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SYNTHESIS 334

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Automated Pavement Distress Collection Techniques

A Synthesis of Highway Practice

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 334

Automated Pavement Distress Collection Techniques

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Staff
Transportation Research Board

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

Information exists on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, “Synthesis of Information Related to Highway Problems,” searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice.*

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

This report of the Transportation Research Board documents highway community practice and research and development efforts in the automated collection and processing of pavement condition data techniques typically used in network-level pavement management. The scope of the study covered all phases of automated pavement data collection and processing for pavement surface distress, pavement ride quality, rut-depth measurements, and joint-faulting measurements. Included in the scope were technologies employed, contracting issues, quality assurance, costs and benefits of automated techniques, monitoring frequencies and sampling protocols in use, degree of adoption of national standards for data collection, and contrast between the state of the art and the state of the practice. Three case studies are included as examples of transportation agencies applying a variety of methods for pavement condition data collection and processing.

This synthesis report included a review of published literature of North American and European resources and a survey of state transportation agencies, the FHWA, Canadian provinces, and the World Road Association. In addition, information was gathered from the October 2002 Pavement Evaluation Conference, held in Roanoke, Virginia. Three previous syntheses (NCHRP Syntheses 76, 126, and 203) have summarized much of the background material and are referenced frequently in this report.

A panel of experts in the subject area guided the work of organizing and evaluating the collected data and reviewed the final synthesis report. A consultant was engaged to collect and synthesize the information and to write the report. Both the consultant and the members of the oversight panel are acknowledged on the title page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

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Kenneth H. McGhee, Pavement Consultant, Madison, Virginia, was responsible for collection of the data and preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of John Andrews, Office of Materials and Technology, Maryland State Highway Administration; Carl Bertrand, Texas Department of Transportation; Gary Elkins, Senior Engineer, PCS Law Engineering and Environmental Services, Inc.; Robert Englemann, California Department of Transportation; Thomas J. Kazmierowski, Manager, Pavement and Foundation Office, Ontario Ministry of Transportation; Stephen F. Maher, P.E., Engineer of Design, Transportation Research Board; Ginger McGovern, Oklahoma Department of Transportation; Naveed Sami, Director of Technology, Maintenance Division, Virginia Department of Transportation; Omar Smadi, Scientist, Center for Transportation Research/Education, Iowa State University; Jack Springer, Federal Highway Administration; Jean M.S. Wallace, P.E., Region 4 Operations/Pavement Engineer, Federal Highway Administration, Colorado Division; and Kathryn A. Zimmerman, President, Applied Pavement Technology, Inc.

This study was managed by Jon Williams, Manager, Synthesis Studies who worked with the consultant, the Topic Panel, and the Project 20-5 Committee in the development and review of the report. Assistance in project scope development was provided by Donna Vlasak, Senior Program Officer. Don Tippman was responsible for editing and production. Cheryl Keith assisted in meeting logistics and distribution of the questionnaire and draft reports.

Crawford F. Jencks, Manager, National Cooperative Highway Research Program, assisted the NCHRP 20-5 Committee and the Synthesis staff.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance are appreciated.

AUTOMATED PAVEMENT DISTRESS COLLECTION TECHNIQUES

SUMMARY

This document is a synthesis of the information collected in 2003 on highway community practice and research and development efforts in the automated collection and processing of pavement condition data typically used in network-level pavement management. The scope of the effort covered all phases of automated pavement condition data collection and processing for pavement surface distress, pavement ride quality, rut-depth measurements, and joint-faulting measurements. Included in the scope were the technologies employed, contracting issues, quality assurance (QA) issues, costs and benefits of automated techniques, monitoring frequencies and sampling protocols in use, degree of adoption of national standards for data collection, and contrast between the state of the art and the state of the practice in automated data collection and processing. Although emphasis was on network-level pavement management, project-level or research-level work, such as the Long-Term Pavement Performance Program, was included where it was helpful in contributing to the knowledge base on the subject matter.

To expedite the gathering of available information, a questionnaire was sent to all U.S. state transportation agencies, the FHWA, Canadian provinces, and the World Road Association (Permanent Association of World Road Congresses). A total of 56 responses were received from 43 state highway agencies, 2 FHWA offices, 10 Canadian provinces or territories, and Transport Canada. Additional material was acquired through a literature search of North American and European resources, with more than 150 references retrieved through that process.

It was discovered that essentially all North American highway agencies are collecting and using pavement condition data through some automated means. Almost all of those data are collected in a single pass by an integrated machine capable of capturing forward, lateral, and downward images as well as both longitudinal and transverse profiles. Virtually 100% of those responding to the questionnaire are using automated means to collect International Roughness Index (IRI) data on at least a portion of their systems. Most agencies collecting IRI data (52) also collect other data measured by electronic sensing devices (laser, acoustic, or infrared). Of these other sensor data, rut-depth measurements are by far the most popular (50 agencies) with joint-faulting measurements employed by some 30 agencies. Pavement surface images are collected through automated means by 30 agencies, whereas automated processing of pavement surface distresses from those images is employed by only 14 of those agencies. The others apply manual data reduction techniques to obtain surface distress data from the images.

Thirty-three agencies use vendors to collect at least some of the automated data. In many of those cases, the vendor collects sensor data on longitudinal and transverse profiles while the agency collects pavement surface distress data through manual surveys. The most popular means of procuring contracted services is through a request for proposal, as used by 18 agencies. Seven agencies use a request for qualification approach, whereas eight use advertised contracts and a low-bidder approach. Several agencies use more than one approach to contracting. A typical contract is for 2 years, although some agencies use a 1-year period and one uses a 4-year period. Several provide for up to 5-year negotiated extensions of shorter-term original contracts. Six agencies have warranty provisions in their contracts, whereas only one requires a performance bond. A total of 22 agencies have QA provisions in their contracts and 12 have price adjustment clauses. Typical price adjustment clauses relate to delivery dates and accrue

in the form of penalties for late delivery. No agency mentioned a bonus for early delivery. Agencies reported a low estimated cost of $0.60 per km ($1 per mi) for agency-collected IRI data up to $106 per km ($170 per mi) for vendor collection and processing of images and sensor data in an urban environment. Roughly $30 per km ($50 per mi) is considered average for that same work. In special circumstances, such as urban areas or extremely remote locations, costs may be expected to vary widely from those cited here.

Some agencies have done extensive work to develop very thorough QA requirements or practices. Some of the Canadian provinces have been exceptionally productive in this area and have established procedures that could well provide the foundation for national or international approaches. However, in general, there is a need for additional development work in pavement data QA, for there is a scarcity of information on inherent variabilities of the processes involved. Further additional work appears needed on developing quality management programs for pavement data.

One of the major benefits that agencies cited from automated collection of pavement condition data is in the area of safety. Many agencies noted the danger of having people on the roadway to collect data manually, whereas it can be collected safely and at traffic speeds with modern automated equipment. Others cited the efficiency of operation for automated procedures. Still others noted the benefit of having a permanent record of pavement condition; greater objectivity is obtained through automated means, and improved data consistency comes through automation.

Not all agencies responded positively to automated procedures, as some believe that data quality is compromised. On the other hand, several mentioned an improved data quality through automation. It is suspected that the difference lies in the use of reliable and realistic QA procedures.

Three case studies are included in the synthesis. The first is of the Maryland State Highway Administration, which does all automated pavement data collection and processing in-house. The second case is that of procedures followed by the Louisiana Department of Transportation and Development, where all data are collected and processed through contracts. The third case is of data collection and processing activities of the Mississippi Department of Transportation. Its' data collection and processing are done by a vendor, but with specific protocols provided by the agency.

The issue of state of the art versus state of the practice for automated pavement condition data collection and processing is cause for concern. Although there seems to be little gap in roughness measurement, there is a significant one for both cracking and rut-depth measurement. For joint-faulting measurements, the automation issues are not well enough developed to determine either the state of the art or state of the practice. For cracking measurements, some agencies seem hesitant to invest in the new technologies until they have been more thoroughly proven. For both rutting and joint-faulting measurements there is little consensus on what is really required to furnish quality data, therefore, additional protocol work seems needed.

Research needs identified in this synthesis project include

- A study of automated data collection standards,
- A study of automated surface distress processing standards,
- Development of quality management programs for automated pavement data collection and processing,
- Development of a "toolbox" for automated pavement data collection and processing, and
- Development of metadata standards for pavement condition data.

CHAPTER ONE

INTRODUCTION

To meet increasing demands for network-level pavement condition data, state and local highway agencies are faced with the problem of collecting more data, at lower cost, with improved quality, in a safer manner. Moreover, most agencies are attempting to meet those needs with reduced resources. Recent state-of-the-art advancements in computer technology, digital pavement imaging, and digital image processing provide greatly enhanced methods to collect and interpret the required information. Currently, highway agencies are employing a wide variety of approaches to collect, store, analyze, and disseminate information on pavement condition. The need to synthesize and incorporate the information on these varied approaches into a single resource document became evident and gave rise to the present synthesis, which, in many ways, is an update of several earlier similar undertakings as will be described later in this chapter. The reader is cautioned that the synthesis attempts to cover what is being done in the field, but it does not constitute a "toolbox" (a how to do it) of automated pavement data collection and processing. The synthesis effort ultimately revealed that the development of such a toolbox is one of several research needs.

OBJECTIVE

This synthesis focuses on automated pavement condition data collection techniques, specifically for the measurement of pavement cracking, roughness, rutting, and faulting. The major objective was to document how agencies conduct automated data acquisition and processing for network-level pavement management. Other information included contrasting state of the art with the state of the practice from the perspective of user agencies. Furthermore, it was desirable to synthesize the contractual arrangements in use by the various agencies, as well as the costs of automated data collection and processing. Finally, data quality assurance (QA) programs were to be synthesized.

SCOPE AND ORGANIZATION

The synthesis (1) reviews the literature to document methodologies and equipment available to highway agencies to automate the collection and processing of pavement condition data and (2) reports the results of a survey of state highway agencies to determine the current state of their practice in adopting automated distress collection techniques. The available international information is included. The synthesis is limited to network-level data only. Project-level data are beyond the scope and are not generally discussed, except to the extent that some data elements (e.g., linear referencing) can have both network and project applicability.

The automated pavement distress data collection technologies addressed by this synthesis may be grouped into two classes: (1) imaging technologies involving the capture and interpretation of images of the pavement surface and (2) sensing technologies involving the use of noncontact sensors to measure deviations of the pavement surface from a horizontal plane.

Specific information captured in the synthesis includes the following:

- A discussion of automated versus semi-automated techniques, including the degrees of automation used and human intervention required;
- The benefits of automated techniques (including any benefit–cost studies);
- Methods of procurement (in-house, contracted, etc.);
- Contracting procedures (warranties, penalties, audit procedures, period of performance, etc.);
- Quality control (QC) and QA procedures used to validate and evaluate data, or to determine data accuracy, variability, and consistency;
- Equipment specifications and test protocols that states are using;
- Monitoring frequencies, by system;
- Degree of adoption of AASHTO, ASTM, and other standards;
- Costs of automated techniques (including costing method used);
- Additional features being collected by the automated equipment, such as right-of-way, drainage, and signage inventory, excluding devices that monitor only these features;
- Case studies of states using different methods;
- Limitations of available technologies; and
- The contrast between the state of the art and the state of the practice.

The synthesis is organized to first present a general discussion of background materials, methodology of development, and questionnaire responses. Sections that roughly parallel the questionnaire's organization follow that general discussion.

However, because those items are applied in approximately the same way regardless of the distress under consideration, location reference, distress monitoring frequency, and roadway sampling frequency are discussed before the distresses themselves. The distress sections cover the collection and processing of surface distress, smoothness and roughness, rutting, and joint-faulting data. The latter chapters of the synthesis address the more general issues of data management, contracting procedures, costs of automated data, advantages and disadvantages of automated collection and processing, and QC and QA issues. Finally, Appendices A, B, and C, respectively, present the questionnaire itself, responses to the questionnaire, and identify the agencies that responded.

BACKGROUND

AASHTO provides the following definition of the subject being studied: "A pavement management system (PMS) is a set of tools or methods that assist decision-makers in finding optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition over a period of time" (*1*). Although called by other names, programs directed at providing the best possible highways at the lowest practical cost to the taxpayer have been in use since the first state highway agencies were established. Since the time such agencies were created, a need for securing some measure of the condition of the highway network(s) being managed was recognized (*2*). Almost all earlier data were collected through visual surveys (*3*). Even pavement roughness was seldom measured until about the 1950s (*3*), with mechanical measures of pavement condition in use for only about the last half-century. Over that time, there evolved a recognition that safety issues and issues relating to data volume and quality dictated that high-speed and objective means of automated pavement condition data collection and processing were needed. The following discussion provides the background for the technologies involved in pavement condition evaluation and how those technologies have evolved. Three earlier syntheses summarized much of the background material, and they are referenced frequently in this report.

One of the earlier documents to catalog methods of pavement condition evaluation was *NCHRP Synthesis of Highway Practice 76,* published in 1981 (*3*). The focus of that synthesis was on the collection and use of pavement condition data, and the scope included discussions of the need for condition data, the types of data collected, the sampling programs employed, and the costs of various data elements. Interestingly, even in 1981, only a relatively small number of agencies were involved in pavement data collection on a large scale. For that reason, only nine agencies (including the U.S. Army Construction Engineering Research Laboratory) were surveyed. All those agencies were collecting data on pavement distress, ride quality, structural integrity, and skid resistance.

In 1981, the method of choice for pavement distress evaluation was the visual survey, because even photographic methods were only in the research phase at that time. Most agencies doing roughness monitoring were using response-type road roughness measuring systems (RTRRMS), such as Mays or Cox meters mounted on passenger cars or on trailers. Although widely used at that time, this technology was severely limited because the equipment measured only vehicle response to the longitudinal road profile rather than the profile itself. Furthermore, RTRRMS roughness values were subject to all kinds of vehicle suspension and other variations, so that frequent calibrations were required to achieve any consistency of results. Of the agencies surveyed, only the U.S. Army Construction Engineering Research Laboratory reported using a laser profilometer to measure actual profile. No automated methods of collecting rut-depth or joint-faulting measurements were reported in that synthesis.

The next related synthesis was the 1986 *NCHRP Synthesis of Highway Practice 126: Equipment for Obtaining Pavement Condition and Traffic Loading Data* (*4*). Again, the pavement-related information gathered was on surface distress, roughness, structural capacity, and friction. Weigh-in-motion equipment development was in its infancy, but it was included. A questionnaire was circulated in 1983 to all 50 states, and responses were received from 44.

By that time, a few agencies were using photologging techniques to capture pavement surface condition, although most still used visual surveys. The study reported that transfer of distress data from the photographs proved to be both time consuming and expensive. Most road roughness monitoring still was done by RTRRMS, although profilometers and profilers were being used by a number of research units. At the same time, five states had started to use a new version where road meters using ultrasonic waves measured vehicle displacements relating to road roughness. Furthermore, the surface dynamics profilometer, employing two spring-loaded following wheels, was in production use in four states. Also, by then K.J. Law Engineers had developed a noncontact profilometer using an optical reflectivity system to measure profiles in both wheel paths. No agency reported routine use of this version of profilometer in 1983. Apparently, a compelling reason that profiling equipment was slow in coming into widespread use was the huge gap in investment cost between those devices and the RTRRMS. The synthesis reported a cost of some $15,000 for a ride meter-equipped automobile and approximately 15 times that much for a profilometer.

By the time a third synthesis effort was undertaken in 1994, several federal initiatives had provided special impetus to pavement data collection activities through mandated or semi-mandated programs. One of these, the Highway Performance Monitoring System (HPMS), requires that states provide pavement condition information to support the functions and responsibilities of the FHWA. The *Highway Performance Monitoring System Field Manual* has been published in numerous editions, the latest of which was issued in December 2000 (*5*). That manual requires a periodic section-by-section report of pavement condition parameters for highways designated as HPMS sections. Those sections generally number in the hundreds to thousands of sections per state, depending on the size of the system administered. The major pavement condition data requirement is either the International Roughness Index (IRI), described later, or the present serviceability rating, described in the HPMS manual, on a biennial basis. The HPMS manual also provides for a standardized linear reference system that is now used by many agencies.

The Intermodal Surface Transportation Efficiency Act of 1991 provided another federal incentive through a mandate that all roads eligible to receive federal-aid monies were to be covered by a PMS by January 1, 1995. Although ensuing directives lifted the mandate, by that time many of the states had implemented PMSs and were collecting the supporting data for their own purposes.

The third related synthesis is *NCHRP Synthesis of Highway Practice 203: Current Practices in Determining Pavement Condition* (*6*), published in 1994. The scope of that report addressed the measurement or collection, reporting, and use of pavement condition data, including roughness, surface friction, distress, and structural evaluation. Location-reference methods and data management approaches also were addressed in that synthesis. Questionnaires were widely distributed and responses were received from all 50 states, the District of Columbia, and 9 Canadian provinces.

By 1994, essentially all agencies were collecting pavement condition data in one form or another. There was still no consensus on how distress surveys were conducted, although many agencies still were using windshield or walking surveys. Six agencies had adopted video distress collection techniques and one was using photologging. None reported automated distress data processing techniques (automated reduction of distress types, frequency, and severity from images) at that time. The synthesis did report that about one-half of the agencies were using automated means to collect rutting data. There was no elaboration on those automated methods.

