.85454**
Road Name	HW99E	**0.84173**	0.61776	**0.71720**
	HW20	0.69820	0.26536	0.12914
	Granger Av.	-0.17288	-0.02938	0.38451
	HW99W	**0.90586**	**0.83658**	**0.93844**
	Walnut	**0.91049**	**0.73232**	0.62808
	Wal-Har.	0.53259	0.59591	0.52099
	Monroe	0.46041	**0.75314**	0.51412

In Figure 7.10, the regression analysis for PCI values for each inspection is presented. The three categories of analysis show linear relationships for each inspection. The linear regression equations are provided. The equations are expected to be very useful in predicting the real pavement conditions from the video inspection. The R^2 values in the Figure show good relationships for field and video inspection.

The regression analysis is extended in an analysis of variance (ANOVA), described in Table 7.6. The purpose of this ANOVA test is to assess the fit for the simple linear regression models produced [Ramsey and Shafer, 1997]. The ANOVA test examines the hypothesis that slope factor (β_1) is zero. From the ANOVA table, the p-values or significance of F can be obtained from F-statistics. The three regression models show very low p-values, which mean strong evidence for rejecting the null hypothesis. Therefore, the linear regression models are sufficient to explain the relationship between two inspections.

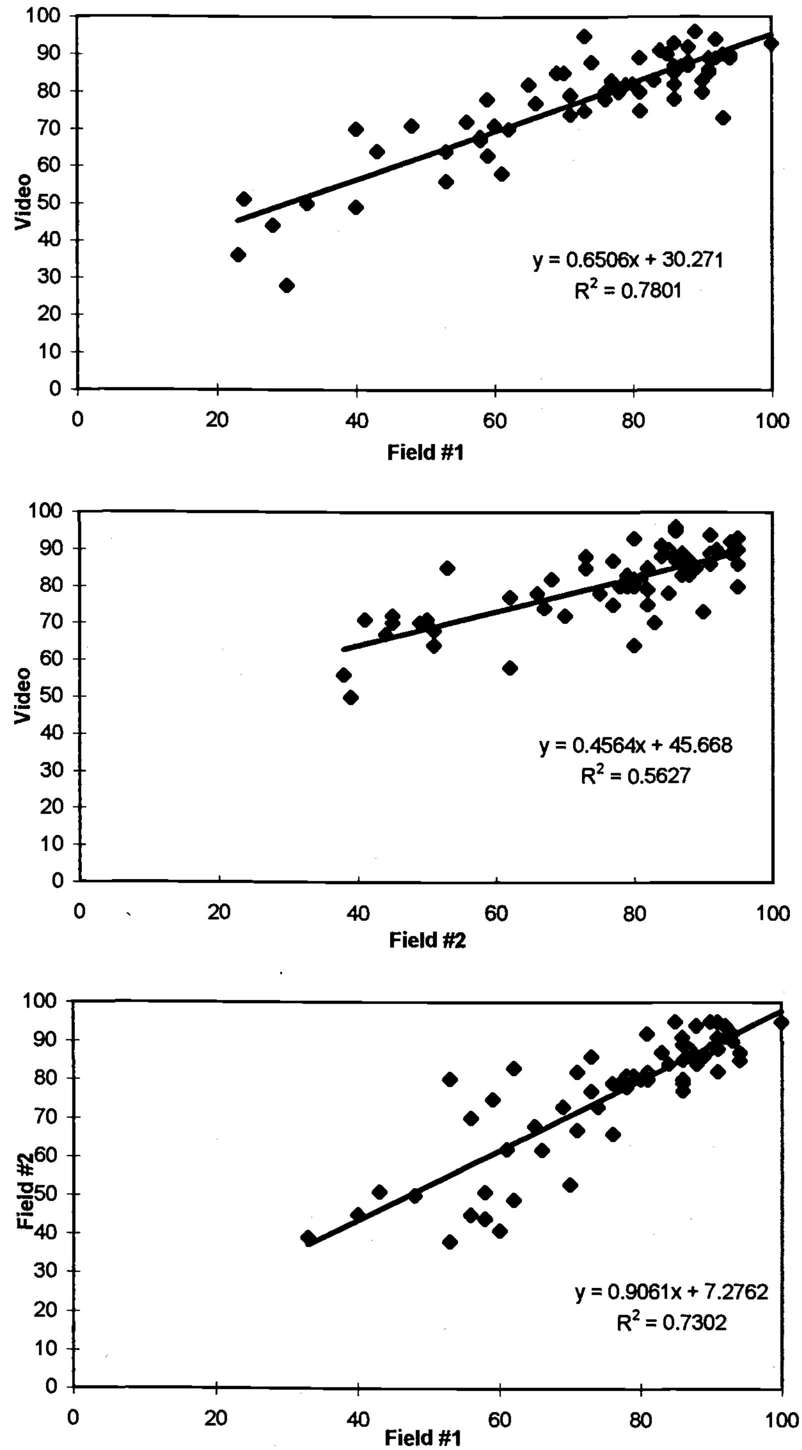


Figure 7.10 Regression Analysis for PCI values by MTC Evaluation.

Table 7.6 ANOVA Test for Linear Regression Models.

Regression		ANOVA Table				
		Degree of Freedom	*Sum of Square*	*Mean Square*	*F Statistic*	*Significance F*
Field #1 vs Video	Regression	1	10510.12	10510.12	230.5222	4.69297E-23
	Residual	65	2963.52	45.59		
	Total	66	13473.64			
Field #2 vs Video	Regression	1	3345.34	3345.34	75.6520	3.65457E-12
	Residual	59	2608.99	44.22		
	Total	60	5954.33			
Field #1 vs Field #2	Regression	1	11736.10	11736.10	159.7068	1.97037E-18
	Residual	59	4335.63	73.49		
	Total	60	16071.74			

In Figures 7.11 - 7.13 below, the total PCI deduct values for alligator cracking, linear cracking, and weathering and raveling are displayed. The three distress types are distress types mainly detected during the inspection by the MTC approach. As shown in Figure 7.11, the deduct values in alligator cracking are mainly observed on four road sections (HW99E, HW20, HW99W, and Walnut-Harrison). For HW99E and HW20 sections, the deduct values from field inspections show higher values than video inspections. However, on HW99W and Walnut-Harrison sections, the distribution is almost same. The field #2 inspection of the HW99W section shows low deduct values, since there was a patching work performed after the first filed inspection.

Longitudinal and transverse cracking is detected in almost all of the sections, as shown in Figure 7.12. Generally the deduct value distribution is similar for each inspection. The total deduct values by video inspection are usually higher than field inspections. As shown in the distribution of deduct values for two crack type distresses, the distress observations generally occurred in both field and video inspections. However, there was some discrepancy in estimating the extent of distress between the two inspections. Since, for MTC application in this study, frame by frame sampling approaches are applied, it is assumed that extent measurements do not reflect the total extent of the inspected section. Thus, it is desirable to correct the inspected results from the proposed video inspection approach with proper conversion factors. Thus, before implementation of video logging by MTC-PMS can go forward, further study is required.

As shown in Figure 7.13, weathering and raveling distress is not observed or estimated any less than the observation through field inspections. Since the weathering and raveling do not appear very clearly in video images, this type of distress may be difficult to detect correctly by video logging. Thus, weathering and raveling distress may require alternative detection methods to that of video logging. However, generally weathering and raveling are not significant for pavement condition evaluation. The MTC evaluation in this study also shows that the PCI deduct values are much smaller than PCI deduct values from other distress types.

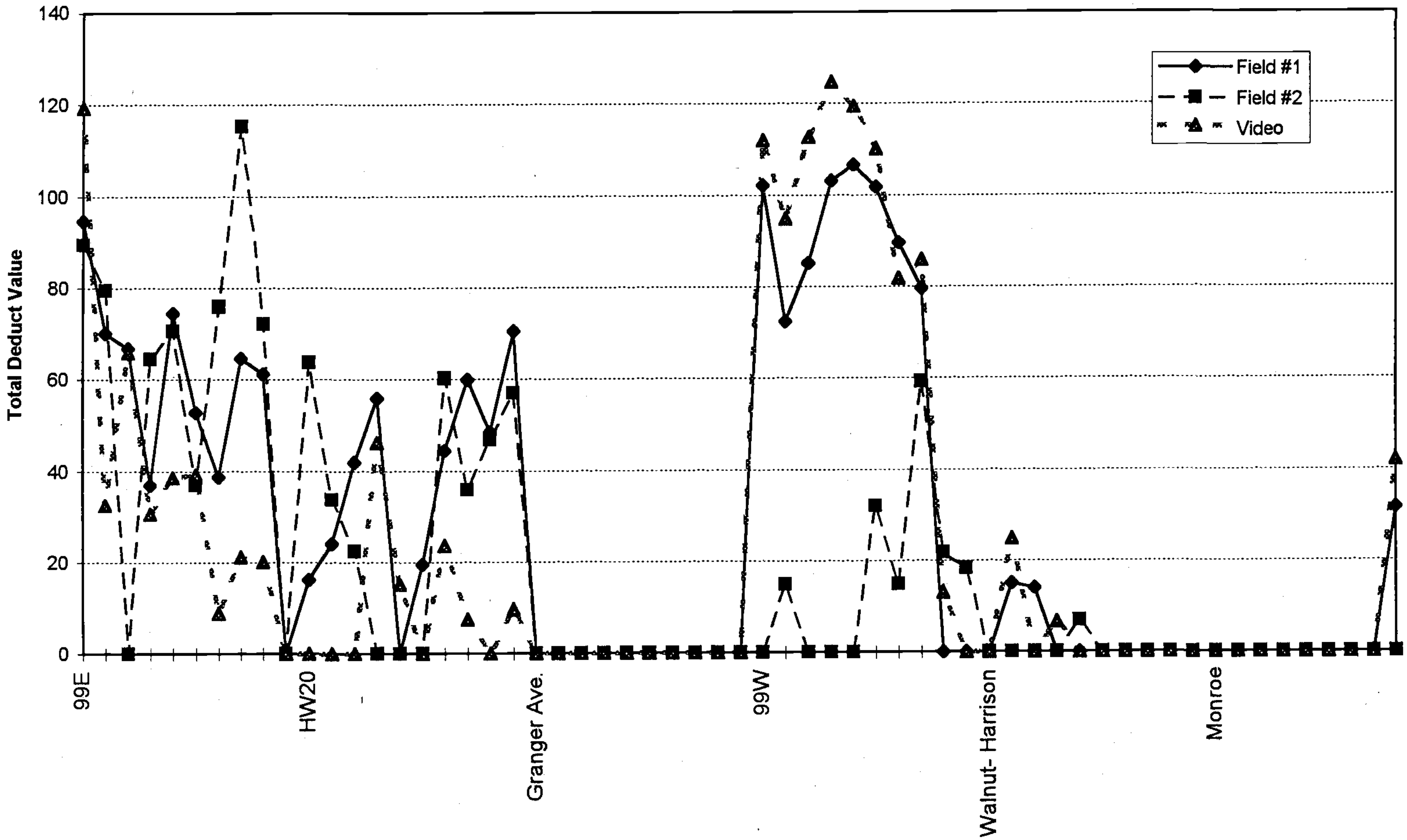


Figure 7.11 Total PCI Deduct Value for Alligator Cracking.