In the late 1980s and early 1990s, roughness data collection had undergone an enormous evolution. By 1994, nearly all agencies were collecting and reporting IRI data to the HPMS program. Although an FHWA initiative, the HPMS program had a special advantage for the states, because it provided a standard making it possible to compare roughness data between states. *NCHRP Synthesis 203* (*6*) describes the IRI as a standardized roughness measurement that is calculated by mathematically applying a reference quarter car simulation to a measured profile. Based on extensive research, the World Bank established those simulation parameter values that best represented roughness-related measuring equipment being used worldwide (*7,8*). The IRI is measured in units of meters and kilometer or inches and miles, and it can easily be related to those measurements obtained by RTRRMS. This index is very useful for relating a roughness measure to overall ride quality, which is obtained at highway speeds.

However, pavement profiling is still an evolving science, as demonstrated by the trials of the Long-Term Pavement Performance (LTPP) program as highlighted in the *LTPP Manual for Profile Measurements* (*9*) and *LTPP Profile Variability* (*10*). These documents address the "how to" and the variability issues of profile measurement, respectively, for the program.

At least three national efforts have contributed to developments in pavement condition evaluation in general and to automated surveys in particular over the past decade: the development and implementation of the Strategic Highway Research Program (SHRP) *Distress Identification Manual for the Long-Term Pavement Performance Project* (*11*), updating of the AASHTO *Pavement Management Guide* (*1*), and publication of AASHTO provisional standards on pavement data collection (*12*).

Starting in 1989, the implementation of the distress identification manual on LTPP general and specific pavement studies gave credibility to a set of pavement distress definitions for both asphaltic concrete and portland cement concrete (PCC) pavements. These definitions were adopted by many agencies that had lacked an agency-specific distress manual. Other agencies made modifications to their procedures to more closely adhere to what was to become somewhat of a national standard. Later work by LTPP contractors assessed the variability of distress data collected for the program (*13*). Still later, work addressed concerns about possible differences in manual versus photographic distress survey results (*14*). That study addressed a proposed consolidation of manual and photographic databases consisting of a reconciliation of differences between the two survey methods. Results showed that such consolidation was unnecessary, for data collected by the two methods could be combined for analysis purposes. It should be noted that LTPP applies a rigorous QA process to both types of data and much of both types is rejected for failure to meet quality standards.

Similarly, the AASHTO pavement management guidelines published in 1990 and revised in 2001 provided agencies with information on what types of data to collect, the importance of various data elements, and the management of much of that data. Perhaps one of the most important guidelines cautioned against gathering "huge amounts of data simply because such collection is automated or available" (*6*). The guidelines make specific recommendations that agencies should make sure that data would be used before resources are expended in their collection and storage.

The development and implementation of the AASHTO provisional standards on pavement data collection have continued over approximately the last decade. The standards relative to this synthesis are those on quantifying cracks in asphalt pavements, quantifying pavement roughness, and determining rut depth and joint faulting of concrete pavements. Because two-thirds of the AASHTO member agencies must approve the provisional standards before they become "standards," revisions and re-balloting may occur for an indefinite time. The most recent versions are dated 2003, but they still carry the designation "provisional." The provisional standards are discussed in detail in later chapters. At this point, it is sufficient to note that they provide a beginning for standardization of the procedures.

In 1999, Wang and Elliott (*15*) studied pavement imaging and distress identification from those images for the Arkansas State Highway and Transportation Department. Although the focus of their work was an automated crack identification and classification system, the study also provided an excellent overview of technology in the area of automated pavement distress surveys and looked at possible future directions. Even in 1999, almost all pavement imaging was through very high speed (VHS) videotaping, because digital technologies were just emerging in the pavement evaluation area. The report concludes that "there still exist limitations in accuracy, speed, and degree of automation with the existing systems" (*15*).

Clearly, the adoption of methods and technologies associated with pavement distress data collection and analysis has evolved rapidly over about the past decade and even more rapidly over the few years since the aforementioned work was reported. Now, pavement management personnel can interact through the Internet and other platforms, such as the annual FHWA-promoted regional pavement management conferences, to exchange information and advance the rapid maturing of the relevant technologies.

Further contributing to this rapid evolution is a parallel rapid evolution in computing and imaging technologies. Today's computers can handle the enormous volumes of data necessary to support pavement management decisions, whereas the digital technology makes it possible to capture pavement images in a much more user-friendly format than was available with photographic and video technologies.

METHODOLOGY

Agency Questionnaire

Information for synthesis development was gathered by means of an extensive literature search and through a questionnaire, which was distributed to prospective user agencies in both the United States and Canada. In addition, information was gained from the Pavement Evaluation 2002 Conference held in Roanoke, Virginia, during late October 2002. This conference provided an opportunity for one-on-one contact with many of the user states and with the vendors furnishing data collection services. In addition, vendors were invited by conference organizers to demonstrate their equipment and procedures on a specially designated test site near the conference center.

The project questionnaire is contained in Appendix A and provides for feedback on these points:

- Whether or not an agency was collecting automated pavement condition information;
- If not, over what time frame, if any, the agency expected to automate some of its pavement data collection activities;
- For surface distress (cracking, patching, etc.), smoothness (IRI), rut-depth measurement, and joint-faulting measurements the following items:
  - Methodologies of data collection,
  - Location referencing used,
  - Monitoring frequencies,
  - Sampling techniques,
  - Data management,
  - Costs, and
  - Protocols used;
- Peripheral data (right-of-way, signs, drainage inventory, other) collected and how;
- Contracting procedures;
- QC/QA procedures;
- Benefits and advantages of automation; and
- Other issues, problems identified, and changes foreseen.

Completed questionnaires were received from 42 states and the District of Columbia, from two FHWA offices, from 10 Canadian provinces and territories, and from Transport Canada (on airfields). Although several prospective vendors requested copies of the questionnaire, none provided a response. All except two of those responding were using automated collection on at least one pavement condition data element. Detailed response tabulations are given in Appendix B, Tables B1 through B9, and are discussed in detail in later chapters.

Literature Search

An extensive literature search made use of the Library of Congress, National Technical Information Service, and Transportation Research Information System (TRIS) databases, as well as those of many of the state transportation agencies. TRIS search parameters of "automated and pavement and distress or automated and pavement and condition" returned 130 documents, approximately one-half of which were directly applicable to the current synthesis. Other sources of information were the FHWA, the Permanent International Association of Road Conferences (PIARC), and the Australian Road Research Board.

The literature surveyed provided general background for the synthesis and an understanding of the technologies involved. In addition, the literature search provided the basis for assessment of the pavement distress data collection state of the art. One project objective was to contrast the state of the art and the state of the practice as conveyed by questionnaire responses. The relevant discussion is found in chapter nine.

DEFINITION OF TERMS

Most of the terms used in this synthesis are those common to the pavement engineering community and for convenience most are defined in the Glossary. However, at least two terms are considered specific enough to this document to warrant special definition. These are "automated collection" and "automated processing" in the context of pavement distress data.

For the purposes of this synthesis, automated collection was defined, in the project scope, by the topic panel as "data collected by imaging or by the use of noncontact sensor equipment." Thus, data collected through manual procedures, even if recorded by laptop computers or by other methods, are not considered to have been collected through automated means. Manual collection is understood to mean that data are collected through processes where people are directly involved in the observation or measurement of pavement surface properties without the benefit of automated equipment (e.g., visual surveys and faultmeters).

The processing of data collected through noncontact sensors is almost always to some degree automated, for the volumes of data relating to transverse and longitudinal profiles are such that manual processing would not be practical. Therefore, for the purposes of this synthesis, automated processing pertains to the reduction of pavement surface distresses, such as cracking and patching, from images. The definition of fully automated is that such distresses are identified and quantified through techniques that require either no or a very minimum of human intervention. Typically, automated in the context of pavement cracking involves the use of digital recognition software capable of recognizing and quantifying variations in grayscale that relate to striations (sometimes cracks) on a pavement surface.

DISCLAIMER

Throughout this synthesis report there are references to vendor reports and websites. These references are used in the course of supporting or explaining technical concepts that arise with many of the issues addressed. Vendor claims about processes and products should be independently verified in the event that a referenced vendor's services are desired.

CHAPTER TWO

DATA COLLECTION ISSUES AND TECHNOLOGIES

This chapter is devoted to a discussion of various pavement distress data collection issues and the technologies involved. To organize the voluminous data from the questionnaire responses and the literature search into a manageable format, several issues, common to all distresses, are discussed early in the chapter. These are monitoring frequency, sampling or reporting frequency, and location-reference methods.

Later in the chapter, the various automated data collection technologies and equipment currently in use by highway agencies are identified and discussed. The equipment used generally conforms to the provisions of the ASTM *Standard Guide for Classification of Automated Pavement Condition Survey Equipment* (*16*). As suggested earlier, the data collection technologies fall into two general classes: imaging of the pavement surface through photographing, videotaping, or digitizing: and the measurement of pavement longitudinal and transverse profile through the use of various noncontact sensors. The existing technologies are discussed in the order they were addressed in the project questionnaire. In addition, several emerging technologies and how they are seen to apply in highway agencies are described. Table 1 provides an overview of pavement data collection and processing.

DATA MONITORING FREQUENCY

Although there are numerous variations, there tend to be differences within many agencies between the monitoring frequency used for pavement surface distress (imaging) and that used for the sensor-measured features (roughness, rut depth, and joint faulting). Essentially, that difference pertains to the relative difficulty in collecting and processing imaging data. Many agencies collect sensor data more frequently than images. Table 2 provides a summary of frequencies from the data gathered through the analysis of questionnaire responses and is detailed in Tables B1 through B4 in Appendix B. Table 2 reflects only those pavement data collected through automated means, whereas the tables in Appendix B cover some elements collected manually as well.

Almost all agencies monitor pavement surface distress (cracking, etc.) at 1-, 2-, or 3-year frequencies, if at all. Variations are that a few agencies do one-half of the system each year, with others doing one-third each year. In the tabulation, these results are expressed as 2 and 3 years, respectively. A few states monitor Interstate pavements at 1-year intervals and other pavements at 2-year intervals (Table B1). Two Canadian provinces use the 3-year interval, whereas British Columbia monitors at a 2- to 4-year frequency depending on the class of highway. Most agencies (18) capture pavement cracking at 2-year intervals, as shown in Table 2.

The 1-, 2-, and 3-year monitoring frequencies apply to all other distress features captured. Almost every agency monitors roughness (IRI). Because that monitoring is at least partly driven by HPMS requirements, it is necessary to do the work on at least a biennial basis. Table 2 shows that the agencies are almost equally split between a 1- and 2-year roughness monitoring frequency. Again, a few agencies monitor their Interstate pavements at 1-year intervals and other roads at 2-year intervals. Finally, two Canadian provinces and Massachusetts conduct roughness monitoring at 3-year intervals. Again, British Columbia monitors roughness at a 2- to 4-year frequency, depending on the class of highway.

Rut depths typically are concurrently determined with measurements of roughness because the same sensor technology can be used. Therefore, there is the same virtually equal split between 1- and 2-year monitoring frequencies. Four agencies reported a 3-year rut-depth monitoring frequency, whereas British Columbia again uses 2 to 4 years. Two agencies that measure roughness do not collect rut-depth measurements.

Far fewer agencies employ automated collection of joint faulting than the other sensor collected parameters. In addition, because some agencies, especially the northeastern states and most of the Canadian provinces, have few exposed concrete pavements, there seems to be some lack of confidence in the automated means (as discussed later) of making the measurements. Several agencies collect joint-faulting data with one or more version of a manually operated faultmeter and are not included in Table 2. Of those collecting automated faulting data, 10 use a 1-year monitoring frequency and 13 use a 2-year cycle.

DATA REPORTING INTERVAL

An initial effort was made to address pavement condition data sampling interval (measured in longitudinal distance or percentage of length). However, it was determined that most agencies using automated means of data collection sample continuously, or very nearly so, on the outer traffic lane. In a few instances, a worst lane is selected for evaluation. In no

TABLE 1
OVERVIEW OF AGENCY PAVEMENT DATA COLLECTION AND PROCESSING
(Number of Agencies)

		Data Item			
Activity	Entity/Process	Cracking	IRI	Rutting	Joint Faulting
Automated Collection	Agency	10	31	30	21
	Contract	20	23	21	12
Automated Processing	Agency	7	—	—	—
	Contract	7	—	—	—
Image Capture	Analog	16	—	—	—
	Digital	17	—	—	—
Sensor Data Collection	Laser	—	44	30	23*
	Acoustic	—	3	15	
	Infrared	—	4	2	
Protocol Use	AASHTO	4	12	6	4
	ASTM	—	19	—	—
	LTPP	5	—	—	—
	Other	21	16	38	10

*By sensor.
Notes: LTPP = Long-Term Pavement Performance; IRI = International Roughness Index.

case is an agency evaluating all lanes. The essentially universal practice is to evaluate the outermost traffic lane (no parking spaces) in one direction for pavements having fewer than four lanes and in both directions for roadways having four or more lanes. For purposes of this discussion, 100% sampling means 100% of the evaluation lane. In cases where shoulders and other peripheral features are evaluated, those evaluations are conducted separately as described later.

Images usually provide continuous coverage at 3 to 5 m (10 to 15 ft) longitudinally per image, whereas sensor measurements often are made at intervals of 25 to 100 mm (1 to 4 in.). Thus, it was deemed more meaningful to address a reporting interval, because that is a more standardized quantity than distance. The results of questionnaire responses concerning reporting intervals are given in Table 3 (details are cited in Tables B1–B4). Only those agencies reporting automated collection are included in Table 3. Even then, a few agencies declined to state a frequency for at least some data items.

For cracking, nine agencies reported only that they sampled 100% of the lane to be evaluated. Many others reported 100% sampling of that lane but listed reporting intervals of 15 to 300 m (50 to 1,000 ft). Such a statistic simply means that all data (100% of the evaluated lane) are used, but that the results are summarized at an agency-dependent frequency. Three agencies collect cracking data on a segment-by-segment basis (usually defined as a pavement management segment of varying length), whereas five sample 10% to 30% of the roadway, usually on a random sampling basis. A few agencies define sampling or reporting intervals in other ways, such as the 500 m employed by New Brunswick. The LTPP program is included as an agency using 100% sampling, although it should be kept in mind that each LTPP site is typically 500 ft long.

TABLE 2
SUMMARY OF AUTOMATED MONITORING FREQUENCIES EMPLOYED (Number of Agencies)

Frequency (years)	Cracking, etc.	Smoothness/ Roughness	Rut Depth	Joint Faulting
1	9	26	24	10
2	18	20	20	13
3	2	4	4	0
Other	1	2	2	0
Total	30	52	50	23

In the case of roughness monitoring, many U.S. agencies employ 100% sampling with reporting intervals at 158 m (0.10 mi or 528 ft). This reporting interval seems to be an "English" version of the 0.1-km interval suggested in the AASHTO IRI provisional standard (*12*) and covers most of the 100 to 300 m (300 to 1,000 ft) range given in Table 3. The Canadian provinces reported roughness results at 50- to 100-m intervals. A few agencies report roughness results by pavement management segment, whereas a few others use reporting intervals ranging from the one city block used by the District of Columbia to 1 mi used by Arizona.

For given agencies, rut-depth measurements tend to be reported in much the same intervals as roughness. Also as cited in Table 3, there are 12 agencies simply reporting 100% sampling, whereas others use reporting intervals of 10 to 300 m (30 to 1,000 ft). Five report results by segment average and three use other intervals such as 1 mi (Arizona) and a sample from each mile (Oregon).

Finally, far fewer agencies employ automated collection of joint-faulting data. However, as given in Table 3, the intervals fit those given for roughness and rut depth. Note that 11 agencies sample 100% of the joints, 5 report faulting at 100 to 300 m (300 to 1,000 ft) intervals, and 7 report average faulting by pavement management segment.

TABLE 3
SUMMARY OF REPORTING INTERVALS USED IN AUTOMATED MONITORING
(Number of Agencies)

Interval	Cracking, etc.	Smoothness/ Roughness	Rut Depth	Joint Faulting
100%	9	12	12	11
100–300 m (300–1,000 ft)	6	20	16	5
10–50 m (30–160 ft)	6	13	15	3
Segment	3	2	3	1
10%–30%	5	0	0	0
Other	1	5	4	3
Total	30	52	50	23

LINEAR REFERENCING

A major input to location-referencing systems is the linear-referencing element. The method in use by a given agency has very little relationship to the types of distress collected by that agency. Almost without exception, the reference system used for one data element is used for all elements. Table 4 is a summary of the linear-referencing systems in use (details are given in Tables B1–B4). Column totals would not be meaningful because a number of agencies use more than one method at a time.

The column indicating smoothness and roughness probably is the best true indicator of linear reference use, because it is the indicator of the most agencies using an automated method of data collection. For example, because fewer agencies use mile points for joint faulting than for roughness means that fewer agencies collect joint-faulting data; it says nothing about the preferred reference methods.

Clearly, there is a strong preference for the use of mile posts or mile points, and the two terms seem to be used interchangeably, although technically there is a real difference. Mile points refer to a specific location on a roadway, whereas mile posts are the physical markers for those locations. For the purposes of the rest of this synthesis, the term “mile point” will be used to identify either the mile point or mile post designation unless otherwise clearly distinguished in the text. It is also not clear that there is a difference between mile points and the log mile terminology used by several agencies. The data are summarized on the basis that there is no difference between the two. Similarities in linear-reference systems in use and the HPMS linear-reference guidelines suggest that many agencies have adopted those guidelines (*5*).