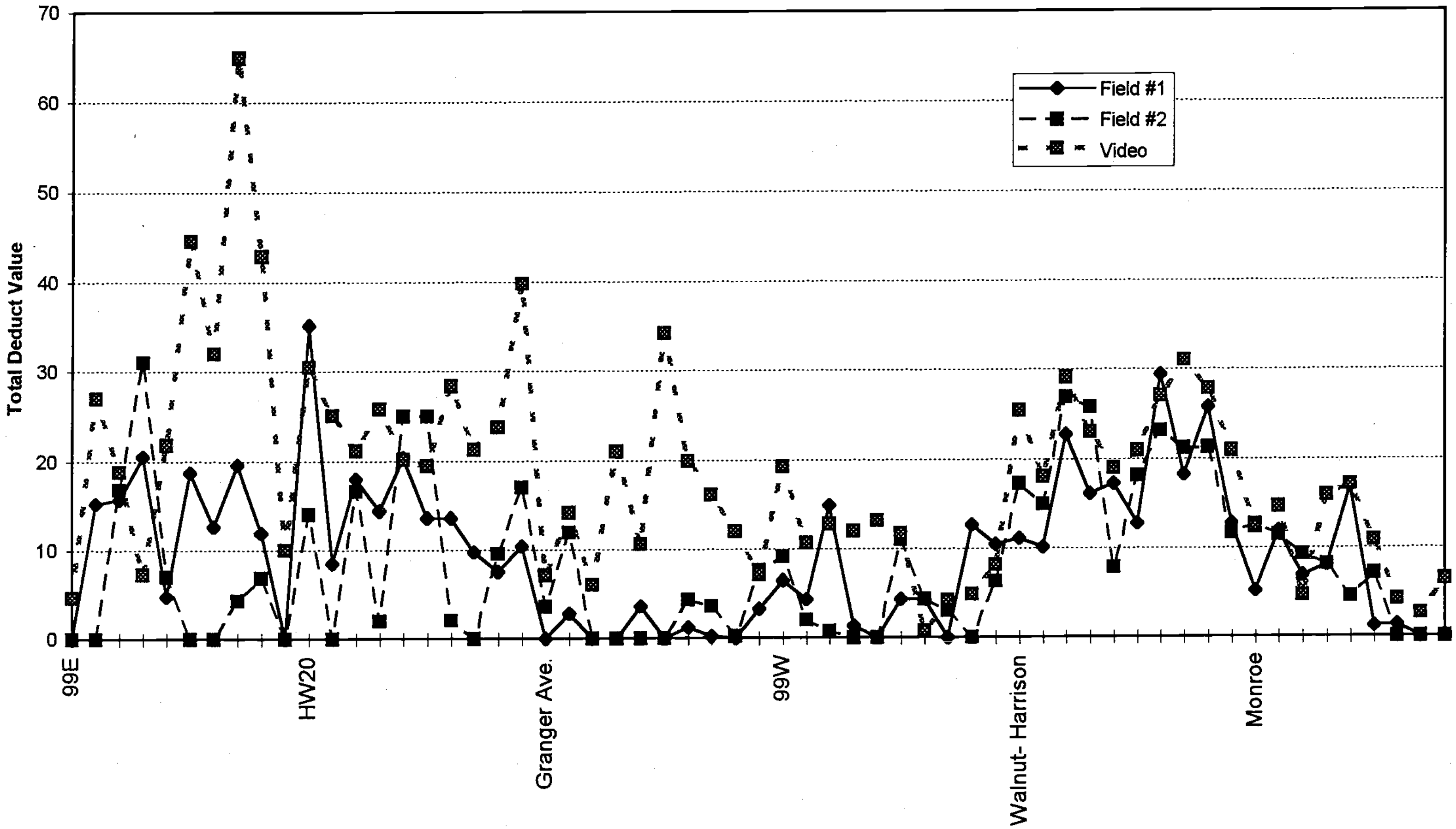


Figure 7.12 Total PCI Deduct Value for Longitudinal and Transverse Cracking.

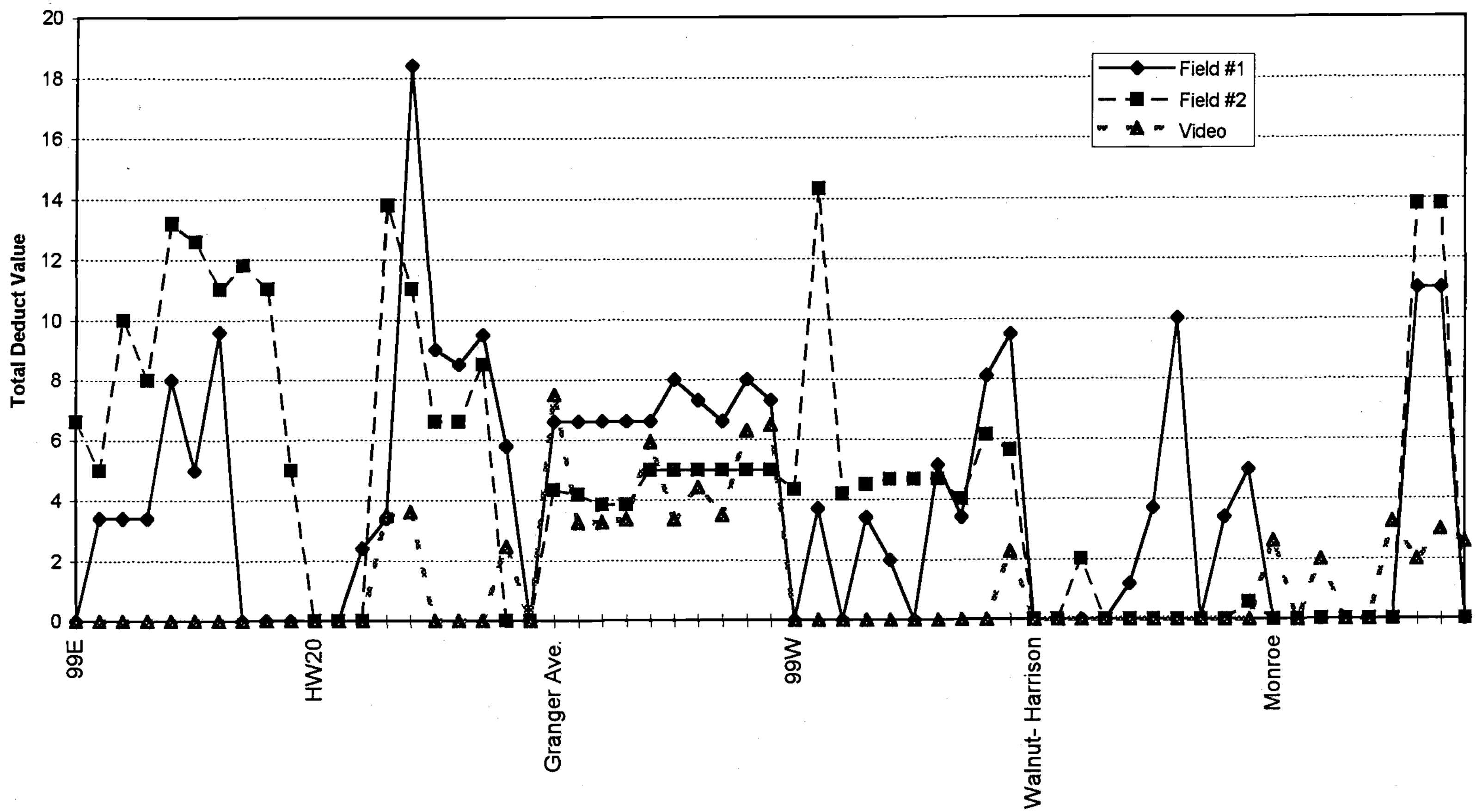


Figure 7.13 Total PCI Deduct Value for Weathering and Raveling.

7.4 Comparison of Video Evaluation by MTC and ODOT Approaches

In this study, two pavement evaluation approaches (MTC & ODOT) are applied on designated pavement inspections. The two approaches are different in many aspects of pavement management activities including management philosophy, maintenance strategies, inspection procedures, condition calculations, condition categories and so on. However, it is expected that the two approaches have some relationship on their final condition index values, considering they have the same scale with similar condition category definitions. In Figure 7.14, video evaluation results by two approaches are described. The x-axis represents overall index values from the ODOT video evaluation. The y-axis shows PCI values from the MTC video evaluation. A total of 67 sections are plotted on the Figure.

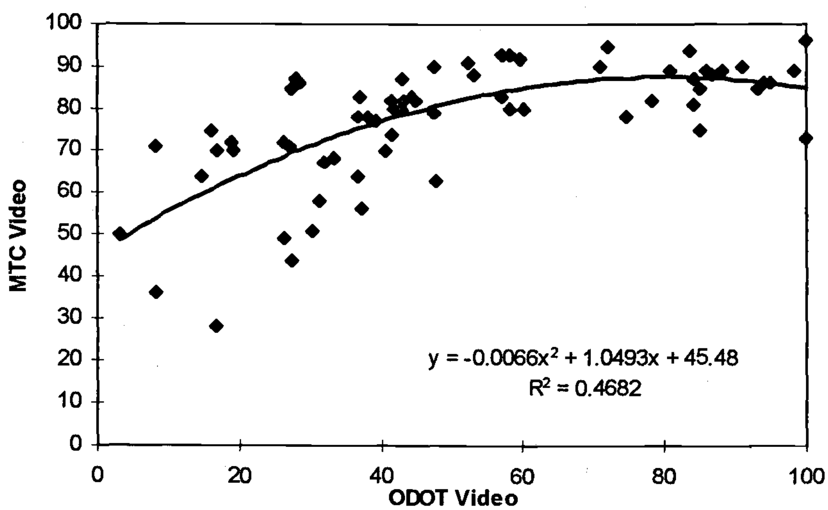
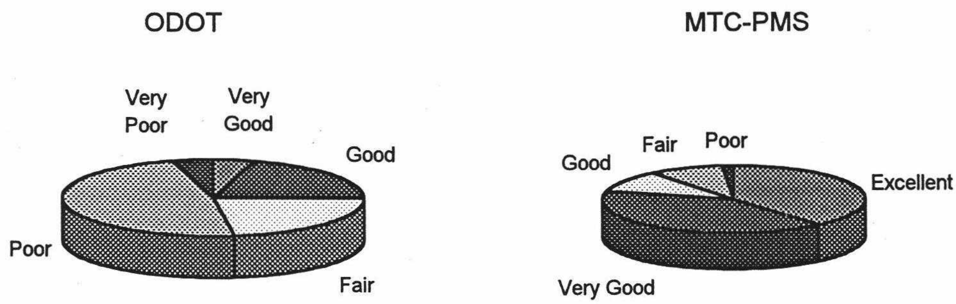


Figure 7.14 Comparison of Video Evaluations for ODOT and MTC Approach.

As shown Figure 7.14, the relationship of video evaluation by the two approaches is reasonably explained by a second order polynomial equation ($R^2 = 0.47$).

It is observed that the MTC evaluation is generally a higher condition index than the condition index evaluation by the ODOT approach.

As seen Figure 7.15, pavement condition categories from the two approaches are compared. The condition of 67 sections are classified by several categories; excellent, very good, good, fair, poor, very poor, and failed. The index values for each category is different for each approach.



Index Category	ODOT Overall Index	MTC PCI
Excellent	****	100-85
Very Good	100-99	84-70
Good	98-76	69-55
Fair	75-46	54-40
Poor	45-11	39-25
Very Poor	0-10	24-10
Failed	****	0-9

Figure 7.15 Condition Categories from Video Inspections by Two Approaches

As indicated in the Figure 7.15, most of sections examined using ODOT approach are classified as "poor" or "fair". However, most of sections examined using the MTC-PMS approach belong to "excellent" or "very good" categories. The average of the ODOT overall index is calculated as 50.8, while the average PCI of MTC is calculated as 77.2. Obviously, the MTC approach is more optimistic than the ODOT approach.

ODOT, however, has established a goal to have 90% of their pavements in "fair or better" condition. In 1996, ODOT evaluated that their 78% of pavements are in "fair or better" condition [ODOT, 1996]. For the MTC evaluation, the management goals vary by the different agency's situations. However, most agencies set their goals for "very good" conditions for their pavements [MTC, 1990]. Also, the ODOT approach is primarily focused on the pavement management of interstate highways or state highways, while the MTC approach is generally used for the pavement management of city or county streets. Thus, it is expected that more restrict maintenance strategies will be applied to the ODOT approach as opposed to the MTC-PMS method.

It is, therefore, not surprising to see different condition index values from the two approaches, since the management philosophies of the two systems are differ greatly. Even though there were large differences between the index values from the two approaches, each condition evaluation from video inspections is still considered to be very useful. Also, both approaches were considered here because some sections were "local" type and some sections were "state" type roadways.

7.5 Evaluation from Image Analysis

The unified crack index (UCI) values obtained from image analysis were also evaluated by statistical analysis to evaluate the repeatability and variable effects of the data. The statistical analysis is presented in this section.

7.5.1 Repeatability Testing

In this section seven test loops (treatments) of the evaluation methods of the crack index are compared. These seven treatments are described in terms of the several factors including vehicle speed, camera angle, lighting, and pavement condition as described in Chapter 4. Two additional variables were not intended to be included in the first stage of test design, they do effect to the performance of the video images. Thus, "time" and "shadow" were added subsequent to the inclusion of the first four variables. The time variable is divided into two categories, morning (AM) and afternoon (PM). Although the shadow effect was not a controlled variable, it is encountered in many of the sample video images, and the effect should be critical for the crack index calculation. As shown in Table 7.7, the six variables are considered for further analysis.

Table 7.7. Variables Used for Video Tests

Variables	**Loop1**	**Loop2**	**Loop3**	**Loop5**	**Loop6**	**Loop7**	**Loop13**
1. Speed	High	Low	High	High	Low	High	High
2. Camera Angle	Normal	Normal	Normal	Angle	Angle	Angle	Angle
3. Lighting	No	No	Yes	No	No	Yes	No
4. Condition	Dry	Dry	Dry	Dry	Dry	Dry	Wet
5. Time **	PM	PM	AM	AM	AM	AM	AM
6. Shadow	*	*	*	*	*	*	*

* The shadow effect is decided from observation of each image obtained.
** The time variable is evaluated using test time divided by two categories: morning (AM) and afternoon (PM).

From the UCI values obtained from images of the seven test loops, box-plots are displayed for AC pavements and PCC pavements (Figures 7.16 and 7.17, respectively). The box plots were created using S-PLUS statistical analysis software, version 3.3. In the box plots, the horizontal line in the interior of the box is located at the median point for the data. The boxes are located between the third quartile and the first quartile of the data. The outliers are indicated by horizontal lines [Statistical Sciences, Inc., 1995].

As seen in Figure 7.16, for AC images, loop1 shows a higher crack index distribution than the other test loops. For PCC images, as shown Figure 7.17, loop2 and loop5 are higher than the other test loops. It is deemed that shadow effects on the images produced the high crack index values in loop2 and loop5. To test the repeatability of each loop, further statistical analysis is required. The following statement describes this analysis.

Let, Y_{ij} be the jth crack index obtained from the ith treatment (test loop). Let $\mu+\tau_i$ be the expected crack index parameter from the ith treatment, i.e., $E(Y_{ij})= \mu+\tau_i$, where μ is the overall mean parameter regardless of treatments and τ_i is the parameter to compensate the ith treament from the overall mean parameter μ, i.e., $\tau_i = E(Y_{ij})- \mu$.

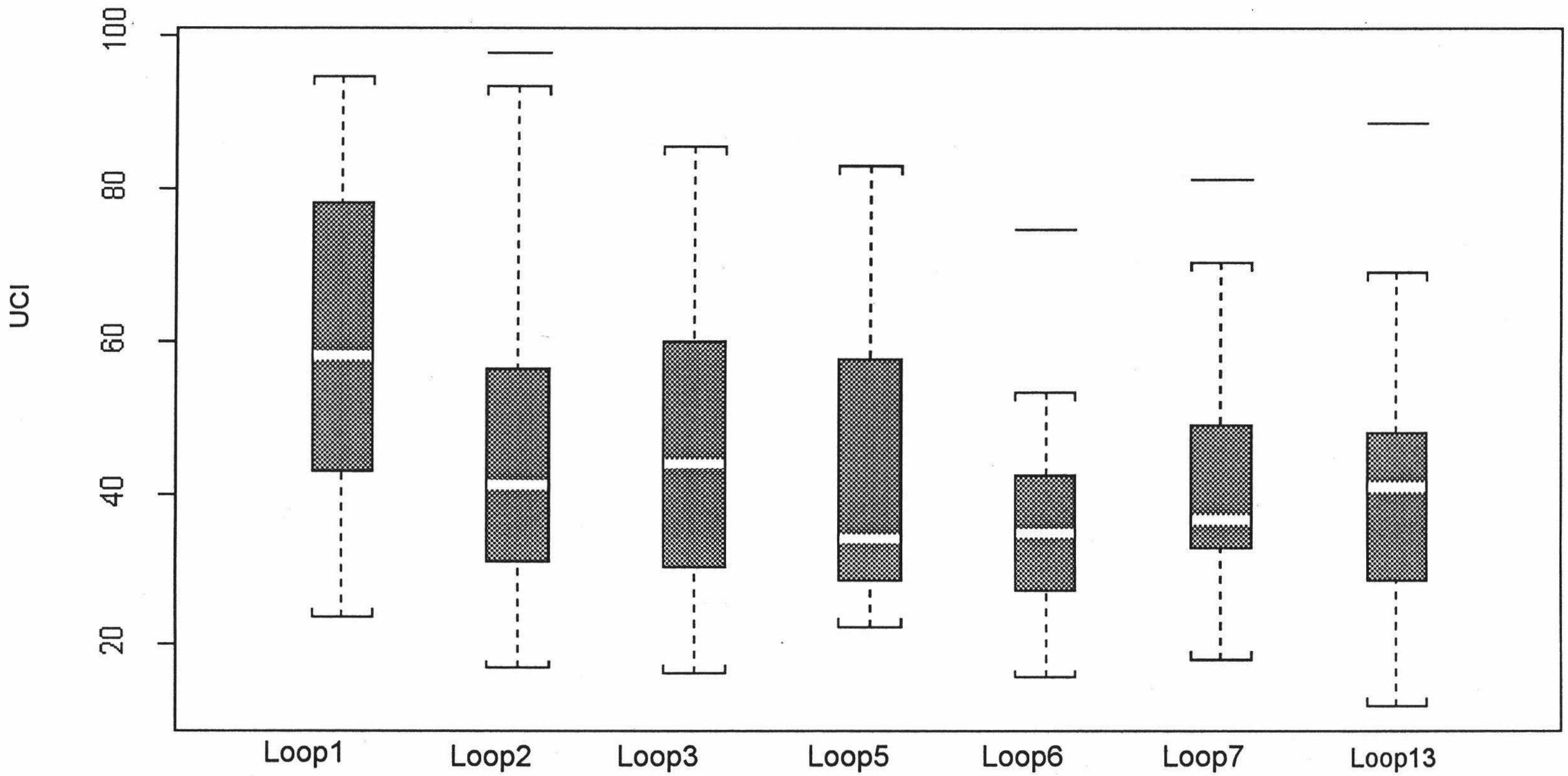


Figure 7.16 Box Plots of UCI Distribution for AC Section Images.

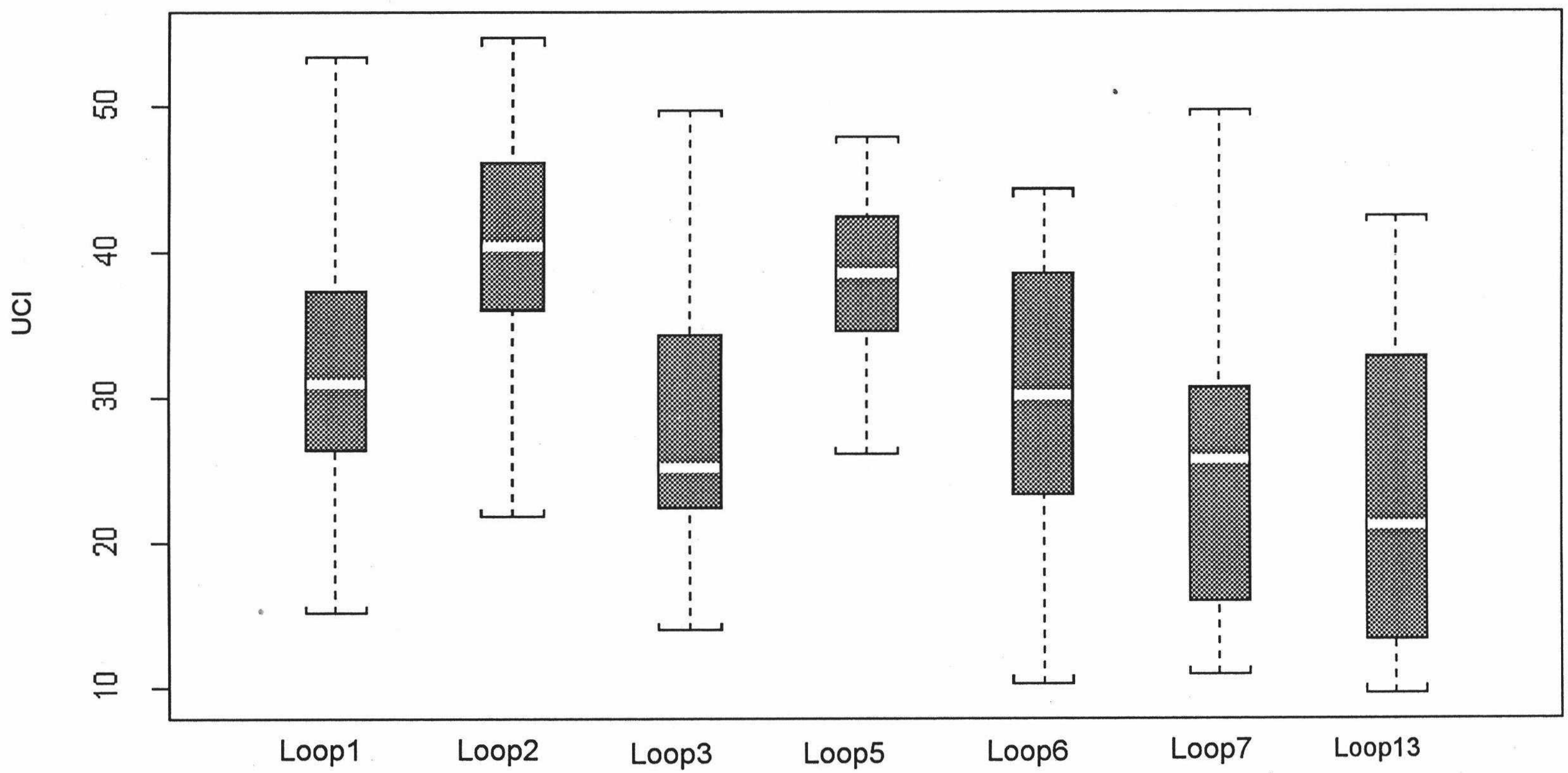


Figure 7.17 Box Plots of UCI Distribution for PCC Section Images.