TABLE 4
SUMMARY OF LINEAR-REFERENCE METHODS USED IN AUTOMATED MONITORING (Number of Agencies)

Method	Cracking, etc.	Smoothness/ Roughness	Rut Depth	Joint Faulting
Mile Point (post)	33	46	35	23
Latitude–Longitude	12	15	14	8
Link-Node	5	5	5	2
Log Mile	3	1	1	0
Other	2	1	1	0

Interest in the use of a geographic information system (GIS) and even the Global Positioning System (GPS) was identified in *NCHRP Synthesis 203,* although no tabulation of users was provided (*6*). There is currently a definite trend toward the use of GPS coordinates (latitude and longitude) for location-reference purposes, although the technology has not been broadly accepted as the only method. In all except two cases, agencies reporting the use of GPS coordinates also continue to use mile points. There is some indication that this dual use may be temporary and that more agencies eventually will adopt coordinates as the sole method. However, there is some recognition that a tremendous volume of archived highway data has used only mile points, so that abandonment of that approach would require absolute certainty of good correlation of the two methods. Furthermore, discussions with highway maintenance personnel strongly suggest that physical mile posts will be in use for working purposes well into the future.

PAVEMENT SURFACE DISTRESS

Procedures in Use

Numerous procedures for asphalt pavement crack identification and collection are in use in various agencies, although four agencies reported the adoption of AASHTO Provisional Standard PP44-01, *Standard Practice for Quantifying Cracks in Asphalt Pavement Surface* (*17*). That standard defines a crack as a discontinuity in the pavement surface with minimum dimensions of 1 mm (0.04 in.) wide and 25 mm (1 in.) long. It further defines a low-severity crack as less than 3 mm (0.125 in.) wide. The existing imaging technology seems capable of reliably capturing the latter cracking through automated means, although there is some effort to capture even finer cracks. In a data collection contract, Alabama has suggested that a 0.5 mm (0.02 in.) minimum would be desirable in its system. In response, the contractor stated, with regard to its latest (November 2002) high-resolution digital camera, “We are unable to detect these (½ mm) reliably and, frankly, we do not think any system existing today can do so, most certainly for network level uses and at network level prices” (personal communication, letter to S. George, Alabama DOT, from Roadware Group, Inc., Nov. 18, 2002). The contractor went on to propose a minimum 2 mm (0.08 in.) crack as a level it could be confident in achieving.

Other procedures include that developed for the LTPP program (*18*) in use by LTPP and several other agencies, and the pavement condition index (PCI) approach developed by the U.S. Army Corps of Engineers (*19*) and in use by Wyoming, and as one input to the procedures used by numerous others. In those cases, the standards are being adapted to automated data collection. In addition, some 20 agencies are using agency-specific protocols for crack data collection and classification, usually by manual collection methods. Many of those agencies expressed an interest in the AASHTO standards, but they have not moved to its adoption. For those familiar with the AASHTO procedure, most resistance to adoption appears to be related to an unwillingness or technical inability to do away with a workable agency protocol that is not totally compatible with the AASHTO standard. Often there are large databases of historical data collected through an existing protocol that may be lost to an agency when adopting the AASHTO provisional standards.

Fourteen agencies provided copies of their asphalt pavement surface distress rating procedures in response to the synthesis survey. Although almost all were written for manual surveys, they are now used to support automated procedures.

Because agency and AASHTO procedures typically define types of cracking with reference to vehicle wheel tracks (also referred to as wheel paths), there have been efforts to put dimensions on those areas of the pavement. The definition of wheel paths and the related survey area used by AASHTO Provisional Standard PP44-01 is given in Figure 1. Note that the wheel paths and area between them are fixed regardless of lane width. Variable lane widths are accommodated in the left and right areas outside the wheel paths.

Some agencies use location with respect to the wheel paths as a determinant of fatigue cracking. Those agencies will define wheel tracks as a part of their automated distress processing methodology (see chapter three).

Automated data collection is being used on PCC pavements as well. Twelve agencies provided copies of their concrete pavement distress rating procedures in response to the synthesis survey. Again, most were developed for manual surveys, but may be used to support automated procedures at this time.

Methods of Data Capture

Pavement surface distress is captured by several different methods, as summarized in Table 5. Agencies doing manual surveys are included for comparison purposes only. Although approximately one-half of the agencies reported using a manual collection methodology, it is clear from stated plans that automated approaches will be coming into progressively more use. Also, a few agencies are in a transition period and use some manual and some automated collection methods. A few others use manual surveys on low-traffic-volume roads and automated approaches where safety is a major issue owing to high-traffic volumes.

In the past, there have been some efforts to capture pavement cracking through the use of acoustic or laser sensors that attempted to relate cracking to abrupt variations in pavement texture (*6*). Such approaches seem to have gained little favor and have lost out to the imaging methods now used.

The major methods of pavement imaging are generically termed “analog” and “digital.” Analog refers to the process

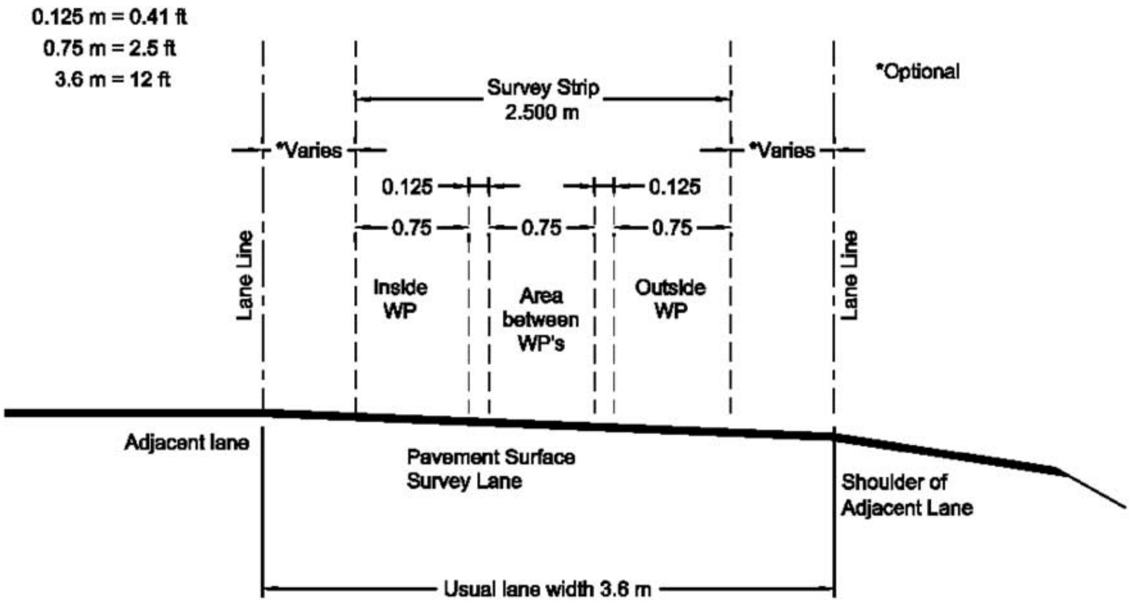


FIGURE 1 Cross section of survey lane showing wheel paths and defined survey area between wheel paths as defined by AASHTO (*17*).

TABLE 5
METHODS OF SURFACE DISTRESS CAPTURE
(Number of Agencies)

		Analog		
Agency Type	Manual	Photographic	Video	Digital
State	17	0	13	15
Province	6	0	2	1
Federal	1	1	0	1
Total	24	1	15	17

wherein images are physically imposed on film or another medium through chemical, mechanical, or magnetic changes in the surface of the medium. Digital imaging refers to the process wherein images are captured as streams of electronic bits and stored on electronic medium. The digital bits can be read electronically for processing or reproduction purposes. A third emerging method, three-dimensional (3-D) laser scanning, will be discussed later.

Although much of the earlier work has been done with analog photographs or videotapes, digital imaging is fast becoming the most popular method, owing to the quality of images that can be produced, the ease of data manipulation, and the applicability to automated data reduction (to be described later). Digital images may be captured on videotape or on other media, such as computer hard drives, compact discs, or digital video discs. Whatever means of image capture is used, these images are almost always “stamped” with date, time, and some means of location-reference so the image can be tied to a given location.

Pavement imaging methods are described here in more detail. Much of the discussion is derived from a draft Transportation Research Circular, *Automated Imaging Technologies for Pavement Distress Survey,* provided by TRB Committee A2B06, Pavement Monitoring, Evaluation, and Data Storage (*20*). The circular presents the concept of pavement surface distress surveys using pavement images, reproduced in Figure 2. The system consists of data acquisition, data storage, and data display and processing subsystems. In addition, a database system is used for archiving and retrieving the processed data.

Analog Imaging

The predominant use of analog imaging of pavements is in photographing (usually with 35-mm film) and videotaping. Images obtained can be of high quality, but they are not easily converted to digital format for computer storage and manipulation. Analog imaging has been less frequently used in recent years owing to the maturing of digital technology. The draft TRB circular (*20*) sums up the analog technology.

> The quality of televisions and videotapes, including Super VHS (S-VHS) format videotapes and 12-in. laser discs, is determined by the analog video standard set by the National Television Systems Committee in the early 1950s. Although an analog video signal can be transmitted and copied through narrow bandwidths, it is difficult to manipulate, copy, and distribute the signal without introducing electronic noise into the original signal, which degrades image quality. It is also difficult to integrate analog video with other types of data, such as text and graphics, unless high-end video production equipment is available and used. The resolution of the standard analog video signal is also relatively low compared with that of digital alternatives. Therefore, today’s highway users of videotapes have largely transitioned into using computer-based digital technology.

Still, the photographic method, popularly known as photologging, was used by a few agencies for many years. It probably became most well known for its adoption as the method of choice for the LTPP program now managed by the FHWA and described by Gramling and Hunt (*21*).

The photologging methodology essentially consists of photographing the pavement surface, usually with 35-mm film, and reduction of distress data through review of the film at a workstation. Photologging vans typically use a downward-facing camera and possibly one or more facing forward or in another direction, depending on user needs. Most earlier work

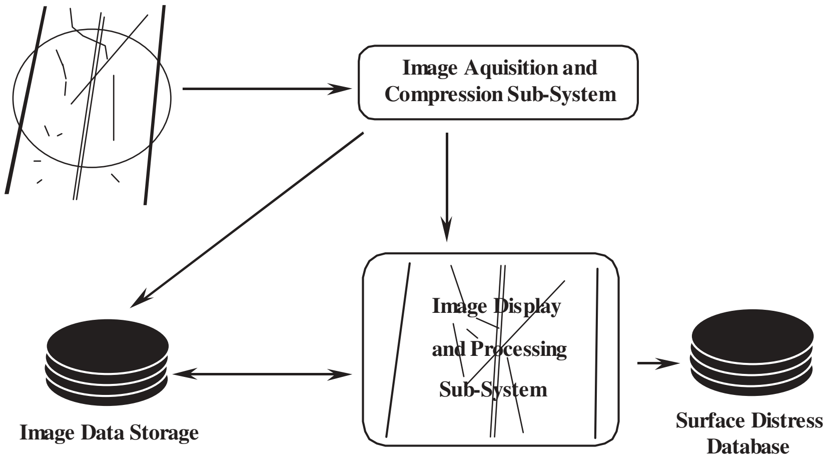


FIGURE 2 System concept in the pavement surface distress survey (*20*).

was done by contract on a cost-per-mile basis. Much of the work was done at night using lighted cameras to overcome problems with shadows cast by survey vehicles, traffic, or roadside features that can mask pavement features critical to proper distress evaluation. In most cases, photologging was continuous over what the agency defines as a roadway section or sample of a roadway section. At least one film image vendor reported the capture of cracks as fine as 1-mm (0.04-in.) wide at speeds up to 96 km/h (60 mph) when controlled illumination is used (*22*).

NCHRP Synthesis 203 (*6*) noted that three agencies still used the photographic approach about 10 years ago. Now, only LTPP reports using photologging. LTPP makes full use of the technology on test sites throughout the United States and Canada. "Instead of shooting one frame at a time, the film used in LTPP is continuously exposed to a moving pavement surface, forming a contiguous image of pavement. In order to control illumination to guarantee image quality, shooting is normally conducted at night" (*20*). LTPP reported that cracks of approximately 2.5 mm (0.1 in.) or less are not consistently seen on film depending on lighting, moisture, and other conditions (*13*). Interestingly, the LTPP imaging contractor uses a unique method of estimating rut depths from a transverse line superimposed on the pavement image. That photographic method is discussed later in this chapter.

The method of choice for pavement imaging by many agencies is a videotaping technology that consists of the capture of pavement images on high-resolution videotapes, usually of the S-VHS variety. Questionnaire responses showed that approximately one-third of the agencies reporting have adopted video imaging for at least part of their pavement surface distress data capture. Typical survey vehicle configuration consists of one or more downward-facing video cameras, at least one forward-facing camera for perspective, and any number of additional cameras for the capture of right-of-way, shoulder, signage, and other information depending on agency requirements. As with photologging, pavement cameras may use special lighting to reduce shadows that can mask distress features.

Reduction of distress data from videotape images also involves the use of workstations and manual review of the images to classify and quantify distresses. The method is cumbersome and has given way in recent years to digitizing of the images for more ready data handling and processing, as described in chapter three.

Digital Imaging

The employment of digital cameras is rapidly becoming the preferred method of pavement imaging. As with analog videotaping, slightly more than one-third of the responding agencies have begun to use digital imaging to capture pavement surface distress data. Survey vehicle configuration is similar to that for videotaping in that one or two cameras capture the pavement image while any number may be used for other data required by the agency. Again, special lighting may be used to overcome shadowing problems.

A major force behind the move toward digital imaging of pavements is the opportunity to reduce distress data from those images through automated methods. Another advantage of digital imaging is the availability of random access to the data. As mentioned earlier, digital images lend themselves to automated analysis because of the ability to analyze variations in grayscale as those variations relate to pavement features. Several automated analysis methods are in use and others are under development to accomplish that task, as discussed in chapter three.

There are two types of cameras currently used to digitally image a pavement surface. These are known generally as the "area scan" and the "line scan" methods, although some vendors are using other terminologies. Wang and Li (*23*) provide a good overview of digital camera pavement imaging. The National Endowment for the Humanities has funded a digital imaging tutorial developed by and available from Cornell University (*24*). Furthermore, the TRB draft circular (*20*) includes a primer on digital imaging. The two scanning approaches are depicted in Figure 3.

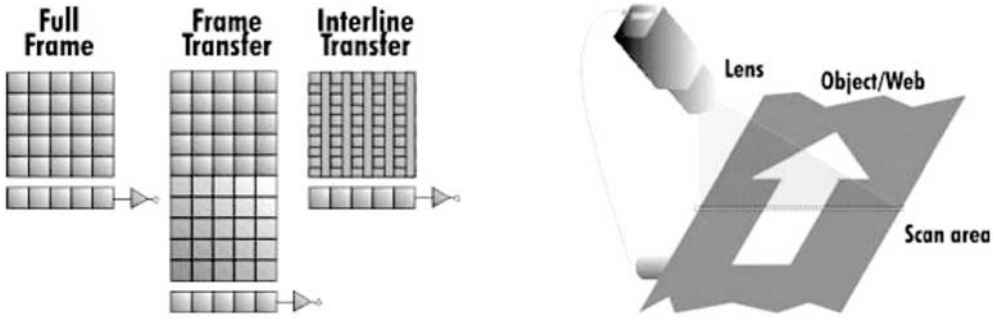
Area Scan

This method of digital imaging refers to that in which an image consisting of thousands of pixels depicts some defined pavement area, usually one-half to full-lane width and 3 to 5 m (10 to 15 ft) long, depending on camera features (lens, camera angle, placement) and vehicle speed. In pavement imaging, camera angle is of great importance, for distorted pixels (and images) will occur if the camera is not perpendicular to the pavement surface.

The resolution varies somewhat among agencies and vendors and is increasing steadily as the technology evolves. Area scanning uses a two-dimensional (2-D) array of pixels in a conventional sequence of snapshots. The three basic types of area scan arrays are full frame, frame transfer, and Inter-Line Transfer, shown in Figure 3a. Descriptions of these technologies are given in the draft TRB circular (*20*). An example of a pavement image taken with an area scan camera is shown in Figure 4 at the resolution of 2,048 pixels transversely in Joint Photographic Experts Group (JPEG) format (*20*).

Line Scan

The most common example of line scan imaging is the fax machine. Line scan imagers use a single line of sensor pixels (effectively one-dimensional) to build up a 2-D image. The second dimension results from the motion of the object being imaged. The 2-D images are acquired line by line by successive single-line scans while the object moves (perpendicu-



(a) Area Scanning

(b) Line Scanning

FIGURE 3 Two scanning approaches in digital imaging [*Courtesy:* DALSA Corporation and Wang (*20*)].

larly) past the line of pixels in the image sensor, shown in Figure 3b (*20*).

Thus, line scan pavement imaging is performed through the digital capture of a series of transverse lines that are full-pavement-lane width. These lines are "stitched" together to form a continuous image or an image broken at intervals set by the user. The International Cybernetic Corporation (ICC) describes its line scan setup in this way:

> ICC's pavement digital imaging system uses a linescan camera with a resolution of 2048 pixels by "N" lines. [N is adjustable from 130 mm (5 in.) up to 9 m (30 ft) of longitudinal pavement coverage.] The width of the image is determined by the height of the camera above the pavement. Image width is adjustable between 9 ft and 15 ft with the standard boom (*25*).

Mandli, Inc., reports that 3-mm (0.125-in.) wide cracks are clearly visible on full-lane width line scan images (*26*). Wang and Li (*23*) provide a good discussion of the relationship between vehicle speed and the number of pixels required per line. They also note that the resolution of line scan cameras was as high as 6,000 pixels per line in 1999.

At least one vendor uses the area scan approach for forward and right-of-way images and a line scan camera for pavement images at a claimed crack visibility down to 1 to 2 mm (0.04 to 0.08 in.) (*22*).

A particularly onerous problem with line scan imaging can result from any shadows cast by the survey vehicle itself. Because of the line scan feature, any shadow from the vehicle that falls onto the pavement surface will appear as a continuous shadow in the scanned image. If this shadow falls in a critical area of the pavement, a wheel path, for example, the image can be rendered virtually useless. Special precautions and sometimes special lighting must be used to avoid this problem with line scans. The ICC confronts the shadowing problem by using a 10-fixture lighting system for all line scanned pavement images (*25*).

An example of a line scan pavement image is given in Figure 5 and an image with a vehicle-cast shadow is shown in Figure 6. As with the other methods of imaging the pavement surface, digital images require a workstation with the appropriate software to capture pavement cracking and other fea-

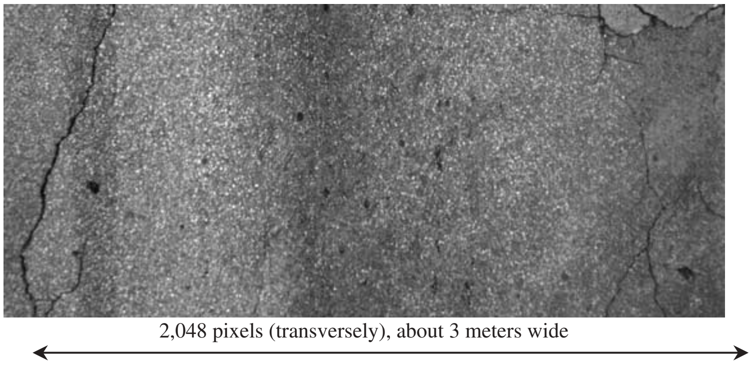


FIGURE 4 A 2,048-pixel resolution image in JPEG format (area scan digital camera) [*Courtesy:* Wang (*20*)].

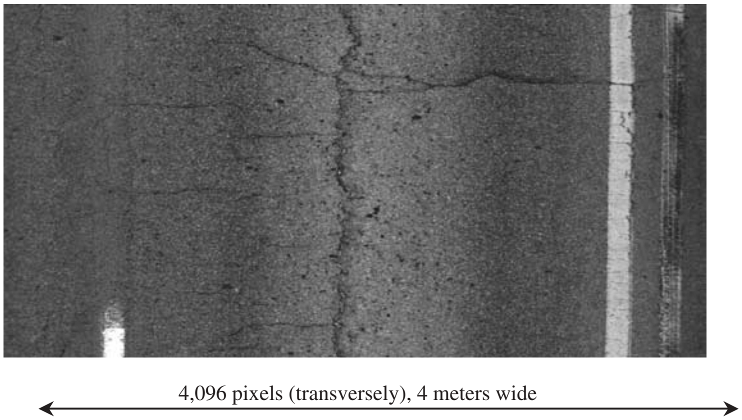


FIGURE 5 A 4,096-pixel resolution image in JPEG format (line scan digital camera) (*20*).

tures for pavement management purposes. These issues are discussed in chapter three.

Three-Dimensional Laser Imaging

The TRB draft circular provides the following description of an evolving technology using 3-D imaging (*20*):

> Phoenix Scientific Inc. (http://phnx-sci.com) has developed a phase-measurement Laser Radar (LADAR) to measure the 3-D properties of pavements. The Laser Radar uses scanning laser and reflector to measure the reflecting times across pavement surface, therefore establishing a 3-D pavement surface after the Laser Radar moves longitudinally along the traveling direction. Its system, as claimed, is able to produce roughness and rutting data. Another company, GIE Technologies Inc. in Canada (http://www.gietech.com/), has the LaserVISION system, which also models the 3-D surface of pavements. The lasers are stationary and four of them are used to cover full lane-width. The service it provides is primarily for roughness and rutting survey. At this time, there is no independent evidence that laser based technologies are able to provide usable data for pavement cracking survey and other condition survey. The primary reason is they do not provide high enough resolution.

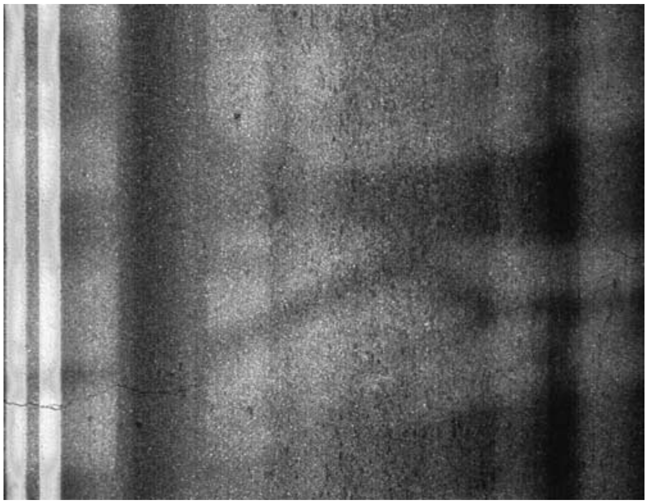


FIGURE 6 Linescan pavement image with vehicle-cast shadow in left wheel track (*Courtesy:* Virginia DOT).

PAVEMENT ROUGHNESS

Engineers have long considered ride quality, sometimes referred to as roughness and sometimes as smoothness, as a favorite indication of the functional capability of a pavement surface. One primary reason is that numerous studies have shown that ride quality is the pavement feature that will most often trigger public response and is a factor in determining vehicle operating costs. A 1995 National Quality Initiative (NQI) survey of highway users found that less than one-half were satisfied with pavement condition, especially smoothness (*27*).

The first 50 years or so of roughness measurement in the United States was summarized in the Background section of this report. It was seen that the technologies applied have evolved from subjective seat-of-the pants methods through response-type road meters to the sophisticated noncontact sensor-based methods in use today.

Procedures in Use

In the United States, a strong impetus for the collection of roughness data is provided by the FHWA HPMS (*5*). Although many agencies measured roughness on at least major highways long before the HPMS program was instituted, HPMS required more consistent and uniform measurements. As a result, essentially all highway agencies now measure ride quality of pavements.

The HPMS program requires the reporting of IRI for all National Highway System (NHS) roads on a biennial basis. The information from this program is integral to the allocation of federal funds to the states. The HPMS manual cites the following advantages of using the IRI as the roughness measure. It is

- A time-stable, reproducible mathematical processing of the known profile;
- Broadly representative of the effects of roughness on vehicle response and users' perception over the range of wavelengths of interest, and is thus relevant to the definition of roughness;
- A zero-origin scale consistent with the roughness definition;
- Compatible with profile measuring equipment available in the U.S. market;
- Independent of section length and amenable to simple averaging; and
- Consistent with established international standards and able to be related to other roughness measures.

The standard accepted by most agencies for determination of the IRI is AASHTO Provisional Standard No. PP37-00 (*28*). This standard provides for the use of a longitudinal profile determined in accordance with ASTM Standard E950, Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference (*29*). More than 80% of the agencies responding to the questionnaire reported using some variation of AASHTO, ASTM, HPMS, or World Bank roughness measurement protocol. Follow-up phone calls or e-mails to some agencies revealed that in many cases there are different names used for the same AASHTO standard. Other respondents used agency-specific protocols, but provided few details.

Sensor Technologies

Now, virtually all network-level roughness monitoring reported in the United States and Canada is conducted with instrumented vehicles using accelerometers and at least one of three types of sensors: lasers, acoustic, or infrared. The accelerometers provide a horizontal plane of reference, whereas the sensors measure pavement deviations from a horizontal plane. Most sensors work on the basis of a simple concept that the distance from the reference plane to the road surface is directly related to the time it takes for the signal to travel from a transducer to the road and back. Lasers, however, work on the basis of a phase shift of the refracted laser beam in a process beyond the scope of this synthesis (*30,31*). The faster the signal, the more frequent sampling can be done at a given vehicle speed. Although fairly simple in concept, the measuring process is not so simple in application, for very high-speed and high-capacity electronic components are required to capture the large volumes of data generated.

The vehicles, known generically as profilers, produce in one pass a "continuous signal or trace related to the true profile of the pavement surface" (*6*). This longitudinal profile is the basic measure of the pavement surface from a ride quality point of view. However, converting profile features into a useful index of ride quality was the subject of extensive research that culminated in the almost universally used IRI (*7,8*).

The automated roughness-monitoring technologies in use by the various agencies are summarized in Table 6 by the number of agencies using each type of technology. Lasers are the most popular by a wide margin, and in one case an agency using acoustics reported plans to move to a laser in a replacement vehicle. At present, 38 states, 4 provinces, and 2 FHWA offices use lasers. Each of the automated roughness sensing technologies is discussed briefly in the following paragraphs.

Laser Sensors

Several vendors use or sell (sometimes both) pavement condition survey equipment where lasers are the principal means of profile measurement (*22,25,32*). The laser technology has evolved rapidly over about the last decade so that they now operate at very high speeds. Such high speeds permit the collection of profile data at intervals of 25 mm (1 in.) or less at vehicle speeds of up to 96 km/h (60 mph) (*22*). Depending on user needs, vehicles may be configured with from 1 up to numerous (often 37) lasers. One laser can be used to measure the longitudinal pavement profile in one location, whereas any number may be used if there are attempts to capture several longitudinal locations and the transverse profile as well.

Acoustic Sensors

Acoustic sensors were the basis for some of the earlier noncontact profilers developed. One of the best known of these was developed by the South Dakota DOT and is still referred to as the South Dakota profiler. A typical configuration was of three sensors and two accelerometers on the front bumper. In 1986, only South Dakota was using the device, whereas in 1991 the number had increased to 25 agencies (*6*). Now, as Table 6 shows, only three agencies reported using the acoustic technology for roughness monitoring (more use it for rut-depth measurements). The change appears to be related to the availability of the high-speed lasers that are not subject to some acoustic sensor problems with obtaining reliable measurements on coarse textured pavements.

Infrared Sensors

Infrared sensors are used by a few agencies, principally those using a newer version of the K.J. Law, Inc., Profilometer. That company has recently been sold and the buyer (Dynatest Consulting, Inc.) has moved to a laser sensor technology (*33*).

TABLE 6
TECHNOLOGIES USED IN ROUGHNESS MEASUREMENT (Number of Agencies)

Agency Type	Laser	Acoustic	Infrared
State	38	2	2
Province	4	1	2
FHWA	2	—	—
Total	44	3	4

Few specifications were readily available on infrared sensors at the time this synthesis was developed.

Profile and IRI

The output from pavement profilers is a standardized process (*29*) as is the determination of IRI from that profile (*34*). The first of these, *Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference* (*29*), covers the measurement and recording of profile data. The standard also addresses requirements of profile measurement equipment, the recoding of profile data, calibration requirements, dealing with faulty tests, determination of precision and bias, and reporting of the data.

The IRI standard, *Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements* (*34*), covers the mathematical processing of the road profile data to produce the IRI statistic. In addition, the standard addresses the determination of precision and bias as well as reporting of the data.

The ASTM profiling standard is also an integral part of the AASHTO provisional standard on IRI. AASHTO, however, refers back to the basic research (*8*) rather than to ASTM for the actual IRI calculation.

RUT-DEPTH MEASUREMENTS

Forty-six of the reporting agencies collect automated rut-depth measurements, nearly always concurrently with roughness monitoring, because generally laser or acoustic technologies mounted on the same vehicle are applied. A few states reported that their rut measurements are received as a part of the profile measuring program, but that no use is made of the data.

Procedures in Use

Currently, there is no consensus concerning the number of sensors devoted to rut-depth measurement. As can be seen in Table 7, the states are equally divided over the 3- and 5-sensor methods at 16 each, whereas 11 have adopted the "rut bar" with from 7 to 37 sensors (five states use a 37-sensor rut bar). Two Canadian provinces use 37-sensor rut bars and three use 4 to 5 sensors. Eastern federal lands use more than five sensors, whereas the LTPP program uses a unique shadow line projection method supplemented by laser profiling.

TABLE 7
METHODS OF RUT-DEPTH MEASUREMENT
(Number of Agencies)

Agency Type	3 Sensors	5 Sensors	>5 Sensors (Usually 31)
State	16	13	11
Province	0	3*	2
FHWA	0	0	1
Total	16	16	14

*Two use five sensors, one uses four.

The LTPP method, where 35-mm films are used to capture pavement images, called the PASCO RoadRecon, is described by LTPP (*35*):

> The PASCO RoadRecon system incorporates a van driven across the test section at night. A boom, on which a 35-mm camera has been mounted, extends from the rear of the van at the top of the unit. A strobe projector, mounted on the bumper, contains a glass plate that has a hairline etched onto it. The strobe and the camera are synchronized so that when the camera is triggered to take a picture, the strobe projects a shadow of the hairline onto the pavement surface at a specific angle in relationship to the van (and thus at an approximate angle to the pavement surface). The coordinates along the hairline image for each picture are later digitized and stored on a computer. Photographs are taken approximately every 15.2 m (50 ft).

In practice, few agencies actually use all of the sensors theoretically available on the 37-sensor rut bar. That bar provides for a sensor each 100 mm (4 in.) on a 3.6-m (12-ft) wide lane. However, because of safety concerns, agencies usually limit the bar length to approximately 3 m (10 ft) with 31 sensors.

The AASHTO provisional standard on rut-depth measurements is given in Figure 7 (*36*). The equations for calculation follow the figure. This standard is intended for use with a vehicle traveling over the pavement at highway speeds, although it is adaptable to a manual measurement as well. Most of the 15 agencies reporting a five-sensor measurement have adopted some form of this protocol. From the standard comes the following explanation:

> The transverse profile is determined on the basis of the vertical distance between an imaginary string line run across the traffic lane from the shoulder to the lane line. The string line may bend at the hump between the wheel paths where the hump is higher than the outside and centerline of the lane. For manual measurements, the use of a string line will require D_1, D_3, and D_5 to be zero (*36*).

Five-Point Rut-Depth Calculation

$$R_o = D_2 - \frac{D_1 + D_3}{2}$$
$$R_i = D_4 - \frac{D_3 + D_5}{2} \qquad (1)$$

where

R_o = rut depth outside wheel path estimate (mm);
R_i = rut depth inside wheel path estimate (mm);

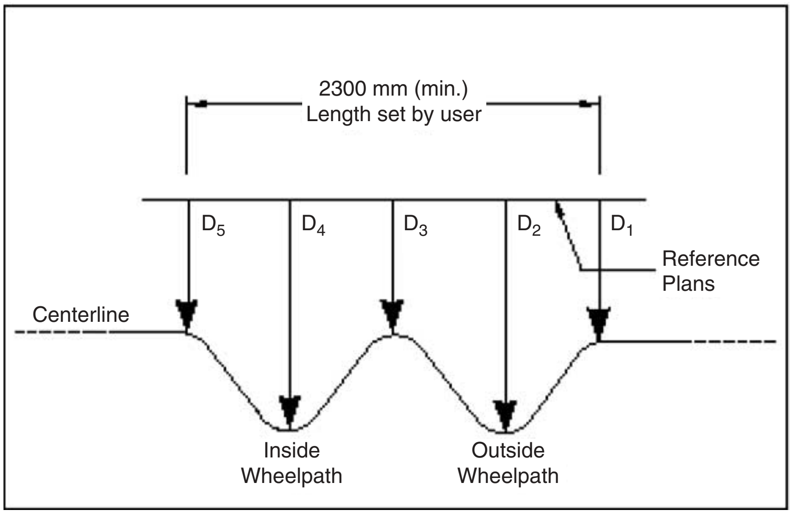


FIGURE 7 Rut-depth measurements [after AASHTO (*36*)].

R_o = is not less than 0;
R_i = is not less than 0; and
D_1, D_2 . . . D_5 = height measured as shown in Figure 7 (mm).

Recent Developments

Rut-depth measurement has been the subject of much discussion in recent literature. The three-sensor method has come under a great deal of criticism, with a number of researchers and others taking the position that it does not measure rutting with sufficient accuracy to be useful (*37*). The AASHTO provisional standard, as described, requires a minimum of five sensors. Still others are not satisfied with the five-sensor approach. Simpson (*38*) has reported that a minimum of nine sensors is required to achieve rut measurements with sufficient accuracy for pavement management. That work was based on comparison of a five-sensor rut bar to rod and level elevations and by systematically reducing the number of data points (sensors) that would be required to achieve acceptable correlation coefficients with "true" profiles. Questionnaire results show that the Vermont Agency of Transportation (VAOT) has adopted a nine-sensor rut bar on a state-owned van, although its contractor (Roadware) uses 30 sensors. Then, as given in Table 7, some agencies have gone to 30-sensor rut bars. This approach was introduced in the configuration of the Automatic Road Analyzer (ARAN) SmartBar (*39*). The sensors are placed 100 mm (4 in.) apart and theoretically provide full lane width coverage. The numerous data points offered by this technology suggest a much more accurate profile, but no independent validation has been discovered to date.

Faced with the fact that the 37-sensor configuration results in a dangerously wide 3.7 m (12 ft) rut bar on the survey vehicle, vendors have introduced still another technology of rut-depth measurement referred to as the scanning laser (*39–41*). An example is depicted in Figure 8. The approach provides for high-powered pulse lasers mounted on the back of the van to project a line across the pavement. One vendor using two lasers claims "lateral resolution is 1280 points across the width of the pavement (4 m). Depth accuracy is 0.5 mm or approximately $\frac{1}{32}$ in." (*39*). The same vendor continues, "Proprietary software will enable the vendor to provide the same 37 points of data to permit the use of existing well-proven algorithms and to provide compatibility with existing customer databases" (*39*). This technology was developed by a Canadian optical technology firm (*40*) and no independent validation has been published. A different company (*41*) developed the one laser system depicted in Figure 8 and, again, no independent validation is available.