The model that shall be considered for the observed crack index is,

$$y_{ij}=\mu+\tau_i+e_{ij} \qquad \text{(Eq. 7.3)}$$

where i=1,2,3,5,6,7,13 (video test loop number), and j=1, ..., n_i, e_{ij} is the random variable with the normal distribution with the mean equal to zero and the standard deviation as σ [Kleinbaum et al., 1997]. This model shows that the observed crack index y_{ij} is explained by the jth treatment effect, with random error accounting for the remaining variation.

A natural question to ask is whether these seven treatments or test loops lead to different conclusions of the crack index. To answer this question, a testing problem to be proposed is the null hypothesis that there are no differences in the expected crack indices between the seven treatments. This statement is equivalent to the simpler form of the null hypothesis, H_0: $\tau_1=\tau_2=\tau_3=\tau_5=\tau_6=\tau_7=\tau_{13}$. A statistical scheme for this testing problem is the one way Analysis of Variance (ANOVA).

The ANOVA procedure is designed to handle balanced data (data with equal numbers of observations for every treatment). The data set in this study includes some incomplete observations due to blurred images or technical difficulties in determining the same spots. These incomplete data sets are estimated by averaging across the repeated measurements of the same treatment and the observed crack indices on the same location across the other six treatments.

The ANOVA table for the testing problem of H_0: $\tau_1=\tau_2=\tau_3=\tau_5=\tau_6=\tau_7=\tau_{13}$ is given in Table 7.8. In the AC section images, the observed F value 5.44 is significant at the level of p=3.08344E-05. Also in the PCC images, the observed F value 9.41 is significant at the level of p=1.34209E-08. The two small p-values imply that there is a strong evidence for rejecting the null hypothesis. This means that there are significant differences in the expected crack indices between the seven test loops, indicating poor repeatability. Thus, from the image analysis, it was concluded that the repeated measures are not showed consistent crack index values for each test loop.

Table 7.8. ANOVA Test for Seven Test Loops

(AC Images)

SUMMARY

Groups	Count	Sum	Average	Variance
Loop1	30	1808.60	60.29	456.78
Loop2	30	1450.90	48.36	482.67
Loop3	30	1357.43	45.25	388.23
Loop5	30	1280.60	42.69	374.38
Loop6	30	1084.60	36.15	146.28
Loop7	30	1239.77	41.33	209.16
Loop13	30	1209.62	40.32	285.01

ANOVA

Source of Variation	SS	df	MS	F	P-value
Between Groups	10920.33	6	1820.06	5.44	3.08344E-05
Within Groups	67933.43	203	334.65		
Total	78853.76	209			

(PCC Images)

SUMMARY

Groups	Count	Sum	Average	Variance
Loop1	20	650.30	32.52	73.11
Loop2	20	799.95	40.00	67.77
Loop3	20	573.53	28.68	85.58
Loop5	20	761.81	38.09	35.73
Loop6	20	603.82	30.19	96.18
Loop7	20	501.57	25.08	107.60
Loop13	20	465.26	23.26	115.54

ANOVA

Source of Variation	SS	df	MS	F	P-value
Between Groups	4688.06	6	781.34	9.41	1.34209E-08
Within Groups	11048.77	133	83.07		
Total	15736.84	139			

For AC sections, as shown in Figure 7.16, test loop1 is suspected as an outlier since it shows a higher crack index than the other test loops. For PCC sections, as shown in Figure 7.17, test loop2 and loop5 show high crack index values. So, the tested the null hypotheses, H_0: $\tau_2=\tau_3=\tau_5=\tau_6=\tau_7=\tau_{13}$ (for AC sections) and H_0: $\tau_1=\tau_3=\tau_6=\tau_7=\tau_{13}$ (for PCC sections), excluding the observations which are classified as outliers. The ANOVA table for this reduced hypothesized problem is given in Table 7.9.

Table 7.9. ANOVA Test for Reduced Test Loops

(AC Images without Loop1)

SUMMARY

Groups	Count	Sum	Average	Variance
Loop2	30	1450.90	48.36	482.67
Loop3	30	1357.43	45.25	388.23
Loop5	30	1280.60	42.69	374.38
Loop6	30	1084.60	36.15	146.28
Loop7	30	1239.77	41.33	209.16
Loop13	30	1209.62	40.32	285.01

ANOVA

Source of Variation	SS	df	MS	F	P-value
Between Groups	2647.04	5	529.41	1.68	0.140701142
Within Groups	54686.67	174	314.29		
Total	57333.71	179			

(PCC Images without Loop2 &Loop5)

SUMMARY

Groups	Count	Sum	Average	Variance
Loop1	20	650.30	32.52	73.11
Loop3	20	573.53	28.68	85.58
Loop6	20	603.82	30.19	96.18
Loop7	20	497.48	24.87	105.15
Loop13	20	453.86	22.69	106.98

ANOVA

Source of Variation	SS	df	MS	F	P-value
Between Groups	1267.21	4	316.80	3.39	0.012225064
Within Groups	8873.07	95	93.40		
Total	10140.27	99			

In the Table 7.9, for AC sections, the observed F value 1.68 is significant at the level of the p-value 0.1407. This relatively high p-value indicates that there is insufficient evidence against the null hypothesis H_0: $\tau_2=\tau_3=\tau_5=\tau_6=\tau_7=\tau_{13}$. This high p-value suggests that there is no difference between the mean crack indices from six test loops. In other words, the mean crack index values for the six test loops are not significantly different.

For PCC sections, the observed F value 3.39 is significant at the level of the p-value 0.0122. This small p-value indicates that there is an evidence for rejecting the null hypothesis. This p-value indicates that there are still differences between the mean crack indices from the five test loops, even after the two loops were removed from analysis. This also means that there are significant differences in the expected crack indices between the five test loops, indicating poor repeatability.

7.5.2 Linear Model Analysis for Variable Effect Testing

In the previous section, seven treatments with various combinations of factors are compared to see if there are any differences between the mean crack indices from the different treatments. These factors, listed in Table 7.7, include the vehicle speed, camera angle, lighting, pavement condition (dry/wet), and time (morning/afternoon). These five factors will be indicated by variables x_1, x_2, x_3, x_4, x_5 , respectively. In addition to the five variables some shadow affect has been encountered in the sample images. To control the shadow effect, each sampled image was categorized into one of two groups: the image with significant shadow effect and the image with insignificant shadow effect. The variable x_6 is used to indicate the existence of a shadow effect. The model equation that shall be used is;

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + e_I \qquad \text{(Eq. 7.4)}$$

where e_i is the residual error in the normal distribution with mean zero [Kleinbaum et al., 1997]. The general linear model procedure in the SAS software on the UNIX DEC system is employed to evaluate the six estimated coefficients of x variables in the model of Eq. 7.4 [SAS/STAT user's guide, 1990]. The output table is given in table 7.10.

Table 7.10. Result Summary by General Linear Model Analysis.

			T-Statistic	P-Value	Estimate	Note
AC	Model Estimation		8.24*	**0.0001**		
	Variables	Speed	3.35	**0.0010**	8.3918	high speed
		Angle	-0.96	0.3385	-3.6247	angled camera
		Lighting	0.92	0.3598	3.2450	without lighting
		Dryness	1.61	0.1085	6.1811	dry condition
		Time	2.31	**0.0223**	10.4338	morning
		Shadow	2.37	**0.0189**	6.7330	shadow effect
PCC	Model Estimation		15.17*	**0.0001**		
	Variables	Speed	-1.41	0.1618	-1.7888	high speed
		Angle	-1.53	0.1277	-2.8524	angled camera
		Lighting	4.81	**0.0001**	8.1832	without lighting
		Dry	4.01	**0.0001**	7.3057	dry condition
		Time	-1.21	0.2278	-2.7342	morning
		Shadow	12.42	**0.0001**	15.9784	shadow effect

* : For model estimation, F-statistic is used.

In Table 7.10, two general linear models (for AC and PCC) are estimated using F-statistics. The p-values are calculated as 0.0001 for both AC and PCC. These small p-values mean that there is strong evidence to reject the null hypothesis, *Ho*: $\beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = 0$. In another words, the crack index values with the variable effects are explained very well by the developed linear models.

The significance of each variable is tested by the t-statistic as shown in the Table above. The p-values indicate the level of significance of the t-statistic. The small p-values indicate that there is strong evidence to reject the null hypothesis, *Ho*: $\beta_i = 0$. These small p-values mean that the variables have significant affect to the crack index values. The "estimate" column on the Table 7.10 indicates the estimation of the degree to which the variables affect to the crack index values. For example, the speed variable in AC sections affects positively in crack index values as 8.3918 by high-speed control. In other words, crack indices from high speed data are higher than low speed crack indices by 8.3918.

The small p-values are indicated above in bold. For AC pavements, the significant variables are "speed", "time", and "shadow". The "speed" variable indicates that the high-speed images have significantly higher crack index values than slow-speed images.

However, the reason for the significance of the "speed" variable on AC is difficult to ascertain. It is suspected that the crack indices of loop1 greatly affected the speed variable estimation, since loop1 has very high index values. Further study of this area is required.

The "time" variable is categorized as morning and afternoon. This variable explains the differences by repeated measure in a different time rather than just morning or afternoon. The repeated measure could vary by different environmental conditions even on the same day. The small p-value for the time variable indicates that the differences from repeated measures tend to be more serious in AC than PCC. Also, as expected, the "shadow" effect is very significant to crack index values.

For PCC pavements, the significant variables are "lighting", "dry", and "shadow". The "lighting" variable indicates that lighting can be sensitive on the PCC pavements. It can be explained by the reflectivity concept. The PCC surface has a reflectivity of 0.30 to 0.35, while asphalt has a reflectivity of 0.05 to 0.1[El-Korchi and Wittels, 1990; Averly and Berlin, 1992]. The reflectivity of 0.30 means that 30 percent of all the incident light is reflected back from its surface. This implies, even with a very weak intensity of lighting, that the lighting on PCC surface can be reflected more than AC surface. It produces more bright images in PCC than AC, which is producing low crack index values.

The "dry" variable is estimated to be significant. In this test, however, ideal dry and wet conditions were difficult to control. Thus, only one test loop (loop13) was treated as wet pavement condition. Unfortunately, even this test loop was not a very good "wet pavement condition". Therefore, it is doubtful that this dry variable shows any truly meaningful results.

The "shadow" effect is estimated as a significant variable. Both in AC and PCC, shadow was a big problem. Thus, for video image processing, shadow effects should be controlled by proper techniques such as artificial lighting. As described in section 3.3.3, to remove shadow effect, the high-powered lighting (approximately 5,000 Watts) should be considered.

The above analyses using the crack index concept implies some limitations, since the crack index calculation does not necessarily reflect correct surface conditions. It is observed that the index calculation is affected by the various factors listed below;

1) The digitized images have distortion and blurring on the top and bottom parts of the images.
2) The images from the same location are not displayed in perfectly the same place.
3) Although the effects are possibly consistent, the characters in the images were also processed for calculation, producing incorrect crack information.
4) The white lane strip in images produces unexpected results.
5) The joints in jointed PCC images are also considered as cracks.

Additional error may have been introduced because the above statistical analysis is also based on relatively small sample sizes. Some analysis results may be difficult to accept without more testing. The analysis of this section, however, shows very promising results in various aspects. The significant variables which are used in image data collection are estimated by statistical analysis. The analysis results could be applied for future system development or image-processing process development.

7.6 Discussions for Proposed System Evaluation

The proposed video imaging system is evaluated in this section by all of the research elements. The evaluation description is based on the evaluation performed on this project, including: system element selection, field video image collection, video inspection in office, and analysis results of the system performance.