JOINT-FAULTING MEASUREMENTS

Rigid pavement joint faulting is a distress feature that many agencies do not collect, in part because they do not have

FIGURE 8 Scanning laser [*Courtesy:* Mandli Communications (*41*)].

jointed concrete pavements. Of those that do collect the data, seven use manual or visual methods. Several agencies do a visual assessment as part of or in addition to overall visual condition surveys. Where joint faulting is measured manually, most agencies use specially designed faultmeters, the most popular of which is the Georgia Faultmeter developed by the Georgia DOT (*42*). A few agencies do some manual measurements by agency personnel, while vendor data are collected through automated means.

Procedures in Use

Twenty-three of the reporting agencies apply automated means to collect joint-faulting data. Those agencies overwhelmingly combine faulting measurements with roughness monitoring, because IRI is also affected by joint faulting. Most use two sensors (usually to measure longitudinal profile as well) and apply protocols developed by vendors or equipment manufacturers. Table 8 summarizes the methods reported in the survey responses.

The AASHTO provisional standard for joint-faulting measurements provides for the methodology given in Figure 9 (*43*). It is applicable to both manual and automated methods. Here, the user may vary the distance from the joint to the points of measurement, but must keep those points 300 mm (12 in.) apart. Faulting is defined as simply the elevation difference between the two points of measurement (P_1 and P_2) to the nearest 1 mm (0.04 in.), with a difference of 5 mm (0.2 in.) defined as the threshold of faulting. In questionnaire responses, only four agencies cited the AASHTO or a modified AASHTO standard. Most listed an agency or vendor protocol and provided few or no details.

TABLE 8
METHODS OF JOINT-FAULTING MEASUREMENT (Number of Agencies)

Agency Type	Manual	Sensor
State	9	22
Province	1	1
FHWA	1	—
Total	11	23

INTEGRATED SYSTEMS

The emphasis on the collection of massive amounts of pavement condition and other roadway data over the past few years has led to a proliferation in the development of what can be described as integrated systems. In a single pass of a data collection vehicle configured as an integrated system, a variety of data will be collected, depending on specific vendor and user requirements. Some of the data elements collected are pavement, right-of-way, and other images; longitudinal and transverse profile measurements; and in some cases, a texture-measuring system. All incorporate a distance measuring instrument (DMI), while many now include a satellite-driven GPS.

Although many systems are vendor owned and operated, others are sold directly to user agencies. An example of such a multipurpose vehicle is given in Figure 10. This van features a digital line scan camera mounted above a very intense lighting system.

In questionnaire responses, several agencies indicated that they were in the process of buying or upgrading systems. In many cases, one emphasis will be on achieving real-time cracking, smoothness (IRI), rutting, faulting, and other data in

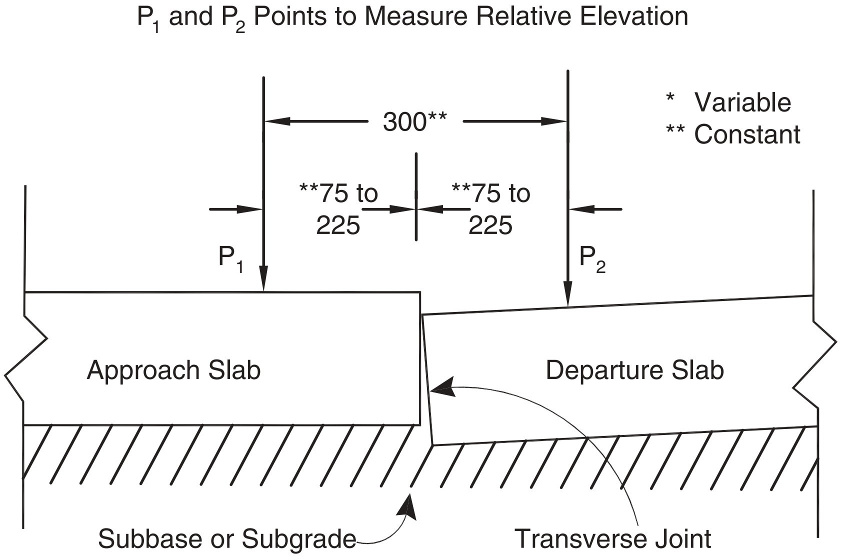


FIGURE 9 Points to measure for faulting by automated measurements (all measurements in millimeters) [after AASHTO (*43*)].

FIGURE 10 Typical multipurpose van [*Courtesy:* International Cybernetics (*25*)].

a single pass of a data collection vehicle. A typical new integrated system will incorporate one or more versions of imaging equipment, an ASTM Class II profiling system, and a means of positive location reference. Many systems will have the ability to provide roadway lighting synchronized with imaging equipment to alleviate the problem of shadows from either the equipment itself or from features surrounding the roadway. Added to some systems are right-of-way images and methodologies to provide such information as guardrail and signage inventories.

Gunaratne et al. (*44*), at the University of South Florida, have reported on a comprehensive evaluation of a vehicle proposed for pavement surveys by the Florida DOT (FDOT). This ICC vehicle contains digital imaging, laser sensing, and location-reference technologies and was shown by the researchers to be capable of fully meeting FDOT's pavement data collection needs. However, it was noted that visual surveys would still be needed "until FDOT acquires reliable software for automatic analysis of pavement distress videologs." A paper offered for presentation at the 2004 TRB annual meeting continued the evaluation, focused on digital images from the Florida vehicle, and identified several limitations of the equipment (*45*). Among these was a finding that light "noise" is very difficult to cope with in daylight imaging therefore night operations were recommended.

TABLE 9
EQUIPMENT IN USE

Supplier	Agencies Using
Dynatest and Law	5
GIE Technologies	2
International Cybernetics Corporation (ICC)	9
INO	2
Pasco/CGH/ERES	1
Pathway Services	9
Roadware Group, Inc.	19
Agency Manufactured	1

Table 9 lists the systems in use, by manufacturer, as given by the responses from the various agencies. In that table, there is no differentiation of agency-owned and hired equipment. There is also no claim that the listing is complete, because some agencies were hesitant to mention equipment manufacturers' names for various reasons. Furthermore, the table does not reflect that many agencies where the equipment is owned will own a number of the same devices. One agency reported owning eight profilers by one supplier. In addition, several agencies own equipment furnished by more than one of the suppliers listed. Therefore, Table 9 does not reflect the number of pieces of equipment in use, but rather the number of agencies to which a given supplier has either sold equipment or has provided recent hired services. Finally, Texas manufactures the equipment it uses. Retired equipment or older hired services are not reflected.

Each of the commercial equipment suppliers listed in Table 9 has a corresponding World Wide Web address listed in the website directory in this synthesis. In most cases, detailed descriptions of the equipment furnished are provided in the various websites.

SUMMARY

It is clear from the responses to the survey questionnaire and discussion in this chapter that the automated collection of pavement distress data is in a state of rapid evolution. This finding probably is most true in the area of cracking or surface distress collection, where the imaging technology may be changing faster than the users can adjust to those changes. This situation is highlighted by the change in just one decade from the use of 35-mm film to capture most images through the use of analog video technologies to the use now of high-speed, high-resolution digital cameras and line scanning instrumentation. Still, some agencies reported that they are struggling with achieving pavement images at highway speeds and with acceptable quality.

Roughness monitoring is a more mature science wherein the major changes over the past few years have been in the protocols applied and in the new technologies brought into use, primarily in the area of the sensors used. Currently, high-speed laser sensors have replaced practically all of the acoustic and infrared types for longitudinal profile measurement and the resulting IRI statistic.

Automated rut-depth measurement constitutes a science that is in an unsettled state, because there is so little consensus on the number of points to measure (how many sensors to use). Although an AASHTO provisional standard suggests a minimum of five sensors, many agencies still use three. However, one researcher is promoting at least 9, whereas some of the vendors have moved to 30 or more, and some are promoting thousands of data points collected by a scanning laser. Rut-depth measurement clearly is an area needing additional research to arrive at an optimum testing scheme and protocols.

Automated joint-faulting measurement is an area that has not received great emphasis by many agencies. This finding is demonstrated by the relatively few agencies actually collecting the data through automated means. Some of those that do use automated means professed to have little confidence in the data collected. If others collect the data at all, most are using manual methods such as simple straight edges or the Georgia faultmeter. Although the latter seems to have a good reputation among users, its greatest disadvantage is that it is still manual, extremely time consuming, and limited to project-level work. Again, there is a need for further investigation of automated methods of joint-faulting measurements.

Equipment manufacturers and vendors are continually upgrading pavement condition data collection and processing equipment to incorporate the latest technologies. Much of this effort is inspired by a desire for more real-time data analysis as more agencies collect more data. Almost every vendor maintains a website with descriptions of the equipment availability and features.

CHAPTER THREE

DATA PROCESSING TECHNOLOGIES

This chapter addresses the various technologies employed to gather useful information from the data collected through automated means. Modern high-speed computers and data storage devices have led to quantum leaps in the ability to deal with some of these issues in just a few years. The result is that there are at least three general classes of methods used to reduce pavement condition data to useful information. Depending on the degree of human intervention required to achieve useful results they are purely manual, semi-automated, and fully automated methods. For the most part, the manual and semi-automated methods apply only to pavement cracking and patching (image-collected data). The analysis of ride quality, rutting, and joint-faulting data collected with sensors has been largely automated. Only semi-automated and automated methods are discussed in this synthesis.

PAVEMENT IMAGES

Figure 11 is a generic schematic of the automated and semi-automated pavement cracking analysis now used in approximately 20% of highway agencies. Activities on side A of Figure 11 are performed in the data collection vehicle as the combination of cameras, lights, and DMI produce referenced images of the roadway. The images are then stored on an electronic medium for either processing in the vehicle or delivery for off-line processing.

Activities on side B of Figure 11 may take place in the data collection vehicle, sometimes as real-time processing, or be delivered to either agency or vendor personnel doing off-line (out of the vehicle) processing. In the case of real-time processing, one of the fully automatic procedures described later in this chapter will be used. For off-line processing any of the semi-automated or fully automated procedures described will be used. Although the schematic would apply to manual processing as well, those methods are not discussed in the synthesis.

Questionnaire responses indicated that of 30 agencies using automated crack data collection, 20 used manual processing, 10 automated or semi-automated processing, and 1 some manual and some automated. Processing is done predominately by vendors. Only Connecticut, Maine, and Maryland use agency resources to both collect and process cracking data through automated means. All three use the WiseCrax technology described later in this chapter. Table 10 summarizes the reported processing methods in use by the various agencies.

A typical workstation used in pavement distress data reduction is depicted in Figure 12. In that figure, the left-most monitor displays a summary of distress data collected from images displayed in the center monitor, while the right-most monitor gives a perspective or forward view of the pavement under review. This view provides the rater with a better means of identifying some distresses (such as skin patching) that often are not discernible in the downward view. (Note that a special keyboard has keys dedicated to types and severities of the various distresses to be evaluated, depending on user or client needs.)

Semi-Automated Methods

Semi-automated methods of distress data reduction include those methods in which there is significant human intervention. In some cases, the process is primarily manual and involves a trained rater sitting at a workstation where pavement images are systematically reviewed and the various distresses identified and classified as to extent and severity. Such workstations are equipped with images players, integrated distress rating and location-reference software that can access image and database files, high-capacity storage devices, and one or more high-speed processors.

Image viewing requirements depend on whether filmed, taped, or digital images are captured. The manual element of distress data reduction from images typically involves the use of multiple image monitors and at least one computer monitor for data display. Multiple image monitors are required to provide a rater's perspective for location purposes and to assist in identifying certain types of distress that are not readily discernible in downward images. As with any means of imaging, there may be a substantial loss of resolution compared with what is visible to the human eye from the same source.

Where the images were captured through photologging or videotaping, the control of film or tape progression and tying images to specific mile points can be an onerous task. For that reason, almost all image collection procedures now require that the images be date, time, and location stamped. The location will often be coordinates derived from GPS instrumentation on the survey vehicle. This in turn means that agency roadway files (inventory) must also be tied to those coordinates.

The identification of various distress types, as well as their severities and extents from images requires observers or raters

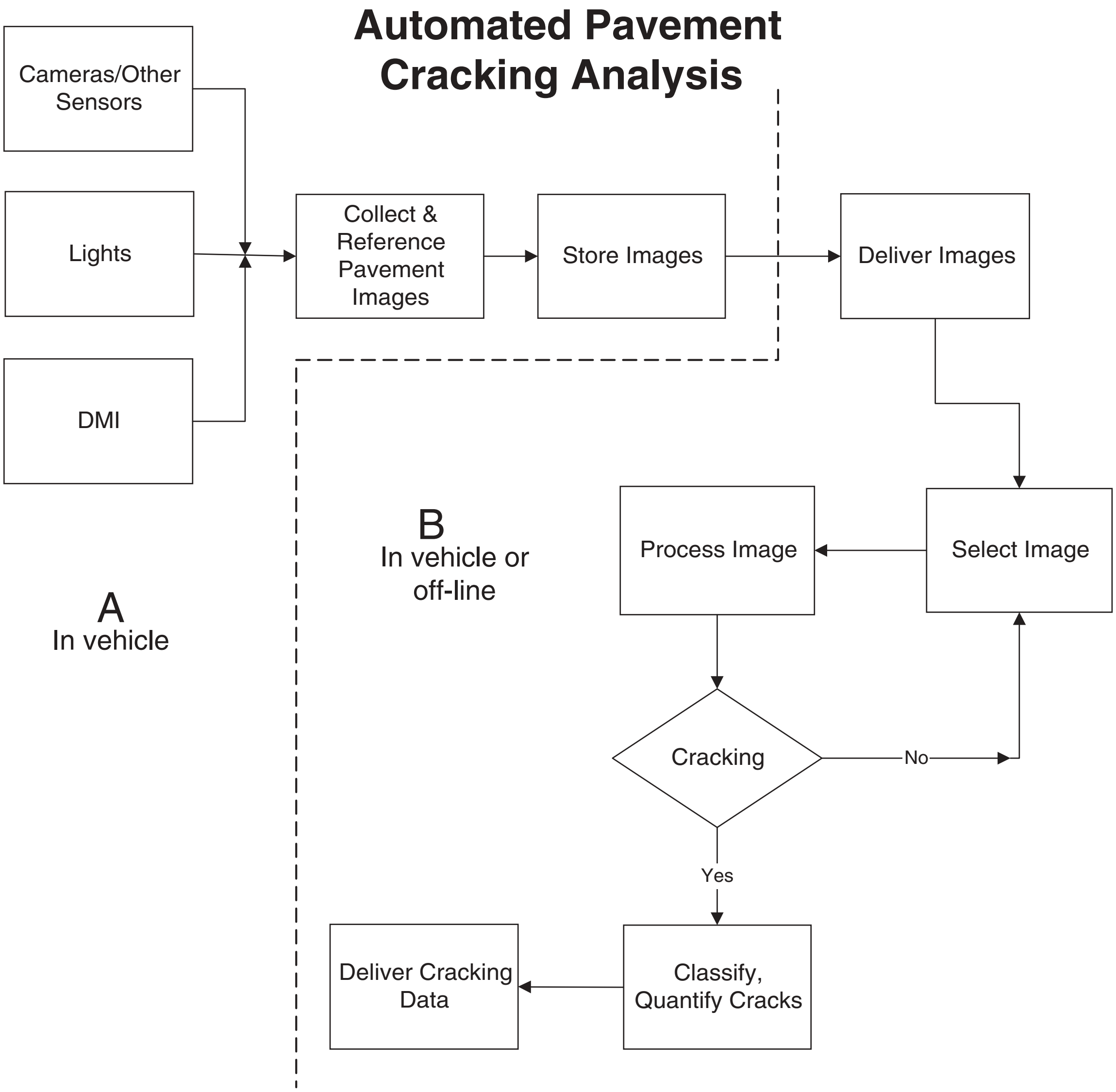


FIGURE 11 Automated pavement cracking analysis.

who have been well trained in both pavement distress evaluation and in the use of the workstation hardware and software. Such raters are not readily available in most agencies or in most job markets, such that almost all require extensive training in at least some aspects of the process. Also, the rating process is extremely demanding, for raters must be able to coordinate the simultaneous use of several monitors while keeping track of the observed distresses and entering those observations into rating software.

TABLE 10
IMAGE PROCESSING METHODS IN USE

Agency Type	Manual	Semi-Automated	Fully Automated
State	16	1	7
Province	3	1	0
FHWA	1	—	1
Total	20	2	8

FIGURE 12 Typical digital work station (*Courtesy:* ARA-ERES, Inc.).

Early efforts at reduction of distress data from images have been learning experiences for some agencies. The Virginia DOT (VDOT) found that distresses identifiable on the roadway do not necessarily correspond to those discernable from images. Cracking visible from walking or even low-speed windshield surveys may not be visible from images. Also, certain types of patching that blends well into the surrounding pavement may not be detected from images. These findings led VDOT to develop a pavement distress rating manual specific to videotaped images (*46*). The essential difference between the videotape rating manual and that for field surveys is that fewer distress severities are defined, whereas some field-observed distresses (e.g., bleeding) simply do not occur in the videotape version. The VDOT work was performed using two systems: one a videotape system provided by Pavetech, the other provided by Transportation Management Technologies that used digital area and line scan images.

The draft TRB circular (*20*) summarizes several systems that were used earlier, but not reported to be in use by agencies responding to the synthesis survey. One of these systems was built in the late 1980s by the Japanese consortium Komatsu. The system consisted of a survey vehicle and an onboard data processing unit to simultaneously measure cracking, rutting, and longitudinal profile. Maximum resolution of 2,048 by 2,048 pixels was obtained at a speed of 10 km/h (6 mph). The Komatsu system worked only at night to control lighting conditions and represented the most sophisticated hardware technologies at that time. However, it did not provide output for the types of cracking.

From late 1980s to early 1990s, the Earth Technology Corporation created a research unit called Pavement Condition Evaluation Services. The automated system created by that unit was the first to use line scan cameras at a 512-pixel resolution to collect pavement data. The necessary technologies associated with the image capturing and processing were not mature enough at that time (*20*).

For a time, the Swedish PAVUE pavement data acquisition equipment was promoted in North America. The system includes four video cameras, a proprietary lighting system, and four S-VHS videocassette recorders. The image collection subsystem is integrated into a Laser RST van. The offline workstation is based on a set of custom-designed processor boards in a cabinet, to analyze continuous pavement data from the recorded video images. Surface images are stored on S-VHS tapes in analog format. This system is no longer actively used in North America (*20*).

The TRB draft circular further reported that in 1995 the FHWA awarded two continuing contracts to LORAL Defense Systems in Arizona, now a unit of Lockheed–Martin, to provide an Automated Distress Analysis for Pavement, known as ADAPT. The data source is digitized images from PASCO's 35-mm film. The delivered system, after completion of the projects, could not be used.

Several vendors currently market systems for the reduction of cracking data from images. These systems are generally configured as described earlier, and there are special features for determining distress severity and extent. Key differences between systems depend heavily on differences in software, almost all of which is proprietary. The degree of human intervention varies somewhat from system to system.

The Pavement Distress Analysis System (PADIAS) used by CGH Engineering and applied to the LTPP program projects a high-resolution image onto a digitizing tablet where it is viewed by an operator (*22*). In using PADIAS, the operator uses a mouse and pop-up menus to select distress type and severity level for any distress viewed on the screen. The PADIAS data files are convertible into ASCII format for uploading into an agency's existing database. Although the distresses built into the system are those used in the LTPP program, they are capable of modification to meet other user needs.

A second system is provided by Pathway Services and is known as the Pathview I: Video and Sensor Playback System (*47*). The system will support up to six videotape players and monitors. Examples of digital images of each distress and their severity levels are available for review to maintain consistency between raters and for QC purposes. The software provides data entry fields used to input the pavement distress features to be evaluated. The system also reads the number of the image being evaluated, as well as location-reference information, and it displays those data on the computer monitor. As the analysis is completed, a database with the distress features is created.

A semi-automated system requiring somewhat less human intervention is the D-Rate Digital Distress Rating System (*32*). This system operates on digital images such that the "operator can locate, classify, and determine severity and extent of distresses by using a mouse to draw boxes around distress areas and selecting distress type from a menu." Then, the computer calculates lateral and longitudinal coordinates of the distresses as well as length and area of distress, and it automatically enters these into a database. The program also incorporates other computer-aided features, one of which is the definition of wheel-path areas with respect to the distresses. This feature aids in the definition of load-related distresses such as fatigue cracking.

Another system requiring less intervention is the Roadview GDPlot (*26*). The system uses a 3-D digital imaging process. The system generates 3-D images of the pavement surface by combining the plots of successive laser scans. The vendor asserts that 3-mm (0.125-in.) cracks are clearly visible in 4.2-m (14-ft)-wide images providing continuous full-lane coverage of the pavement. The system is not considered to be fully automated, because through early 2003 the vendor did not address features allowing distress summaries to be developed and reported. No independent evaluation of this system has been reported.

A final semi-automatic system is described by Miller et al. (*48*), as applied to transverse cracking by the Kansas DOT. The system uses ICC Digital Imaging and Distress Measurement Analysis Software. The researchers reported that a 2,048-pixel digital line scan camera, a computerized controller, and an illumination system allowed cracks as fine as 1 mm (0.04 in.) wide to be recorded at speeds up to 96 km/h (60 mph). Comparisons of pixel grayscale ratings to predetermined threshold values permitted a pixel to be considered a crack pixel when its gray value was less than the threshold gray value. Manual intervention was used to determine crack severity and extent from the Kansas DOT's algorithms.

A comparison of distress data from roadway observations with that derived through semi-automated systems and from images is given in chapter six.

Fully Automated Methods

In the context of this synthesis, the definition of fully automated is that distresses are identified and quantified through processes that require either no or very minimal human involvement. Typically, fully automated in the context of pavement cracking analysis involves the use of digital recognition software capable of recognizing and quantifying variations in grayscale that relate to striations (or cracks) on a pavement surface.

It is in these fully automated methods of distress data reduction from images that the greatest amount of research and development work seems to have occurred over the past decade. That emphasis is no doubt the result of the difficulties involved in manual reduction of these data as described earlier and related to resources required to accomplish the manual tasks encountered.

WiseCrax

From the survey, the most widely reported of the automated methods is that known as WiseCrax (*32*). Of 30 agencies indicating automated surface distress data collection, 8 reported that they own or contract for the use of processing equipment provided by the WiseCrax vendor. The vendor describes the system in this way:

> WiseCrax processes the pavement image video tapes from the ARAN. It will automatically detect cracks (length, width, area, orientation); classify them according to type, severity, and extent; and generate summary statistics and crack maps.

In the early WiseCrax system, pavement surface images were collected with two continuous video cameras, covering the survey lane of approximately 4 m (13 ft). The video images were recorded into S-VHS format. Each camera is approximately 2.4 m (8 ft) above the pavement surface and covers a 2-m (6.5-ft) wide area. Captured images have the resolution of 640 by 480 pixels after digitization to grayscale images. Since 2000, the vendor has captured digital images directly, making the analog to digital step no longer necessary. The other parameters are similar for the new system (*32*). A typical digital pavement image is given in Figure 13.

For crack detection, an initial setup is required where the workstation operator selects images used to determine an optimum set of detection parameters accounting for pixel-by-pixel grayscale variation as related to crack contrast, brightness, and surface conditions. During this setup phase, the program provides visual feedback of the detection results in the form of crack maps traced over the underlying images of control pavements. These crack maps in turn provide instant feedback on the efficiencies of the parameters. Through an iterative process, the optimal detection parameters are selected for each control pavement. Once the settings are selected, WiseCrax is programmed to automatically process the pavement images to detect cracks. The beginning and end of each crack are location referenced using an *x–y* coordinate system. For each crack, the length, width, and orientation are also computed and saved. An example is a digital crack map as shown in Figure 14 from the digital image given in Figure 13.

Wang and Elliott (*15*) describe the WiseCrax crack classification process as the following:

> Since the definitions of distress categories vary from agency to agency, WiseCrax compares the location, length, and width of cracks against (agency) criteria for various crack distress categories. For instance, if cracks in a block pattern are more than 300 mm (12 in.) apart it may be classified as block cracking. If they are closer together, it may be classified as fatigue cracking. WiseCrax has the flexibility to process data as new classification definitions are developed.
>
> WiseCrax operates in two modes: automated and interactive. In automated mode, all processing is done without human intervention, once the initialization parameters on pavement type, camera and light settings, etc., are set. Interactive mode allows the user to review, validate, and edit the WiseCrax results. For instance, the automated mode can be run first; the display shows the pavement image with overlaid color lines indicating the presence of cracks. The user can then point-and-click to add, delete, or modify the results. For quality control purposes, the inter-

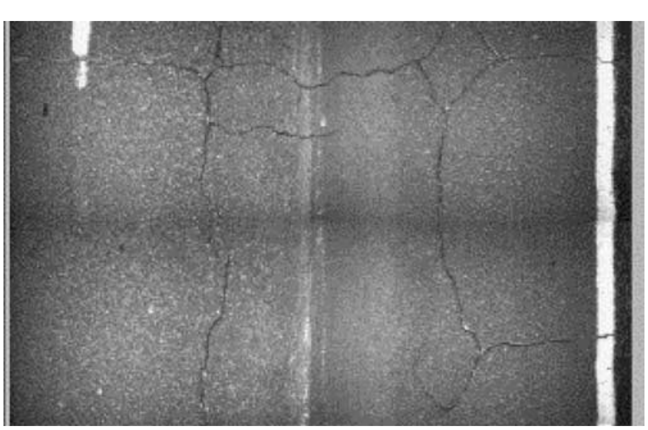


FIGURE 13 Typical digital pavement image (*32*).

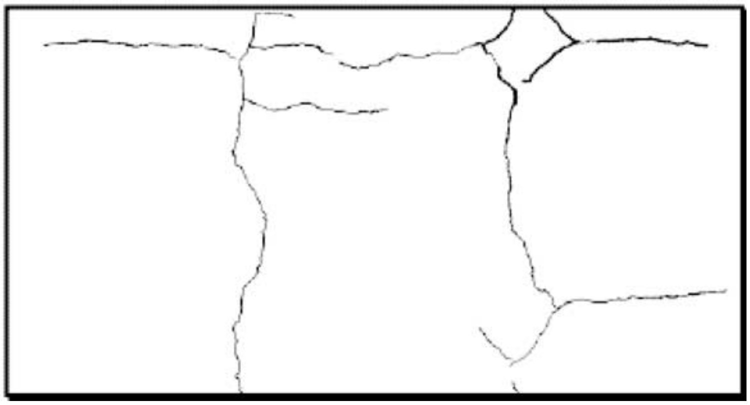


FIGURE 14 Example crack map (*32*).

> active mode is normally used to perform statistical validation of automated results using random samples of data.

The vendor, Roadware Group, Inc., has noted several limitations of the WiseCrax technology. First, all digital image analysis is limited by the quality and resolution of the images. Then, the minimum crack width that can be automatically detected by WiseCrax is approximately 3 mm (0.125 in.) or approximately 1 pixel wide. The vendor goes on to note that finer cracks may be detected manually from the same images, because the human eye can perceive finer crack lines than the image can clearly display. For this reason, cracks with nonuniform widths may be identified as several shorter cracks. Finally, certain types of pavement surface, chip seals, for example, provide poor crack visibility, as does crack sealing material. Such features typically need to be evaluated in the interactive mode, because the automated process is unable to discriminate those features without human intervention.

Accuracy of the WiseCrax system is determined by sampling sections of roads and manually reviewing the output of the automatic processing program. WiseCrax output is compared with trained observers' reviews of sampled videos. A percent accuracy is calculated from the ratio of the cracks found by WiseCrax to those found by the trained observers.

In 1999, Wang and Elliott (*15*) conducted an evaluation of the WiseCrax system for the Arkansas Highway and Transportation Department. The objectives of that study were to evaluate both the vendor's data collection system and WiseCrax, and to make appropriate recommendations to the agency about the capabilities and performance of WiseCrax. In that study, the comparison of data between the results from WiseCrax and the results from manual surveys demonstrated that there are still large differences between them. The authors continued that the automated system had no difficulty in finding cracks. The problem was the classification and quantification of the cracks. They further noted "the problem was not vendor specific and has been a research topic for years."

In a later study, Groeger et al. (*49*) reviewed the implementation of the WiseCrax system in Maryland (see case study in chapter eight). Their conclusion was that "automated network level crack detection is a viable and efficient tool. However, a strict QC/QA regime must be instituted in order to achieve consistent and repeatable results."

Digital Highway Data Vehicle

In 2001, Wang et al. (*50*) reported on the University of Arkansas Digital Highway Data Vehicle. (The vehicle was also developed by the principal author.) The study was of distress data digitally captured and reduced in real time on a 4.5-km (2.8-mi) section of highway divided into 0.16-km (0.1-mi) subsections. The authors described the system as follows:

- The vehicle is based on a full-digital design. It does not use any type of analog medium for data storage. The operating software environment is based on 32-bit technology.
- The vehicle includes a subsystem for pavement surface image collection. This subsystem has one frame-based digital camera and four strobe lights for illumination.
- The vehicle has an automated survey subsystem that can be integrated into the data acquisition subsystem to identify and classify pavement cracks at real time.
- The vehicle acquires the exact location of itself through the use of a GPS device and a DMI, and it saves the data to the computer's database.
- The software system used in the on-board computers of the vehicle employs a real-time relational database engine, intercomputer communication techniques, multicomputer and multi-CPU (control processing unit)-based parallel computing, and generates multimedia databases.

In regard to that study, it is important to note that driving speeds were 32 to 64 km/h (20 to 40 mph) and that imaging was done at night with a van equipped to illuminate the roadway to ensure the best quality images. Distresses were classified in accordance with three different protocols: the AASHTO provisional standard (*17*), the World Bank Universal Cracking Index (*51*), and the Texas DOT method (*52*).

The emphasis was on real-time processing of the digital images to detect, classify, and quantify surface distresses. The 28 pavement subsections were each evaluated once with all three protocols. In addition, for the Universal Cracking Index protocol, a total of four runs were conducted to secure a measure of process repeatability.

The results showed similar distributions of cracking extent for all three protocols. All three methods were deemed to clearly show the same problem spots on the pavement section and the same associated severity levels. Multiple runs on the same section yielded a coefficient of variation of approximately 15%, suggesting reasonable repeatability. The authors concluded that the "solution to the problem of automating distress survey is finally at hand" (*50*). They conceded that the system is not perfect and that there is more work to be done. The authors further commented that "newer versions of the crack analyzer have already demonstrated better accuracy." Results of their applications will be published at a later time (*50*). In 2003, Wang reported, "With an acquisition system with twice the resolution and further improvement of imaging algorithms, such as more accurately determining lane markings on both sides, it is anticipated that in the next few years widespread use of fully automated crack survey systems will be a reality" (*53*). Finally, it was recently reported (K. Wang, personal communication, August 2003) that an imaging system at a 4,096-pixel resolution could detect coarse surfaces. Automation for that type of survey is not "there yet," but it can be done.

GIE GIECRK

GIE Technologies applies an "automated" surface distress analysis package in at least two agencies (Manitoba and Rhode Island). Information on this technology is limited, with no published user evaluations yet discovered. The GIE website description states only that "the data is digitised, synchronized, and correlated so as to allow an automatic analysis and diagnosis free from subjective interpretation and human error" (*54*).

IMS-Terracon uses a laser road surface tester designed and developed by the company's own engineers. The unit uses a video technology to capture and analyze pavement surface condition information in real time (*55*). The company's PAVUE technology uses advanced camera technology and high-speed image processing to automatically collect and assess pavement distress data. The company website relates the following:

> Four downward looking cameras, in conjunction with a strobe lighting system that provides consistent illumination, collects continuous, high clarity pavement images that are analyzed using a patented process to determine and assess the pavement surface distresses (*55*).

The company keeps its procedures somewhat confidential and there is no known independent published evaluation. Although a news release addressed work in New Mexico by IMS-Terracon using a 3-D technology (*56*), the pavement distress aspects of that work have not been reviewed by the agency's DOT personnel. The state pavement management engineer (R. Young, New Mexico State Highway and Transportation Department, personal communication, August 2003) indicated that the vendor was collecting different distresses from those used in the state's pavement management program and that there are no current plans to use the vendor's data.

SENSOR-MEASURED DATA

For automated data collection equipment, the processing of sensor-measured data is almost all real time and done in accordance with the collection protocols employed. Processing basically involves the analysis of longitudinal and transverse profiles and the extraction of key information from those analyses. The principal products are the IRI, rut-depth measurements, and joint-faulting measurements. Because each of these products is described fully in the data collection and QA chapters (chapters two and six), they are not addressed further here.

SUMMARY

Although the automated collection and processing of pavement distress data have progressed greatly in the last decade, there still are barriers to overcome before the technologies involved can come to fruition as real-time, reliable, and generally applicable tools. First is the need for development of systems capable of consistently producing high-quality digital images under most data collection conditions (lighting, angle of the sun, shadowing, etc.). Although there is evidence that the technologies have progressed to the needed capability, they are not generally applied within the industry.

Once good images are consistently produced, greater progress can be made in the second major problem area: that of improving the quality of data automatically reduced from those images and the speed with which data can be acquired. Again, there is strong evidence that the necessary technologies exist, but they seem to need further maturing to address both quality and speed. There may be a need for a focused effort to bring about that maturity.

CHAPTER FOUR

DATA MANAGEMENT PROCEDURES

This chapter presents the various pavement condition data management procedures and hardware used by the vendors and agencies. Although one would like to address the details of computing platforms, types of storage devices, and various programs used to manage the myriads of data collected in a typical process, questionnaire results do not support such detailed discussion. It is clear that some data management issues are more logistical than hardware related (e.g., the linking of time and location on data files as they are generated in the field).

Efficient data management has become an ever-increasing concern as more and more data are collected with a single pass of data collection vehicles. Now that many of those vehicles can collect images (both pavement and other roadway), roughness, rut-depth, and joint-faulting data with one pass over a roadway, the tools for managing all the data at once also are changing. As would be expected, most users, both agency and vendor, begin by using data management systems incorporated into the data collection vehicle by the equipment manufacturer. However, the investment in a fully equipped vehicle is substantial; therefore, vehicles generally cannot be replaced each time a significant improvement in data management hardware or software takes place. The result is that for most systems an almost constant updating process takes place.