7.6.1 Video-Image Collection System

Video Camera

The video camera used for this study performed adequately to accomplish the purpose of this study. The camera was light enough to place on the mounting bars, and the camera shutter speed (maximum 1/90,000 sec) was fast enough to capture the movement of the road surface during high speed driving. The camera has a variable shutter speed that was operated in the auto-shutter mode. The camera controls the shutter speed automatically; when it detects high-speed motion, the shutter speed is automatically increased up to setting mode (e.g. 1/90,000 sec for this study). The function was very useful in most cases. However, for some reason, at times if the camera did not detect the change to high-speed motion, the shutter speed is dropped to lower level causing *image blurring* on the video pictures.

The blurring problem occasionally occurred during the field video test. The problem usually occurred when the camera detected an insufficient incoming light level. The failure of the night survey was partly due to this problem. Wide shadow effects or abrupt changes in vehicle driving speed also produced the blurring problem. The problem was almost unpredictable; however, they could be solved if the shutter speed could be set at the maximum level. The fixed shutter mode requires an additional camera device. Otherwise, the camera should be replaced with an alternative model, since some cameras are produced as a fixed mode or alternative mode for their shutter speed-operating mode. Thus, the modification from auto-shutter mode to fixed shutter mode is expected to increase the quality of video image for purposes of this research.

Camera mounting system

The camera mounting system was generally acceptable for the purpose of this study. However, the mounting system was a fixed structure designed to allow camera angle adjustment only in longitudinal directions. More adjustments to permit diverse camera movement are required to enhance the capability of camera detection. It may also be necessary to design a more flexible system to meet safety requirements and to allow for mounting of multiple cameras. And finally, further flexibility to adjust the camera angle for transverse directions is important to detect the condition of shoulder pavements or adjacent lane pavements.

Survey vehicle and on-board equipment

The survey vehicle and on-board equipment of ODOT were used for this study without significant modifications to the current equipment structure. Their equipment was generally acceptable for the purpose of this study. However, some modification of the equipment structure would enhance the future capability of the system (such as an additional generator for lighting).

Lighting

The lighting was a critical problem in the video imaging system. The video image can be affected by shadows from trees, camera mounting bars, the survey vehicle itself, and other vehicles. The direction of the sun can also change the image from one time of day to another. To reduce or remove the shadow effect, artificial lighting is required. Lighting is also necessary to produce consistent incoming light levels. The lighting can be designed by various ways. The survey with lighting can be conducted both day and night. The night surveys with fixed lighting is expected to produce consistent light level condition. The lights can be set at certain angles so that consistently created shadows can be used to help identify crack width, elevation differences, etc [Smith, 1995]. If still video images are of major concern, strobe lights can be used. El-Korchi et al [1991] presented various aspects of lighting design for pavement surface distress evaluation. Also, as mentioned in Chapter 3, the GERPHO system uses a total 5,000 Watts lighting device [Hudson et al., 1987]. Guralnick et al. [1996] proposed a road inspection vehicle with totaling 4,100 Watts.

DMI

To identify the locations during vehicle driving, the DMI was used. This device, however, introduces some errors, which are sometimes rather large. The errors are cumulative in nature, increasing with driving distance. Errors are usually introduced during driving, since the vehicle drivers are unable to consistently drive in the center of the driving lane. DMI operation also introduces errors. Usually the DMI is operated by pressing the device button when the vehicle passes by a standard point (such as a milepost) of the roadway during high speed driving. If the operator presses the button early or late by only 1 or 2 seconds, large distance errors are introduced. However, as suggested earlier in this study, it is desirable to use the GPS technique in conjunction with

DMI. GPS techniques provide a sophisticated approach with precise location information. If using a real-time GPS processor, exact distance information can be acquired instantly.

7.6.2 Video Images

Image Coverage

The video images obtained from the proposed video imaging system displayed reasonable image quality for video logging and image processing. To enhance the capability of the system, it may be desirable to enlarge the image coverage. Current study sets the image width at 10 feet. Each frame of video image displays an image size of 10 feet wide and 7.5 feet long. This image coverage generally covers both wheel tracks, which are the most damaged parts on the pavement. However, sometimes it may be necessary to detect the pavement condition for more than the 10×7.5 feet coverage area. The pavement condition of the shoulder may be of major concern to pavement managers. Also, for jointed PCC pavements, detection of the shoulder and lane joints are generally required simultaneously to determine the condition of concrete slabs. Unfortunately, if the image coverage with single camera is increased, a degradation of image resolution and image distortion results. The use of multiple cameras may be considered to enlarge the image coverage without degrading the image resolution. If the same type of camera were used in this study is considered, two cameras could cover the required detection area with some overlap at the center.

Image blurring

The problem of image blurring was explained in detail in the previous section. Image blurring is produced by a combined operation of shutter speed in the video camera, natural lighting, artificial lighting, show effects, and varied driving speeds. For efficient and consistent video imaging, control of image blurring is required.

Image distortion

There was some image distortion in video images in both perpendicular and angled camera orientation. The video images from the perpendicular camera distort radially outward from the image center. The video images from the angled camera are displaced radially toward on the upper side of images and radially outward on the lower side of images [Avery and Berlin, 1992]. The exact amounts of image distortion are difficult to calculate. However, the image distortions can lead the interpreter to erroneous inspection interpretations, especially in decisions as to distress extent. During this study, the image distortions were ignored. For more accurate and precise image processing, it would be desirable to account for the image distortions.

Image resolution

Image resolution was not a big problem for the video inspection in this study. During video inspection, low severity cracks (crack width less than 1/4" for ODOT and 3/8" for MTC) could be detected by visual interpretation. However, in an advanced designed system for digital image processing, the image resolution could become an important issue. Since the system uses videotapes for image storage, there was some resolution degradation. To improve the image resolution, several options can be considered. Use of multiple cameras would provide improved image resolution, since each camera could cover smaller areas than the single camera. Also, if different storage devices were used, the image resolution will improve significantly. Examples that may be considered include S-VHS videotapes (400 lines of horizontal resolution), laser discs (450 lines), CD disk, and computer hard drives.

7.6.3 In-Office System

For the in-office system, several devices were assembled to provide a desktop image-retrieval system. Most of the system devices operated successfully for the research objectives of this study.

Error message on PC screen

The biggest problem encountered during the video inspection was to display a continuous video image on two different screens. For slow moving, frame advance, or pause operations of VCR, the PC screen often showed an error message, since the image capturing card was unsuitable for these operations. If the error message appears, it is required to click "OK" icon every time to advance the screen. This control delays the video inspection and produces a difficulty for displaying same video image in two screens simultaneously. However, it is expected that improved image capturing boards could solve the problem.

IR4 controller

The IR4 VCR controller is used for video inspection. However, the controller requires another computer for operation. The operation of two computers requires two operators to control the system. However, if only one computer can control the system, it may simplify the system and reduce operation costs. This can be accomplished by a modification of the IR4 control software or by a purchasing another high-cost, sophisticated computer controlled VCR equipment.

7.6.4 Limitations of Video Distress Inspection

Depth related distress

The video distress inspection has some limitations in detecting some types of distress. Depth related distresses (such as rutting, depressions, corrugations for AC or faulting for PCC) are very difficult to detect from video inspection, because basically the video images are represented on two-dimensional display monitoring screens. These types of distress were not considered during this study.

However, most of agencies have other options for measurement of these types of distress. It is possible to use other equipment to measure the depth-related distresses. The "rut bar" is the most commonly used device for detecting rutting. This device can be attached to the video-imaging vehicle without great difficulties. Most of transportation agencies such as ODOT performed a rutting investigation regularly using the rut meter device. Therefore, even the video imaging system has limitations for detection of depth related distress, it may not big problem for application of video imaging system to agency's pavement management.

Texture related distress

Texture related distress (weathering and raveling) is another limitation of video inspection. Weathering and raveling do not appear on video images very well. The pavement texture on the video images varies considerably between different test loops. Therefore, the weathering and raveling should be interpreted by another approach rather than visual video inspection. Grivas et al. [1994] proposed a mathematical morphology technique to detect surface texture of pavement images. Since these types of distress are not considered critical to pavement performance, this limitation may not be serious.

Patching distress

Patching over a wide area was also hard to detect. Patching in small areas can be detected from video images, since the inspector finds the contrast between patched area and non-patched area. However, if patching is distributed over a wide area more than single image coverage size, the inspector can not see the contrast. Thus, to detect the large patched areas, it is desirable to record those kinds of patching distress information during video image collection. Then, the recorded information can be communicated to an in-office video inspector.

Joint condition

The joint condition of jointed PCC pavement was another limitation in video inspection. The video images make it difficult to distinguish the differences between joint sealing and spalling distress. Also it was hard to find the differences between sealed joint and unsealed joint.

Extent measurement

Measuring the extent of distress was another difficulty encountered. In still frame image, extent can be measured without difficulty. However, the ODOT approach requires to observe the video images from a slow moving VCR operation, since the ODOT approach needs inspect all of the pavement area. It was hard to measure correctly the distress amount by observing the slow moving video images.

7.6.5 Performance Evaluation

The performance evaluation for video and field inspections was described in sections 7.2 to 7.4. Also the analysis results from digital images are explained in section 7.5. The detailed descriptions are not repeated in this section.

However, from the evaluation process, promising results from the proposed video imaging system are obtained. In general, the video inspection and field inspection in this study show some relationships. Two pavement evaluation approaches (ODOT and MTC) were applied to video inspections and compared with the manual field inspections. From the analysis results, some sections are well matched by video and field survey, however some sections were not. Even though there were some limitations, the system is expected to provide many benefits to transportation agencies. The expected benefits from the proposed system are listed below:

1. The system takes pavement inspectors off the road and therefore separates them from traffic hazards.
2. The data collection can be conducted without interruptions of traffic flow.
3. The inspection can be performed in almost ideal working conditions in an office.
4. The recorded data are a permanent record and can be re-rated if necessary.
5. The system can be used in transportation agency's existing PMS without significant impact.
6. The system can be advanced to digital image processing if required.
7. The pavement evaluation can be performed at low-cost.
8. The system has considerable opportunity for improvement as technology progresses.

7.6.6 Cost Estimation

Since the goal of this study was to develop a low-cost video imaging system, a system development cost is estimated as shown in Table 7.11. The costs incurred at Oregon State University to conduct this study were $2,812. Also, the costs for hardware from the ODOT survey vehicle and borrowed items are roughly estimated as $36,800.

Therefore, the total cost for the prototype system used in this study is estimated as approximately $40,000. For comparison, the price range of commercially available systems is usually from $200,000 to $600,000 [Bell, 1995]. Thus, the initial costs of the proposed system are relatively low, which is promising for application by transportation agencies. Furthermore this meets the primary objective of the research, i.e. to develop a low-cost video imaging system.

Table 7.11 System Development Cost.

Description	Items	Cost used for Research ($)	Estimated Cost ($)
Data Collection Equipment	Camera (Burle TC 392 Color camera)	606	
	Lens and Housing	220	
	Mount device parts	100	
	Halogen lamps	96 (24 x 4)	
	Lights Parts	36	
	Labor and Engineering cost	450	
	Survey Vehicle		25,000
	On-Board monitor		400
	Character generator		1,500
	Distance measuring instrument		600
	Video recorder deck		2,000
	Power Generator and Inverter		2,000
	Video Tapes		N/A
	Subtotal	1,408	31,500
In Office System	Image capturing board (CE1024, Digital Vision Inc.)	400	
	IR4 Controller (Akman Inc.)	385	
	Software	75	
	Serial Cable and IR module	45	
	VCR (Panasonic PV-S7670) Video	399	
	Monitor (Panasonic CT-1382)		400
	Computer (Micron Pentium 166) w/ 17" Micron PC Monitor		2,400
	Laptop Computer		2,500
	Subtotal	1,304	5,300
Total		2,812	36,800
Total Estimated Cost for the system		$ 39,612	

As described in previous discussions, several options can be considered to enhance the capability of the system, including a camera with fixed shutter mode, powerful lighting system, application of real-time GPS, two cameras to enable a wider area to be covered, improved computer controlled VCR, and sophisticated image-capturing board. In Table 7.12, a very approximate cost estimation of each item for an enhanced prototype video imaging system is described.