In view of the very costly collection and processing procedures encountered with pavement condition data, one universally addressed issue is that of data archiving. Virtually every vendor has a rigorous archiving process before data are delivered to the customer, and virtually every agency has a similar process once data are delivered either from a vendor or from agency data collectors. The result is that most data are archived at least twice. A widespread companion problem is what to do with all that data. Although some agencies reported on special efforts to solve the problem, the approach by most appears to be to acquire larger storage areas. The problem was especially severe when most images were videotaped. That part of the problem has been greatly alleviated by the transition to digital images. Certainly, the rapid advances in electronic data storage capabilities over the recent past, which are expected to continue, will do much to reduce the future bulk, if not the lines of data stored.

Because almost all of the data management software and handling procedures are proprietary, it is very difficult to characterize the industry as a whole. However, it is safe to say that the demands of the data collection process are so intensive that the latest and highest speed processors (now in the 2- to 4-GHz range) and the largest data storage devices (now upward to several terabytes) available will be featured on the newest equipment produced by the various vendors. On-board data management is often handled on computers classified as "industry hardened"; that is, they are designed for rough service such as that encountered in moving vehicles. There are certain data collection and processing activities with data management requirements that have much in common across the various vendors and among the various agencies, such that at least the general approaches can be outlined as discussed in the following paragraphs.

There is some need for the development of data standards for pavement distress data. Although numerous data formats and handling procedures are in use in the realm of pavement data collection, nothing has been standardized. This means that essentially every vendor can use different formats and procedures and that customers and others can be at a loss as to how a given data management system works. A primary reason for this is that individual vendors or agencies have developed nearly all systems; that is, there has been little centralized effort to build systems that work for all. Standards would offer another tool that agencies and others could use in the development of data procurement contracts. It would be much easier to specify that a data management system meet a certain standard than as is now done with spelling out specific formats, equipment, etc.

The general term applied to information about data is "metadata," or data about data. Simply put, metadata are the background information that describes the content, quality, condition, and other appropriate characteristics of the data. The National States Geographic Information Council has developed a metadata primer or "cookbook" approach to the creation of metadata (*57*). Although the primer specifically addresses GIS, the concepts are general and the primer offers the following description of the value and uses of metadata standards:

> Metadata serves many important purposes including data browsing, data transfer, and data documentation.
>
> Metadata can be organized into several levels ranging from a simple listing of basic information about available data to detailed documentation about an individual data set. At a fundamental level, metadata may support the creation of an inven-

> tory of the data holdings of a state or local government agency. Metadata [are] also important in the creation of a spatial data clearinghouse, where potential users can search to find the data they need for their intended application. At a more detailed level, metadata may be considered as insurance. Metadata insures that potential data users can make an informed decision about whether data are appropriate for the intended use. Metadata also insures that the data holdings of an agency are well documented and that agencies are not vulnerable to losing all the knowledge about their data when key employees retire or accept other jobs (*57*).

The issue of metadata standards for pavement condition data is in need of a critical evaluation and automated pavement data collection and processing efforts would benefit greatly from the application of these concepts.

The specifics of data management were requested in the project questionnaire. The responses to that question are given in Tables B1 through B4 for surface distress, ride quality, rutting, and joint faulting, respectively. The great variety of responses reflected in those tables makes it very difficult to identify any consensus procedures, such variety highlighting the need for standardization of data management systems.

IMAGE-RELATED DATA MANAGEMENT

Image data management depends greatly on the means of image capture. Where the principal media are videotapes, those tapes typically are delivered to the user after archiving by the data collector (contractor or agency). Images are typically stamped with the date and time, as well as the selected means of location reference. Alternatively, a companion data file is stamped with tape linkages so that time, date, and location-reference information can be integrated. Those companion files typically are temporarily stored on the hard drive of a computer in the data collection van for later archiving and removal to the user's media (usually tape or removable hard drives). Depending on the specific data processing arrangement, there may or may not be an intermediate distress identification and classification step (sometimes with an index calculation) before delivery to the user. As described in chapter three, some processes require digitalization of the video images for distress data reduction purposes. The final step usually involves the copying or installing of the transported media or processed results to a workstation or computer for the users' purposes. In the few cases in which users are still using film, images are handled in much the same way as for those results that are videotaped.

Digital images are managed somewhat differently. They are typically temporarily stored on a hard drive in the data collection van for later archiving and removal to the user's media. Again, image files typically will be integrated with files containing date and time stamps, as well as location-reference information. Files are substantial, requiring large data storage devices—typically hard drives for the day's work—and then downloading to portable hard drives for transfer to either a processing workstation or directly to the end user. Some agencies also receive the data on CDs, DVDs, and high-capacity zip discs. As with videotapes, there may be an intermediate distress identification and classification step before the files are delivered to the user.

Although most vendors provide little detail on data management, the ICC describes its image workstation software on the company website (*25*). The software was designed to manage digital image data to expedite the distress rating process and to maintain rating data. Images from multiple cameras can be synchronized. Then, users can categorize, measure, rate, and save the distress information. That information can be printed and exported in several formats. The use of Microsoft SQL 7.0 technology makes the application network compatible while it also interfaces with Adobe Photoshop 6.0 for special image processing. Other details of the application of the ICC and other software were described in chapter three. Metadata standards would be helpful in the management of image data. The digital imaging tutorial (*24*) makes the case for metadata standards in that area.

The TRB draft circular (*20*) offers some comments on the management of pavement distress data, especially in the area of image compression. Without compression, the storage need for 1 km (0.6 mi) of pavement imaging at 4 m (13 ft) wide is approximately one GB at 2,048 pixels per lane or four GB for 4,096 pixels. Therefore, compression is widely used for image archiving and data management. The predominant compression method in use is that of JPEG, an imaging industry standard-setting body. Normally, there is some loss of information during compression, such that an original raw image will not be fully restored from the compressed image.

However, a new compression standard labeled JPEG 2000 has been designed to overcome some of the loss, because a much greater degree of compression will result in a restored image quality similar to that for traditional JPEG. Two examples are given in the TRB draft circular. The first example (Figure 15) is a restored JPEG image compressed 6:1. The

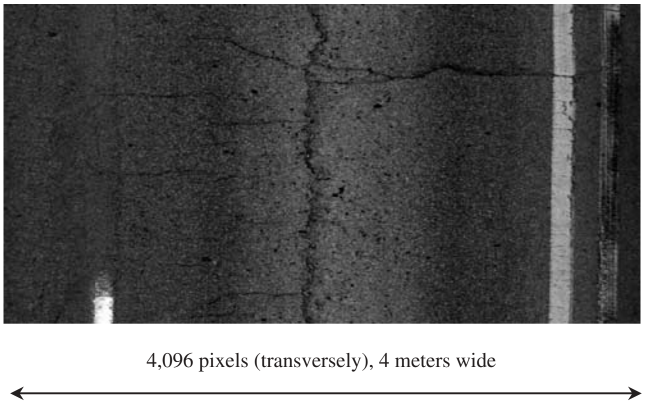


FIGURE 15 A 4,096-pixel resolution image in JPEG format (line scan digital camera) (*20*).

image size is approximately 1.4 MB. The second example (Figure 16) is of the same pavement surface as in Figure 15, but compressed with JPEG 2000. The size of the image in Figure 16 is approximately 400 KB, with a compression ratio of approximately 20:1. The image quality and definition of both figures are comparable. However, it must be recognized that encoding and decoding JPEG 2000 images will take more computing power.

SENSOR-RELATED DATA MANAGEMENT

As with digital image files, those for sensor-related data are large. Data collection vehicles fire lasers or other sensors at high speeds, collecting myriads of data every few millimeters along and across the roadway. Several sensors will be devoted to the longitudinal profile, whereas as many as 37 may be devoted to transverse profile measurement, with several gigabytes of data captured in just a few kilometers of roadway. Again, fast processors, sometimes working in tandem, and large data storage devices are required just to capture and process profile data.

Sensor data also must be integrated with date, time, and location-reference information before they are useful to the user. All of this calls for special software, an example of which is provided by ICC in its Windows-based profiling software (*25*). This program allows the user to collect, store, process, and graph profile data from a single Windows application. The program manages data files while building, saving, and using real-time viewing applications and reports. In addition, it has built-in diagnostics for checking and calibrating the profiler's sensors. All of the information is available in real time for printout or exporting to ASCII text, Excel, and other files. Although other vendors are less specific in the descriptions of their software, requirements of the various systems dictate similar applications. Metadata standards, as mentioned, would be of great benefit in the management of the data.

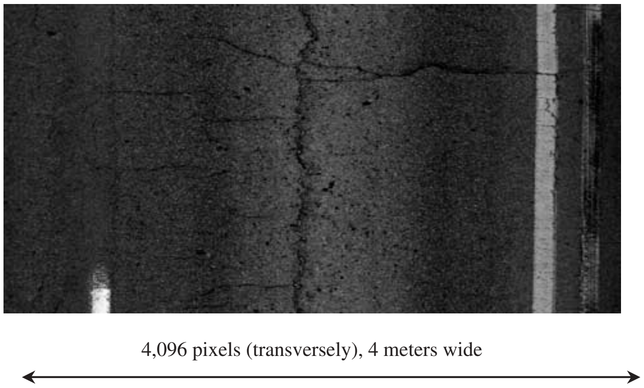


FIGURE 16 A 4,096-pixel resolution image in JPEG 2000 format (line scan digital camera) (*20*).

SUMMARY

The storage and management of pavement condition data and images are common problems for both vendors and users of the data. Although the great volumes of data produced have overtaxed storage capabilities in the past, the data storage industry appears to be solving many problems with the introduction of ever-greater storage capacity devices. Other data management problems are being alleviated with the periodic introduction of increasingly faster processors, a trend that appears to have no end in sight. There may be a data storage problem at some agencies with regard to how to handle the large volumes of historical data, especially if earlier videotape systems were extensively employed. There appears to be a critical need for the development of metadata standards for automated pavement data collection and processing systems.

CHAPTER FIVE

CONTRACTING ISSUES

TYPICAL CONTRACTING ISSUES

Various contracting procedures are used to procure pavement condition data. Some procurement comes through advertised contracts, requests for proposals (RFPs), and requests for qualifications (RFQs), which might lead to negotiated contracts. In addition, warranties are used by a few agencies. The various approaches, as well as some of the pricing information developed, are evaluated and summarized in this chapter.

In regard to the synthesis questionnaire, 30 agencies provided at least some responses relating to contractual issues, and 9 agencies provided copies of typical contract documents. Some of those documents are contracts, whereas some are RFPs and others are requests for expressions of interest, etc. A list of agencies submitting contract documents is given in Table 11 (questionnaire responses on contracts are summarized in Table B6 in Appendix B). The most popular basis for a contract award was an RFP, which was used by 18 agencies. Seven agencies use an RFQ approach and eight use advertised contracts and a low-bidder approach [some of the Canadian provinces use a Terms of Reference (TOR), similar to an RFP]. Several agencies make use of more than one approach. On the other hand, the California DOT (Caltrans) reports in its questionnaire response (see Table B8), "Caltrans has seen a higher quality product for IRI collection by doing the work ourselves."

Typical contract items range from imaging to distress identification and quantification, roughness, rut depths, and joint faulting. In some cases, where image collection and distress reduction from those images are contracted, collection and processing are two separate items. In other cases, the two are combined. By far the most popular approach, cited by 17 agencies, is to contract for sensor-measured data items (IRI, rut depth, and joint fault), whereas surface distress data are collected either under a separate contract or in-house by agency personnel, usually manually.

Some contracts contain separate data management items, usually for hardware and software, and for maintenance of those items. Such items typically appear when the agency does separate QA work in the form of an acceptance process applied to the vendor's deliverables. In such cases, the agency may contract for workstations for internal review and use of the deliverables.

The most popular items appearing in data collection contracts are summarized in Table 12. Although some of the tabulated items appear in other tables, they are repeated here as contract items for reader convenience. Not reflected in Table 12 is that some agencies rely on a combination of agency and vendor collection, usually depending on the highway system under evaluation. Several agencies contract for only sensor-measured data. In comparison, Quebec contracts only for distress data reduction from images collected by the agency.

Although used in collecting pavement-related data, the most popular peripheral item collected by contract is right-of-way images, contracted for by 14 agencies. In addition, a few agencies contract for signage or drainage structure inventories, or for shoulder images.

A typical contract period is 2 years, although some agencies use a 1-year period and one state has awarded a 4-year contract. Several agencies provide for up to 5 years of negotiated extensions of shorter-term original contracts.

Six agencies have warranty provisions in their contracts, whereas only one requires a performance bond to be posted. A total of 22 agencies have QA provisions, and 12 have price adjustment clauses. QA provisions are discussed in chapter six. Typical price adjustment clauses relate to delivery dates and accrue in the form of penalties for late delivery. No agency mentions paying a bonus for early delivery.

AGENCY EXAMPLES

Nine agencies provided documents relating to contracted data collection, although it is not possible to address everything in detail in this synthesis. However, several agencies have been judged as fairly typical, but with at least some unusual features. These experiences are summarized here.

Louisiana Department of Transportation and Development

In 2001, the Louisiana Department of Transportation and Development (LADOTD) awarded a contract to the Roadware Group, Inc., for 32,000 lane-km (20,000 lane-mi) of comprehensive data collection, including GPS, digital right-

TABLE 11
AGENCIES SUBMITTING PAVEMENT DATA COLLECTION CONTRACT DOCUMENTS

Agency	Type of Document	Contract Items
Alberta Ministry of Transportation	Terms of reference	IRI, rutting
British Columbia Ministry of Transportation	Request for proposal	Cracking, IRI, rutting
Louisiana Department of Transportation and Development	Contract	Cracking, IRI, rutting, joint faulting
Manitoba Department of Transportation and Government Services	Contract	Cracking, IRI, rutting, joint faulting
Mississippi Department of Transportation	Contract	Cracking, IRI, rutting, joint faulting
Oklahoma Department of Transportation	Contract	Cracking, IRI, rutting, joint faulting
Ontario Ministry of Transportation	Request for quotations	IRI
Quebec Ministry of Transport	Terms of reference	Cracking data reduction only
Vermont Agency of Transportation	Contract	Cracking, IRI, rutting, forward video

Notes: IRI = International Roughness Index.

of-way and pavement images, IRI, faulting and rutting measurements, and pavement distress evaluation (*58*). Required peripheral data included signage and signal inventories. Contract provisions addressed the vehicle and test equipment configuration and delivery and payment schedules, as well as QA procedures and acceptance criteria. A workstation for review of images and validation of distress data was to be provided at an LADOTD office. The contract called for the completion of four major tasks:

- Preliminary activities, including training of raters and workstation delivery;
- Collection of clear digital pavement images and profile data for each district;
- Distress quantification for all roads tested; and
- Final documentation of the project.

Completed pavement condition data were to be delivered on a district-by-district basis with the provision that data for no less than one district or more than two districts were to be delivered per month. The contract did not address the reason for this stipulation, but it is presumed to relate to the time required for LADOTD evaluation of deliverables. Liquidated damages of $100 per day were to be assessed for each day the data for the required number of districts were not delivered on time and $500 per day for each day the data for all nine districts were not delivered on time. Finally, damages of $300 per day were to be assessed for each day that the final report was not on time.

TABLE 12
POPULAR CONTRACT ITEMS (Number of Agencies)

Agency Type	Pavement Images	Distress from Images	IRI	Rut Depth	Right-of-Way Images
State	16	15	18	17	11
Province	2	3	3	2	2
FHWA	2	2	2	2	1
Total	20	20	23	21	14

Notes: IRI = International Roughness Index.

The Louisiana contract is ongoing, and no assessment of its success or failure has been released. The LADOTD estimated the cost of delivered data at approximately $34 per km ($54 per mi) and did not note, in the questionnaire response, any special problems with the contract.

The LADOTD, with its experiences with this contract and related issues, has been chosen as one of the case studies for this synthesis, and the contract will be discussed in greater detail in chapter eight.

Ontario Ministry of Transportation

Ontario released a TOR (or RFQ) for contracted pavement roughness measurements in April 2001 (*59*). The project was to cover the years 2001 and 2002 and apply to the determination of IRI values on some 18 000 km (11,000 mi) of pavement.

Before bidding, prospective vendors were required to conduct precontract qualification tests on a 12-site calibration circuit. These tests were to be conducted with the exact same ASTM Class II profiling equipment as proposed for production testing, with each calibration site to be tested at least three times. The vendor calibration tests were required to meet two criteria. First, the IRI values determined must have the same rank ordering as Ministry tests on the same sites. Second, the statistical coefficient of determination (R^2) between the vendors' IRI values and those determined by the Ministry was expected to exceed 0.85.

Once the contract was awarded, the vendor was required to again conduct the aforementioned calibration tests and to meet the same criteria. Similar calibrations are required midway through each testing year, at the end of each testing year, and at the end of the 2-year contract period. The agency offers this explanation:

> The final calibration is required to ensure year-to-year consistency of the survey data. If the Vendor will choose to bid for the similar survey work in the Year 2003, and if the Vendor will propose to use the same IRI-measuring device or devices as those which the Vendor used for the 2001 and 2002 survey, the final calibration may be accepted by the Ministry as both the final calibration for 2002 work and the pre-contract qualification calibration for 2003 work (*59*).

In addition to calibration testing, the vendor is required to submit and adhere to a Quality Control Plan using 30 monitoring sites throughout testing. That plan is described in chapter six.

Delivery dates by district are spelled out in the RFQ, as are substantial penalties for failure to meet delivery dates. The penalty varies by deliverable; that is, it is lower for deliverables due early in the contract than for those due toward the end of the contract. Also, being 1 day late is penalized for the same amount as 1 month (5% to 10% of the project price for the year, depending on the deliverable) and increasing by either 5% or 10% for each month or part thereof, depending on the deliverable. The agency provided no cost per kilometer or mile information in its response to the questionnaire.