Table 7.12 Cost Estimate for an Enhanced Prototype System with Two Cameras

Items	Description	Costs ($)
• Lighting	Additional Power Generator	1,500
	Lamps (5 × 1,000 Watts)	1,000
	Subtotal	2,500
• GPS	Real-time processing GPS	5,000
• Two Camera System	Two Cameras with auto iris zoom lens (fixed shutter mode) @ 1,500	3,000
	Mounting Device	1,000
	Two Computers @ 2,500	5,000
	Two Video Monitors @ 700	1,400
	Synchronization device and software for two displays	3,000
	Subtotal	13,400
• Computer controlled VCR	Improved VCR	3,000
• Image Capturing Board	Sophisticated Image Capturing Board	3,000
• Data Collection Equipment	Survey Vehicle	25,000
	On-Board monitor	400
	Character generator	1,500
	Distance measuring instrument	600
	Video recorder deck	2,000
	Power Generator and Inverter	2,000
	Subtotal	31,500
Total		58,400

Several options and various combinations for above items can be considered. The price range also can be flexible by selection of options. However, the total costs including all options are estimated as $58,400. By application of above options, it is expected to enhance the capability of the system greatly. Also from the consideration of above items, it is possible to imagine a video imaging system for a next generation.

In Table 7.13, the system operating costs are compared to the operating cost of ODOT national highway system (NHS). As shown Table, the ODOT invests about $100,000 every year for distress evaluation of NHS. For comparison, the operation cost for the proposed system is estimated using the same unit costs and estimation approach.

Table 7.13 System Operating Cost (Comparison to ODOT NHS).

Costs	ODOT		Proposed System	
	Description	Cost($)	Description	Cost($)
People	8 raters at 1500/ month for 14 weeks	63,000	2 raters at 1500/ month for 41 weeks (36 weeks for inspection, 5 weeks for data collection)	46,125
Travel	Travel at 60/day for 12 weeks	28,800	Travel at 60/day for 5 weeks	3,000
Vehicle	5 Vehicles at 281/month + mileage	7,917.5	1 Vehicle at 281/month + mileage	3,351.3
Equipment	3 Laptops at 300/month	3,150	• Two Computers at 400/month • Data Collection Equip. 105/month • In-Office Equip. 26/month	3,600 132 234
Others			Video Tapes	700
Total Cost/year		102,867.5		57,142.3
Cost/miles (4300)		23.9		13.3

The proposed system requires two operators for data collection and video inspection. Since the speed of video logging was approximately 3 miles per hour, it is estimated that the required period of time for inspection of total 4,300 miles NHS is 36 weeks. This long period inspection may be unrealistic for application. However, the operating costs are estimated for cost comparison.

As shown in the Table 7.13, the total operating cost for the proposed system is estimated as $57,142, and the unit cost per mile is $13.3. Thus, the estimation shows that the proposed system can evaluate pavements at lower cost than the existing approach, which fulfills the primary objective of this study.

8. SUMMARIES AND CONCLUSIONS

The primary purpose of this study was to develop a low-cost video imaging system for pavement evaluation to apply various type roadways including state highways and city/county streets. The secondary purpose of this research was the development of techniques to process video images collected through application of the video imaging system. To achieve these objectives, several processes were conducted in this study. These processes are categorized as:

1) Element selection of video imaging for system development,
2) Video image collection using the developed video imaging system,
3) Video and manual field pavement inspection for system performance evaluation,
4) Sample image digitizing for image processing,
5) Statistical analysis for comparison of video and field inspection, and for evaluation of digitized image data, and
6) Evaluation of the proposed system based on analyses.

The major summaries and conclusions resulting from above processes are presented below for all elements of the study.

8.1 Development of the Video Imaging System

<u>Summary</u>

1. A low-cost pavement imaging system using video technique was developed. The video image-collection system consists of a video camera, a camera-mounting device, a set of on-board equipment (video recorder deck, monitor, character generator, keyboard, distance measuring instrument (DMI), power inverter), and a survey vehicle.

2. The system uses a camera capable of a shutter speed of capturing the pavement images while the camera was mounted on a vehicle traveling at high speeds. The camera was secured on the mounting bars where it was then connected to the data collection

equipment in Oregon Department of Transportation (ODOT) video-log survey vehicle. The system was designed to store the image data collected from video imaging on videotapes for in-office processing. The external camera mounting devices were designed and installed on the survey vehicle to mount the video camera.

3. A lighting system was designed. However, since there was an insufficient vehicular power source, four weak-intensity lights (total of 200 watts) were used for an experimental purpose.

4. An in-office system was developed by assembling several devices to provide a desktop image retrieval system. The in-office system was designed to operate for distress evaluations from the video images. The in-office system consists of a VCR, a VCR controller (IR4), two computers (one for VCR control, the another for image display using an image capturing board), and two monitors (a video monitor and a computer monitor).

Conclusion

1. A low-cost pavement imaging system using video technique was developed. The system consists of several devices for data collection in field and for image retrieval in-office. To collected video images system camera mounting system and lighting system was designed. The developed system is intended for application in conjunction with a pavement management system (PMS) implementation.

8.2 Video Image Collection by Developed System

Summary

1. A field test was performed using the developed system and the ODOT video-log vehicle. A video test plan was prepared and implemented on a selected loop-type test route, covering various types of pavements. Several variables were included in the test plan, including vehicle speed, camera angle, lighting, day/night, and pavement condition (dry or wet).

2. A total of 11 test loops were conducted incorporating different variables and conditions. As a result of the video test runs, seven videotapes (1/2 inch VHS) were selected for further analysis. These runs include loops 1, 2, 3, 5, 6, 7, and 13.

Conclusions

1. The fast shutter-speed (1/90,000 sec) function of the video camera was sufficient to prevent image blurring, even at high vehicle speeds. It was decided that the survey vehicle could drive up to 65 mph while still maintaining good picture quality.

2. Seven daytime loop tests provided acceptable results to allow further image analysis.

3. The night tests were not successful, since sufficient light-intensity was not provided by the survey vehicle. Even though the night tests were not successful, the installation of an additional power source was not considered at this stage of the study.

8.3 Video Inspection and Field Pavement Inspection, Sample Image Digitizing

Summary

1. Video and field inspections were performed using two approaches: the ODOT approach and Metropolitan Transportation Commissions PMS. The inspections were conducted on 107 pavement sections, each 0.1 miles in length (total 10.7 miles).

2. To conduct a video inspection, conversion of videotape mileage to real field mileage was required. The conversion was performed using global positioning system (GPS) technique.

3. Video inspections were performed using the developed in-office video inspection technique for two approaches.

4. Field pavement inspections were conducted for 107 sections using ODOT approach and 67 sections were analyzed using MTC-PMS. Two independent surveyors, represented as field #1 (by author) and field #2 (by another surveyor), performed the field

inspections. For the ODOT field #2 survey, the conditions of only 40 sections (for I-5 and HW34 sections) were evaluated due technical problems.

5. Sample still images were digitized from the videotapes. The same locations for each test loop were captured and digitized. A total of 50 spots were selected, including 30 locations for AC pavements and 20 locations for PCC pavements. Using the image-processing program, crack index values were calculated from the digitized images.

Conclusion

1. Video inspection technique was developed based on the developed in-office system. Two separate video inspection techniques were developed for each approach, since the two approaches were different for distress definitions and survey methodology.

2. The GPS works for mileage conversion provided quick and accurate distance information. The GPS technique can be applied to automate pavement surveys, promptly providing location information with reliable accuracy.

8.4 Analysis from Comparison of Video and Field Inspection Data

Summary

1. A statistical analysis was performed for video and field inspection data.

Conclusion

Analysis from ODOT approach

1. The results form a 2-sided paired t-test indicated that there are no significant differences between the overall condition indices of the field and video inspections for the AC sections of HW34 and I-5.

2. For the concrete sections of HW34 and I-5, it was difficult to draw any significant results from the paired t-test, since most of sections were in very good condition with index value of 100.

3. The correlation coefficient and linear regression analysis showed that the AC sections show a very good relationship between video and field #2 inspection. Detailed analysis show that the HW34 AC sections have a very good relationship between the two inspections, while the I-5 AC sections do not. The PCC sections, again, did not provide any meaningful statistical results.

4. A regression analysis for the three distress indices (fatigue, patching, and non-load), between the video and field #2 inspections on HW34 and I-5 AC sections, was processed. The analysis shows that the fatigue index does not provide a good relationship between inspections. The patching and non-load crack indices show good matching results between the two inspections.

5. A statistical analysis for the remaining 67 sections was processed. Results from the paired t-test and regression analysis indicated a generally good relationship between the video and field #1 inspection. However, this analysis implied lack of independence.

Analysis from MTC-PMS

6. From the results of the paired t-test for video and field inspections, it was observed that the PCI of the video inspection was higher than the PCI of field inspections for the overall 67 sections. The PCI mean differences were calculated as 5.06 for field #1 and 4.31 for field #2.

7. The paired t-test for each road section showed that some sections have differences in PCI values between video and field inspections. However, no differences were observed between the two field inspections.

8. The correlation coefficients (ρ) for overall sections and each individual road section were calculated. The ρ values for overall sections showed good relationships between inspections. For individual road sections, they also showed generally good relationships.

9. A regression analysis showed linear relationships between video and field inspections. The fitness of the linear regression models was assessed using analysis of variance (ANOVA) analysis. The ANOVA test showed that the linear model could be used to sufficiently explain the relationships between the video and the field inspections.

10. Total PCI deduct values for major distress types were examined. The deduct values for alligator cracking generally showed that the field inspections were higher than the video inspection. For linear cracking, the total deduct values for video inspections were usually higher than for field inspections. The PCI deducts in weathering and raveling distress for video inspection were not observed or were less estimated than the field inspection.

Comparison of video evaluation by two approaches

11. From regression analysis, it was found that the relationship between the overall index of the ODOT approach and the PCI of MTC approach could be reasonably explained by a second polynomial equation.

12. From the classification of condition categories, it was observed that the MTC approach was more optimistically evaluated than the ODOT approach.

8.5 Analysis of Digital Images

Summary

1. The crack index values that were calculated from image processing program were analyzed by statistical technique.

Conclusion

1. The crack index values were compared for each test loop. From the observation of box plots of the unified crack index (UCI) distribution for each test loop of the AC pavement, it was observed that the loop1 had the highest crack index values. For the PCC

images, the box plots showed that loop2 and loop5 had high crack index values. It was observed that many images of loop2 and loop5 were affected by shadow.

2. ANOVA tests for each seven-test loop showed that there is poor repeatability for AC and PCC images. Additional ANOVAs performed on a reduced test loop (without loop1 for AC, without loop2 and 5 for PCC) were processed. The tests showed that the mean crack indices of AC images were not significantly different for six test loops, while the mean crack indices of PCC images are still different for the five test loops.

3. The variable effects were tested using general linear model analysis. The variables included vehicle speed, camera angle, lighting, pavement condition (dry/wet), survey time (morning/afternoon), and shadow. For AC pavements, the significant variables were "speed", "time", and "shadow". For PCC pavements, the significant variables were "lighting", "dry", and "shadow".

8.6 System Evaluation

Summary

1. The proposed video imaging system was evaluated by all of the research elements. The evaluation was based on the performance of the system on this project, including; system elements, field video image collection, video an field pavement inspection, statistical analysis, and cost estimation.

Conclusion

1. The video camera performed adequately to accomplish the purpose of this study. However, the auto-shutter mode of the camera sometimes caused image blurring.

2. The camera mounting system and the on-board equipment in the survey vehicle were generally acceptable for this study. Some modifications of system structure, however, were required to enhance the capability of the system.

3. Proper artificial lighting was required to reduce shadow effects or to create consistent light levels. The shadow effect was evaluated as a critical variable for image processing.

4. The DMI introduced some errors in distance information for various reasons. The GPS technique can be used in conjunction with DMI.

5. Accurate reading of the video images requires improvement in various aspects, including enlarging the image coverage, removing image blurring, correcting image distortion, and increasing image resolution.

6. The video distress inspection showed some limitations, such as measurement of depth-related distress, texture related distress, patching, joint condition, and distress extent.

7. Even with some of the limitations of the proposed system, use of the system is expected to generate various benefits listed previously in this thesis.

8. The system development and operating costs were estimated. The total system development cost was estimated about $40,000, which was promising estimation for application on transportation agencies. The operating cost was estimated as $13.3 per mile, which is lower cost than current distress survey cost. The costs for enhanced prototype video imaging system were also approximately estimated.

9. RECOMMENDATIONS

This chapter presents recommendations resulting from all of the elements of this study. The recommendations are described in two categories: 1) recommendations for implementation of the proposed system and 2) recommendations for future system development.

9.1 Recommendations for Implementation of the Proposed System

1. To reduce image blurring, it is recommended to use a camera with fixed shutter-speed mode at maximum speed (e.g. 1/90,000-sec). The fixed shutter mode requires an additional device in the current camera. Otherwise, another camera with a fixed mode or an alternative mode for shutter speed operating should be used.

2. The camera mounting system requires to adjust to more flexible system to meet safety requirements. Further flexibility of the system is required to adjust the camera angle for transverse directions to detect the condition of shoulder pavements or adjacent lane pavements. Also the camera mounting system needs to be redesigned to allow multiple camera mounting.

3. Lighting is necessary to produce consistent incoming light levels. For lighting design, an additional electric generator should be installed to the survey vehicle. Total lighting intensity requirements vary with the situation (such as day or night). More detailed study is required to evaluate the lighting requirements. It is recommended to conduct night surveys with fixed lighting, since it is expected to produce a consistent light level condition. For reference, the GERPHO system uses 5,000 Watts intensity and Guralnick et al. proposed a system with 4,100 Watts lighting intensity.

4. To identify a location correctly during driving by video imaging system, it is suggested to use the global positioning system (GPS) technique in conjunction with

distance measuring instrument (DMI). If using a real-time GPS processor, exact distance information can be instantly acquired.

5. It is desirable to enlarge the video image coverage. The current study used a single camera to cover a pavement area of 10 × 7.5 feet. However, for most implementation of the system in an agency's PMS, it may be necessary to inspect a pavement area wider than 10 feet. The use of multiple cameras may be considered in order to enlarge the image coverage without degrading the image resolution. Using two cameras is the simplest option; Two cameras could cover the required detection area with some overlap at the center without degradation of resolution.

6. For efficient and consistent video imaging, the image blurring should be properly controlled. Blurring can be controlled by various combined operations including shutter speed operation, artificial lighting, control of shadow effects by natural lighting, and varying driving speeds.

7. For operation of the in-office system, it is suggested to operate the system with two operators. One operator needs to control the IR4 VCR controller. The other operator needs to observe two screens and record the distress information observed in a recording form. He also needs to address error messages appearing on the PC screen. However, if one computer can control the whole system, it may simplify system operations with one operator control. This can be accomplished by modifying the IR4 control software or by a purchasing other high-cost sophisticated computer controlled VCR equipment.

8. The video imaging system involves a limitation for detection of some distress types including the following: depth related distress such as rutting for AC or faulting for PCC, texture related distress such as weathering and raveling, wide area patching, and joint condition for jointed PCC. Thus it is required to consider such undetectable distresses.

It is suggested to use other equipment to measure rutting. The "rut bar" is the most commonly used device for detecting rutting. This device can be attached to the video-imaging vehicle with a small modification to the system structure of the vehicle. However, since most of transportation agencies already have such depth measuring device, the rutting may not be a big problem for the video imaging system.

Weathering and raveling should be interpreted by another approach rather than visual video inspection. Further research is required regarding this issue. However, this limitation is not considered seriously, since this distress is not critical to pavement performance. To detect wide area patching, it is desirable to record large area patching information during video image collection. Then, the recorded information can be relayed to an in-office video inspector.

Joint condition estimation for jointed PCC pavement was another limitation in video inspection. The video images make it difficult to distinguish the differences between joint sealing and spalling distress. It was also hard to find the differences between sealed joints and unsealed joints. Further study is recommended for joint condition evaluation.

9. The video imaging system implies another limitation for distress extent measurement. To measure the distress extent in still frame image, it is suggested to develop an image displaying computer program for overlaying grids of various selective sizes with a simple area calculation function. The ODOT approach required inspection of all of the pavement area. To measure all of pavement area, it is required to operate the VCR by accurate frame by frame advance.

9.2 Recommendations for Future System Development

An ideal fully automated and accurate pavement evaluation system without of human intervention has not been developed yet. The next generation of automated pavement evaluation system can be advanced to ideal stages, which are including:

1. Multiple cameras that covering pavements of driving lane and adjacent lanes.
2. Powerful lighting that can be used all situations: weather conditions and day/night.

3. On-board real-time processing and storage of processed data.
4. Accurate and prompt access of location information using GPS technique.
5. Image processing techniques without human-intervention.
6. Data management using geographical information system (GIS).

The proposed system also has the obvious target of achieving above goal. The list below includes recommendations to advance the system to a more automatic stage of data collection and analysis.

1. To achieve real-time processing in a survey vehicle, several modifications should be made to the system structure. One of the fundamental decisions is the choice of either digital or analog signal for image collection. Currently the digital approach has some limitations such as technical problems, cost, and popularity. However, the problems will be overcome within the very near future.

The digital approach requires a digital camera and proper storage device. The use of digital images offers several advantages such as simplified image collection, sophisticated image processing, improved image resolution, and etc.

2. Lighting is also critical to advancing the proposed system to an automatic analysis stage. Since video images can be affected by shadows from various objects, it is required to remove a shadow effect with proper control. If still images are used for analysis rather than a continuous image, strobe type lighting can be considered. Lighting, of course, is also necessary to produce consistent light level conditions.

3. To analyze the collected image accurately without human intervention, a precise image-processing algorithm should be developed. Much research has been conducted for the development of a pattern recognition algorithm to detect pavement distress in pavement images. The accuracy and performance of existing algorithms, however, have not been fully demonstrated. More research for an image-processing algorithm is therefore required.

4. Before processing the collected images by image processing techniques, consistent and undistorted pavement images should be obtained. There are some image distortions in pavement images in both perpendicular and angled camera detection. However, processing images with distortions can lead to misinterpretation of the extent amount of distress. For more accurate and precise image processing, it would be required to correct image distortion effects.

5. The image resolution also must be considered for image processing. Resolution is critical to detect low severity cracks. However, with proper digital image techniques, the resolution will be increased greatly.

6. There are some distresses that are undetectable by image processing. To evaluate such distresses, other approaches should be considered. For weathering and raveling distress and joint condition evaluation, further study is required.

7. To acquire the location information of a pavement image correctly, it is recommended to use the GPS technique extensively. GPS techniques provide a sophisticated approach with precise location information.

8. The resulting information by automated system should be transfered to a geographical information system (GIS) database. Transportation engineers for planning road maintenance may then access the database, which includes the attribute data and images with condition information. GIS information can be shared with persons involved in road management work.

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APPENDICES

Appendix A.

Summary of Distress Evaluation Process and Distress Identification for two Approaches

A.1. ODOT Approach

A.1.1. Distress Evaluation Process

The ODOT's Pavement Services Units has established and defined the pavement distresses that are collected under the Objective Rating Procedure [ODOT, 1996]. ODOT adopted the SHRP manual, Distress Identification Manual for the long-term Pavement Performance Project, as a basis for defining pavement distress types, severity, and extent. A definition for distress type and severity in SHRP distress manual which is used in ODOT's approach is described in next section [SHRP, 1993]. Three different pavement surface types are identified in this manual including asphalt concrete pavement, continuous concrete pavement, and jointed concrete pavement. ODOT performs pavement condition survey to rate state jurisdiction highways on annual basis. ODOT is performing field visual survey in every summer. The condition survey will be accomplished via a "windshield" survey from a slow-moving vehicle operating on the adjacent shoulder. The highway will be rated in 0.1 miles increments with rut depths being physically measured at each milepoint marker. The surface distress will be recorded on distress recording program for each segment rated. The collected field inspection data is processed in the office to calculate three condition index values: a rut index, a crack index, and an overall section index. More detailed description of the condition index calculation is found in the literature [ODOT, 1996].

A.1.2. Definition for Distress Types and Severity

Table A.1 Definition for Distress Types and Severity for ODOT Approach.

(Asphalt Concrete Pavements)

Distress Type	Description	Extent Measure	Severity
Fatigue Cracking	A series of interconnected cracks caused by fatigue failure. Develops into many-sided, sharp-angled pieces, usually less than 0.3m on the longest side.	Linear feet of the wheel track	L: no or few connecting cracks M: Lightly developed pattern, low spalls H: highly developed pattern, high spalling, loose pieces
Transverse Cracking	Perpendicular to the pavement centerline, and may extend across the travel lane	# of cracks	L: crack width less than 6 mm (0.25 in.) M: from 6mm (0.25in) to 19mm (0.75in) H: more than 0.75in
Longitudinal Cracking	Cracks predominantly parallel to pavement centerline	Length of the cracks	L: crack width less than 6 mm (0.25 in.) or sealed cracks M: from 6mm (0.25in) to 19mm (0.75in) H: more than 0.75in
Block Cracking	A cracks that divides the pavement into approximately rectangular pieces (1 sq. ft to 100 sq. ft)	Square feet	L: crack width less than 6 mm (0.25 in.) or sealed cracks M: from 6mm (0.25in) to 19mm (0.75in) H: more than 0.75in

Table A.1 Definition for Distress Types and Severity for ODOT Approach (Continued).

Distress Type	Description	Extent Measure	Severity
Potholes and Patches	Bowl-shaped holes of various sizes in the pavement surface, Portion of pavement surface (greater than 1sq ft) that has been removed or replaced	Square feet	L: less than 1 in deep, any type of low severity distress M: 1 to 2 in. deep, any type of moderate severity distress H: more than 2 in. deep, any type of high severity distress
Raveling	Wearing way of the pavement surface caused by dislodging of aggregate particles	Square feet	L: binder has begun to wear away but not significantly M: binder has worn away, surface texture is becoming rough and pitted H: binder has worn away, surface texture is very rough and pitted

Table A.1 Definition for Distress Types and Severity for ODOT Approach (Continued).

(Jointed and Jointed Reinforced Portland Cement Concrete Pavements)

Distress Type	Description	Extent Measure	Severity
Corner Cracking	Short cracks that begin at transverse joints and are predominantly parallel to pavement centerline	# of cracks	L: crack width less than 3 mm (0.125 in.) no spalling M: from 3mm (0.125in) to 13mm (0.5in) H: more than 0.5in
Corner Breaks	Separation of a corner portion of concrete from the rest of PCC slab	# of breaks	L: crack is not spalled for more than 10% of the length M: crack is spalled at low severity for more than 10% H: crack is spalled at moderate or high severity for more than 10% of the length
Transverse Cracking	Perpendicular to the pavement centerline, and may extend across the travel lane	# of cracks	L: crack width less than 3 mm (0.125 in.) no spalling M: from 3mm (0.125in) to 6mm (0.25in) H: more than 0.25in
Longitudinal Cracking	Cracks predominantly parallel to pavement centerline	length of the cracks	L: crack width less than 3 mm (0.125 in.) no spalling M: from 3mm (0.125in) to 13mm (0.5in) H: more than 0.5in

Table A.1 Definition for Distress Types and Severity for ODOT Approach (Continued).

Distress Type	Description	Extent Measure	Severity
Punchouts	Separation of a block concrete from the slab formed by two closely spaced transverse cracks, a short longitudinal cracks, and the edge of the pavement	# of occurrence	L: crack is not spalled for more than 10% of the length M: crack is spalled at low severity for more than 10% H: crack is spalled at moderate or high severity for more than 10% of the length
Patch	Portion of original concrete slab (greater than 1sq ft) has been removed or replaced	square feet	L: any type of low severity distress M: any type of moderate severity distress H: any type of high severity distress

Table A.1 Definition for Distress Types and Severity for ODOT Approach (Continued).

(Continuously Reinforced Portland Cement Concrete Pavements)

Distress Type	Description	Extent Measure	Severity
T-Crack Spacing	T-crack of CRCP is not considered as distress. However, if the cracks open up, deterioration may result	average spacing between cracks	L: spalled along less than 10% of the crack length M: spalled along from 10% to 50% of the crack length H: spalled along more than 50% of the crack length
Longitudinal Cracking	Cracks predominantly parallel to pavement centerline	length of cracks	L: crack width less than 3 mm (0.125 in.) no spalling M: from 3mm (0.125in) to 13mm (0.5in) H: more than 0.5in
Punchouts	Separation of a block concrete from the slab formed by two closely spaced transverse cracks, a short longitudinal cracks, and the edge of the pavement	# of occurrence	L: spalling less than 3 in. or faulting less than 0.25 in. not include Y cracks M: spalling from 3 in. to 6 in., or faulting from 0.25 in to 0.5 in. H: spalling more than 6 in., or punch down more than 0.5 in.
Patch	Portion of original concrete slab (greater than 1sq ft) has been removed or replaced	square feet	L: any type of low severity distress M: any type of moderate severity distress H: any type of high severity distress

A.2. MTC-PMS

A.2.1. Distress Evaluation Process

The Metropolitan Transportation Commission (MTC), Oakland, California, is the transportation planning agency responsible for more than 100 cities and counties in the San Francisco Bay area. The MTC-PMS was first developed in 1986 to help manage local area networks. The MTC-PMS provides a computerized method for analyzing information about pavement condition and for developing cost-effective maintenance strategies.

The MTC-PMS is a network-level system designed for the budget planning and project identification phase of the pavement management process. The MTC-PMS is used to select, and, to order by priority, candidate maintenance and rehabilitation projects for subsequent detailed project level evaluation. The basic process includes the following

1. Identification of the pavements to be managed,
2. Determination of current pavement condition,
3. Identification of present and future budget needs,
4. Selection of pavement sections for maintenance and rehabilitation consideration,
5. Determination of the influence of different budget levels on the network condition, and,
6. Selection of the most effective maintenance and rehabilitation projects.

The first phase in the inventory process is to divide the road network into uniform pavement segments. And then, information is collected about a particular management section, including: surface types, construction date, maintenance and rehabilitation history, and functional classification.

The second phase in the inventory procedure is to collect information about the pavement condition of each management section. Each management section is then divided into inspection units, which are approximately 10% of the total pavement area. A detailed condition survey is performed within each inspection unit. In the MTC-PMS procedure, seven types of pavement distresses are considered critical and they may be measured in the field to evaluate pavement performance.

A number called Pavement Condition Index (PCI) represents the pavement condition. The PCI rating ranges from 0 to 100. A PCI rating of 100 defines a pavement in a new condition before the development of the first crack. The lower range of the scale, 0 to 10, represents a pavement that has failed to a disintegrated condition [Smith, 1987].

Condition data collected in terms of type, severity, and amount of distress are used to calculate the PCI. The PCI is calculated for individual inspection units within the management section and combined to determine the PCI of the management section if more than one inspection unit is inspected within the management section.

Once the condition of each pavement section is determined in terms of a PCI, a procedure to predict future condition is required in network-level analysis to identify when maintenance and rehabilitation is needed and to determine budget needs. The MTC-PMS projects the PCI of each management section 5 years into the future. A more detailed description of the MTC-PMS can be found in the literature [Smith, 1986; Smith, 1987].

A.2.2. Definition for Distress Types and Severity

Table A.2 Definition for Distress Types and Severity for MTC-PMS.

(Asphalt and Surface Treatment Pavements)

Distress Type	Description	Extent Measure	Severity
Alligator Cracking	A series of interconnected cracks resembling alligator skin or chicken wire (Many sided and sharp angles)	Square feet	L: longitudinal hairline cracks running parallel to each other with one or only a few M: Further development of light alligator cracks into a pattern H: Network or pattern cracking has progressed, the pieces are well defined
Block Cracking	Cracks which divide the surface into approximately rectangular pieces. Size of blocks are ranges from 1by 1 to 10 by 10 ft.	Square feet	Defined by linear cracks L M H
Distortions	Corrugations, bumps, sags and shoving. Abrupt upward or downward displacement of the asphalt surface	Square feet	L: vehicle vibration with no speed reduction M: vehicle vibration with speed reduction H: excessive vibration, speed must be reduced considerably
Longitudinal and Transverse Cracking	Cracks that are either parallel or transverse to the pavement center-line	Linear feet	L: crack width less than 10 mm (3/8 in.) or sealed cracks M: from 10mm (3/8in) to 76mm (3 in) H: more than 0.75in

Table A.2 Definition for Distress Types and Severity for MTC-PMS (Continued).

Distress Type	Description	Extent Measure	Severity
Patching and Utility Cut	Repair of the pavement with new materials	Square feet	L: patch is in good condition M: Moderately deteriorated H: Badly deteriorated
Rutting and Depressions	A rut is depression in the wheel path, Depression is apart of surface lower than surrounding area	Square feet	L: less than 1 in. in depth M: 1-2 inches H: over than 2 inches
Weathering and Raveling	Wearing away of the pavement surface caused by the loss of binder and dislodged aggregate particle	Square feet	L: Aggregate or binder has started to wear away M: Worn away and original asphalt is showing H: Worn away considerably, surface seal has been lost

Table A.2 Definition for Distress Types and Severity for MTC-PMS (Continued).

(Jointed and Jointed Reinforced Portland Cement Concrete Pavements)

Distress Type	Description	Extent Measure	Severity
Corner Break	Crack intersects the joints at a distance less than or equal to one-half the slab length on both side	# of slabs	L: low severity cracks M: medium severity cracks H: high severity cracks
Divided (shattered) slab	Cracks divide slabs into four or more pieces	# of slabs	L: See table of the manual M: H:
Faulting	A difference in elevation across a joint or crack	# of slabs	L: elevation difference 3/8 to 1/2 inches M: 1/2 to 1 inches H: over than 1 inch
Linear Cracking	Cracks parallel to the pavement centerline, long perpendicular, or diagonal to the pavement centerline	# of slabs	L: crack width less than 1 inch M: crack width 1-3 inches H: more than 3 inches

Table A.2 Definition for Distress Types and Severity for MTC-PMS (Continued).

Distress Type	Description	Extent Measure	Severity
Patching and Utility Cuts	Original pavement has been removed and replaced	# of slabs	L: patch is in good condition M: Moderately deteriorated H: Badly deteriorated
Scaling/Map Cracking/Crazing	A network of shallow, fine or hairline cracks which extend only through the upper surface of the concrete	# of slabs	L: only minor scaling present M: scaled less than 15 percent of the slab effected H: scaled over than 15 percent of the slab effected
Spalling	The cracking, breaking, or chipping of the slab edges within 2 ft. of the joint	# of slabs	L: See the table in the manual M: H:

Appendix B. Operation Guidelines for Video Distress Inspection

The proposed video logging system can be applied in many different pavement management systems. However, in this guideline, focus is given to two approaches: ODOT approach and MTC-PMS. If a user needs to implement another system, the procedures in this guideline can be applied with slight modification.

B.1. ODOT Approach

Since the ODOT approach is a 100% pavement section survey, it is required to inspect all of the pavement area.

Asphalt Concrete Pavements

A distress inspection form for asphalt concrete pavements is prepared.

1. The pavement inspection sections are divided into imaginary subsections. The 0.1 miles pavement sections are divided as 0.01-mile (52.8 foot) subsections using second decimal numbers in video mileage.
2. The operator sets the video tape to the starting point of sections based on the distance information acquired by GPS and DMI codes
3. As the video tape is played slowly, inspect the video images and record the distress information observed if required (such as transverse cracks).
4. Once the operator observes a change in the second decimal number, the operator needs to record all of the distress information to the recording form.
5. And then, again, the operator needs advance the tape for inspection of the next segment. This process is repeated until to the end of the sections.

Jointed PCC

For jointed concrete pavements, distress recording form is prepared.

1. Same inspection process is conducted to slab by slab rather than imaginary small segments.

2. As the videotape is played slowly, the inspector inspects the video images and record the distress information observed if required.
3. Once the operator observes a joint, the operator needs to record all of the distress information of the slab.
4. The operator also needs to evaluate the condition of joints.
5. The operator advances the tape for inspection of the next slab. This process is repeated until to the end of all section is reached.

Continuous PCC

For the continuous reinforced concrete pavements, distress recording form is prepared.

1. Same process that is used for the evaluation of asphalt pavements is applied. The inspection is performed based on 0.01 mile segments.

B.2. MTC-PMS

Since the MTC-PMS is a sampling approach, it is required to select inspection units.

Asphalt Concrete Pavements

For evaluation of AC pavements using MTC, a distress recording form is prepared.

1. Frame by frame inspection is applied. The pavement condition is evaluated by observing still-frame video images and recording the distress on recording form.
2. Two still-frames are randomly selected for inspection in every second decimal number of DMI codes (28.4 percent sampling for total pavement).
3. As the videotape is forwarded slowly, randomly stop the videotape two times in every second decimal number.
4. Inspect the still video images and record the distress information.
5. The operator needs advance the tape for inspection of the next still image.
6. This process is repeated until to the end of the sections.

Jointed PCC

Distress recording form for jointed concrete pavements is prepared.

1. Same inspection process is conducted based on slab by slab inspection as in ODOT approach. The differences are the inspection is performed in inspection units within the section.
2. Two inspection units with ten slabs each receive close distress inspection. This represents approximately 60 percent of sampling.
3. The operator set the video tape to the starting point of slabs
4. As the videotape is forwarded slowly, inspect the video images and record the distress information observed if required (such as transverse cracks).
5. Once the operator observes a joint, the operator needs record all of the distress information of the slab.
6. This process is repeated until to reach to the end of the section.

Continuous PCC

In this study, continuously reinforced concrete pavement sections were not evaluated using MTC, since CRCP sections were not included for the sample sections. However, using imaginary joints, the same process applied to jointed PCC can be applied to CRCP.

B.3. System Operation by Two Operators

In this study, the video survey was performed by author alone. The VCR controlled by a remote controller. However, it is desirable to operate the system with two operators. One operator would control the VCR by IR4 controller and the connected computer. The other operator observes two screens and records the distress information. The operators should alternate activities to avoid "burn out" and therefore minimize mistakes.