Again, there is no real indication of how matters have transpired with the contract resulting from this RFQ; however, the Ministry indicated that penalties for failure to meet specified deadlines for deliverables have been invoked.

Quebec Ministry of Transport

The Quebec Ministry of Transport awarded a contract to Pathways Services, Inc., solely for the collection and analysis of surface distress (cracking) on 13 000 km (8,100 mi) of roadway in April 2002 (*60*). An unusual feature of that contract is in the preliminary work. On signing the contract, a first lot of approximately 500 km (300 mi) of roadway was sent to the contractor for analysis. That analysis must be completed and the result submitted to the Ministry within 1 month and must be approved before the contractor can proceed with the remainder of the roadways in the contract.

The Ministry also has a minimum production rate requirement of 300 km (190 mi) of roadway per week, with a penalty equivalent to 5% of the contract unit rate applied for every 2 weeks of delay for each kilometer not submitted. For QA, the Ministry selects from 2% to 5% of kilometers rated for analysis and applies a penalty depending on the percentage of the production accepted. This QA feature is discussed further in the next chapter. The Ministry reported that most contractual problems can be solved with human intervention and application of the fairly elaborate QC plan.

Vermont Agency of Transportation

In June 2000, the Vermont Agency of Transportation (VAOT) entered into a contract with Roadware Group, Inc., to collect pavement condition data for 4 years (*61*). Some 3800 lane-km (2,400 lane-mi) of state and urban highways were to be evaluated in the years 2000 and 2002, and some 1000 lane-km (640 lane-mi) of the Interstate were to be evaluated in the years 2001 and 2003. Pavement data to be collected included fatigue cracks, transverse cracks, block cracks, rutting, IRI, and texture (on the Interstate only). Protocols specified were ASTM E950 for IRI and VAOT for the other items, including a 5-sensor rut measurement. Contract prices amounted to roughly $34 per km ($55 per mi) for Interstate, $22 per km ($35 per mi) for state, and $106 per km ($170 per mi) for urban highways.

Roughness data are verified by checking five separate sites each year selected by VAOT. Each site is run three times, and the results are reported separately for evaluation by VAOT. No specifics of this evaluation are given.

The collection of cracking data is controlled through the use of five precollection sites used for the calibration of WiseCrax data reduction algorithms. In production, 3% to 5% of the network is randomly sampled by VAOT staff and compared with vendor-delivered data. The acceptance process is unique and summarized in Table 13. Note that the table provides for the reporting of invalid data or for retesting, depending on the amount of work considered and on the degree of invalidity encountered in the random sample evaluation. No definition of invalidity is given in contract documents.

Payment for each year of the contract is based on the number of lane-miles actually tested. Twenty-five percent is paid at the completion of field testing, 25% upon delivery of the data, and 50% upon acceptance of the data. The agency reserves 30 days for review and verification of the data.

SUMMARY

Clearly, there are numerous approaches to contract pavement data collection in use by the various highway agencies in

TABLE 13
VERMONT CRITERIA FOR REPORTING INVALID DATA OR RETESTING OF SECTIONS

Amount Tested	Data Quality	Action
One 0.1 mi Section	>50% Invalid	Report reason for invalid data
Ten or More Contiguous 0.1 mi Sections	>25% Invalid >75% Invalid	Report reason for invalid data Retest sections
Node to Node, >1 mi and <5 mi	>25% Invalid >75% Invalid	Report reason for invalid data Retest from node to node
Node to Node 5 mi	>25% Invalid >50% Invalid	Report reason for invalid data Retest from node to node

North America. Because there are a relatively small number of vendors, it logically follows that a more standardized approach could result in economic benefits. Although a "one type fits all" is not a practical or even desirable approach to contract development and execution, it is evident that there could be a great deal more standardization than currently occurs. The most obvious area in which standardization might reasonably occur is in the protocols applied. If vendors did not have to prepare for different protocols in going from agency to agency, they might easily pass on some economic gains to their customers. Effective protocols would address data collection methods as well as QA and acceptance plans.

Some of the major issues one would want to address in a pavement data collection contract are as follows:

- Pavement system definition, that is, what is to be evaluated;
- Data items to be delivered and the delivery format;
- Start-up pilot test requirements;
- Location-referencing requirements;
- Delivery time schedules;
- QA features including QC, calibration requirements, and acceptance criteria for each deliverable; and
- Payment schedules, including any liquidated damages and how they would be assessed.

CHAPTER SIX

QUALITY ASSURANCE

Relatively few agencies provided significant feedback on QC and QA procedures used for pavement data collection and processing. However, some Canadian provinces are heavily involved in QC and QA, especially with sensor-related data, because they have found that those issues must be addressed if high-quality data are to be received from either contract or in-house data collection. Very few states indicated having gone to the extent that Canada has of applying statistical concepts to QM. Therefore, much of this chapter relates to the Canadian experience.

The NQI developed a glossary of highway QA terms that focused primarily on highway construction materials and processes (*62*). Three definitions deemed appropriate to pavement condition data collection and processing have been adapted from that publication.

Quality management (QM)—QM is the umbrella term for the entire package of making sure that the quality of the product, process, etc., is what it should be.

Quality control—QC is defined as those actions taken by the pavement data collector, either contract or in-house, to ensure that the equipment and processes involved are in control, such that high-quality results can be obtained.

Quality assurance—QA is defined as those actions (reviews, tests, etc.) taken by the buyer or user of the data to ensure that the final product is in compliance with contract provisions or specifications. Note that this is a different definition than that used in the materials arena, where QA is defined as making sure that the quality of the product is what it should be. Thus, QM and QA are synonymous from a materials perspective.

These definitions are consistent with, but more specific than, standards issued by ASTM (*63*) and are philosophically consistent with concepts put forth by the International Organization for Standardization (*64*). These definitions will be used throughout the remaining portions of this synthesis such that, for example, QM will refer to the overall process of obtaining high-quality data for a given element. However, it will be evident in some of the discussions that not all participants in pavement data collection follow the same definitions and that the delineations between QA, QC, and acceptance are not always clear.

A key feature of data collected in-house and that collected through contract is the QM philosophy and procedures applied. QM has clearly become a major issue with pavement condition data, as more and more agencies are collecting significant amounts of the data and some have found that the quality is not as it should be. The approaches to QM being used by agencies and vendors are summarized and discussed in this chapter. Some agencies use the guidelines put forth in the AASHTO provisional standards as the basis for their procedures (*12*). An example for asphalt pavement cracking is reproduced here (guidelines for other data elements are similar) (*17*):

> *Quality Assurance Plan*—each agency shall develop an adequate quality assurance plan. Quality assurance includes survey personnel certification training, accuracy of equipment, daily quality control procedures, and periodic and ongoing control activities. The following guidelines are suggested for developing such a plan.
>
> *Qualification and Training*—agencies are individually responsible for training and qualifying their survey personnel and/or qualifying contractors for proficiency in pavement rating or in operating equipment that must be used as a part of quality assurance.
>
> *Equipment*—the basic output of any equipment used shall be checked or calibrated according to the equipment manufacturer's recommendations. The equipment must operate within the manufacturer's specifications. A regular maintenance and testing program must be established for the equipment in accordance with the manufacturer's recommendations.
>
> *Validation Sections*—sections shall be located with established cracking types and levels. These sections shall be surveyed on a monthly basis during data collection season. Comparison of these surveys can provide information about the accuracy of results and give insight into which raters/operators need additional training. Validation sections shall be rotated or replaced on a regular basis in order to assure that raters/operators are not repeating known numbers from prior surveys. As an alternate to this procedure, up to 5% of the data may be audited and compared as a basis for a quality check.
>
> *Additional Checks*—additional checks can be made by comparing the previous years' survey summaries with current surveys. At locations where large changes occur, the data shall be further evaluated for reasonableness and consistency of trends.

Those general statements from AASHTO define a QM framework, but they provide few specifics, because those are left to the individual agencies. One specific concept was provided by Larson et al. (*65*) in defining a vision statement for PMS data collection by Virginia: "To collect pavement condition data with sufficient detail and accuracy to model deterioration and perform multi-year planning with the PMS.

Data variability for each data element must be smaller than the year to year change in that element." Although apparently self-evident, the statement is important because it is easy to overlook the implications of not meeting the implied requirements for data quality. If there is too much inherent variability in the data as a result of equipment, human involvement, or process components, it is entirely possible that there will be too much "noise" to permit meaningful year-to-year comparisons. Depending on the level of noise and whether the data are intended for project- or network-level use, the data may be of limited value.

The elements of QM have been applied to pavement data collection and processing for only a relatively brief period. A major reason appears to be that contract data collection is relatively new to the pavement community. As long as agencies collected their own data, users tended to accept the data delivered as "gospel." Once vendors became active and began to deliver large quantities of data, it became evident that QM was an important issue. It is now recognized as important regardless of who collects the data. The LTPP program has recognized that data variability is a critical issue and has released two major reports addressing manual and image surface distress (*13*) and profile data (*10*). These reports are discussed in more detail in the following sections.

QM of pavement data collection and processing has reached a point similar to that experienced in the past by those working with the QM of highway materials and construction processes. That is, there is no clear delineation between what is the responsibility of the data collector (agency or vendor) and what is the responsibility of the buyer or user of the data collected. The control of data quality can be viewed as the responsibility of the collector, because that entity produces the data and has the tools and resources to influence the quality of those data. On the other hand, the buyer or user is in the best position to assess acceptability of the data provided, because that entity is the ultimate owner of the data. The different responsibilities typically would be reflected in two very different elements of the overall QM plan: the QC plan and the QA Plan.

Morian et al. (*66*) make the point that collection of pavement data can be quite different from a production process.

> While the principles of statistical quality assurance, including quality control, acceptance and independent assurance, are well developed, their application to the collection of pavement management data is quite different. In most cases, these statistical tools are applied to processes in which the desirable product is known and the purposes of the control measures are to ensure the efficient production of that product. However, in the case of pavement management data, the ***right*** product is not known. The product itself is data indicating the actual variability in the condition of the roadway. Thus, the control limits are not constant and are a function of the data itself. It is extremely important to identify the sources of variability in each form of data, and to isolate those that can be controlled in the process from those that must be reflected in the data.

Because automated pavement data collection and processing is both a relatively new and a rapidly evolving area, one of the difficulties with developing QM plans is that there are little usable data, especially for surface distress work. For example, the development of a realistic QM plan for the evaluation of surface distress from images would require at least minimal knowledge of several parameters that have not been addressed by most agencies or vendors. The inherent variabilities of those parameters include the following:

- The condition of the pavement when imaging takes place—How accurately does the condition of the pavement at the time of imaging reflect the "true" pavement condition? The many factors contributing to variability in this instance include the moisture and thermal conditions of the pavement, the surface texture, the degree of shading, and the angle of the sun.
- The imaging process itself—With what degree of accuracy does imaging characterize the roadway it represents? The variability no doubt depends on what type of imaging is used, the characteristics of the cameras employed, the geometric configuration of the data collection vehicle, the lighting employed, and many other factors. For that reason, there will almost certainly be a different set of answers for each vehicle, even from the same vendor or manufacturer.
- The data reduction process—How accurately does the data reduction process from images reflect the true pavement conditions? Again, there is no doubt that there are numerous factors contributing to variability, not the least of which are image quality, the hardware and software used in the evaluation, the training of the operators (or raters), and the protocols used.

The literature does not reveal full treatment of those issues or even complete identification of the issues by the pavement community. Therefore, there are numerous areas of potential fruitful research; however, the community is left to do the best it can without complete information until that research is completed. The various QM procedures discussed here may be viewed as interim procedures that will be revised as time passes and the needed information becomes available.

It should be noted that there has been more work in and better quantification of some of the variability issues for sensor-measured data: roughness, rut depths, and joint faulting. In general, the QM of sensor-collected data is much more straightforward than those collected from images. After all, the former are objective measurements, whereas the latter often are subjective ones.

Before discussing QA issues related to the various pavement distresses, it should be noted that some agencies have such requirements for location reference. Virginia, for example, has proposed a requirement that 90% of pavement management section locations reported by the data collection contractor must fall within 0.016 km (0.01 mi) of the logged locations on Virginia's mile point system [*Pavement Data Collection and Analysis Invitation for Bid* (*IFB*), VDOT, 2002, unpublished].

Because there are significant differences in the way that QC and QA issues are addressed for the various pavement data elements, the major approaches identified for those elements are discussed separately.

SURFACE DISTRESS

Several agencies have developed QA requirements for data reduced from images. Generally, the process is to have data collectors (contract or agency) do pilot runs on selected test sections before beginning production testing. After processing and data reduction, the results of these pilot runs are compared with manually collected data from the same sites. If acceptable, these comparisons establish the data collectors' ability to do the work. Then, during production, there is usually a quality monitoring process employed, usually in the form of a blind testing program whereby the collectors' data and the monitor's data are compared and acceptance criteria are applied. What are needed are better definitions of what constitutes "in control" and what constitutes "acceptable" data quality.

Generally, agencies see the need to compare vendor-furnished distress data to the distresses actually appearing on the roadway. For example, Alabama reported that rather than doing a QA process directly on images, a rating team is sent to random roadway locations, and what the team observed at those locations is compared with the vendor's ratings. No details of the process were provided.

LTPP Work

The LTPP work on distress data reported variability, precision, and bias studies involving comparisons of field manual distress ratings performed during rater training sessions with those on black-and-white photographs of the same sections (*13*). Among the findings was that the level of variability in distress ratings from individuals was unacceptably high. The concern was the range of ratings obtained from individual raters, because that was deemed to reflect the likely variability in the ratings on LTPP sections. It was speculated that discrepancies observed in distress time histories may result from this high variability. Note that this finding is directly related to the Virginia vision statement mentioned earlier, that "variability for each data element must be smaller than the year-to-year change in that element."

The same LTPP study showed that the overall variability of manual distress data is lower than for that taken from film interpretations. Furthermore, the bias (average difference between manual and film interpretations on the same sections) was much higher for the film interpretation than for the manual surveys. However, there was a reasonable correlation between manual and film interpretation values for most pavement distresses. The general trend was that field-determined distress levels were higher than those from photographs, possibly reflecting the relative difficulty in discerning low-severity distress from film as compared with field observations. This finding suggests that generally it is more difficult to discern surface distresses from images than from field observations. It may also follow that surface distress variability needs additional research and quantification before realistic QA provisions can be incorporated in distress data collection contracts. As noted earlier, the LTPP work is of a research nature such that the findings might not be directly applicable to network-level pavement management work.

Other Agencies

Virginia

In an effort to deal objectively with highly variable pavement distress data, Morian et al. (*66*) examined the sources of variability in distress and roughness data in Virginia and recommended an overall process scheme for QA. In addition, they emphasized the importance of basing control and acceptance limits on sample sizes greater than one. These researchers mentioned the following sources of variation in surface distress data:

- Variation in pavement condition linearly along a highway;
- Variation resulting from the method of data collection employed (sample rate and sample size are important considerations);
- Variation owing to a lack of uniformity in rating procedures over time;
- Variation in pavement condition over time;
- Variation between multiple raters; and
- Variation owing to data referencing, processing, and handling errors.

The authors continued their research by addressing each of these sources of variability in the development of both a collection process control plan and an acceptance plan that recognize the inherent variabilities. Their effort is summarized here:

> The effect of these multiple, compounded sources of variability is that the "true" distress condition of a roadway is never known. How then can a reference for controlling pavement management data processing be developed? The answer is that statistical evaluation of distress results must be established which includes all the potential sources of variability inherent in a particular process. Using this approach, it is possible to effectively define an acceptable range of variability, within which results should be maintained. A change in any of the conditions of a distress survey may adversely affect the reliability of the results. As an example, comparing field-collected information with distress interpreted from imaging is analogous to comparing apples and oranges. Each is a different process, and therefore can be

> expected to produce different results. Neither inherently represents the "truth" (*66*).

In earlier work, Stoeffels et al. (*67*) applied an analogy between pavement rating groups and laboratories testing materials, and applied the difference two standard deviation (*D2S*) criteria (*68*) to pavement condition indices in Virginia (*46*). Those criteria state that the difference between two laboratories running the same test on the same material should not exceed *D2S* more than 1 time out of 20 or 5% of the time (i.e., there is a 95% confidence limit) (*68*). In that relationship, *S* is the pooled standard deviation of all paired test results to be compared. In practice, it is possible to apply a similar approach to either process control or as an acceptance criterion. That is, for control purposes, one can have a QC rater who monitors the production and applies the *D2S* criteria to production versus QC work. No more than 1 rating in 20 should vary by more than *D2S.* Similarly, an acceptance team could randomly sample the production and apply the *D2S* criteria to production versus acceptance results. The process as applied was to pavement condition indices; however, it could as well be applied to individual distresses making up the indices.

To establish precision and bias statements for the Virginia rating procedure, the research team evaluated ratings from the production contractor and quality monitoring rater pools. The *D2S* process was used to define the precision. Average results from the two individual rating pools were used to establish the acceptable process bias.

Although the details of the statistical approach applied by those researchers (*66,67*) is beyond the scope of this synthesis, it is clear that the researchers have laid the groundwork for additional studies that could address the further use of applied statistics in the automated collection and processing of pavement condition data. Although there is no doubt that every rating procedure will involve a different set of statistical parameters and that it may never be possible to establish generally accepted limits of variability, etc., a general framework for QM procedures needs to be established. Such a framework would provide for defensible approaches to both process control and to the acceptance of automated pavement data.

Quebec

In Quebec's 2002 cracking analysis contract, QA provisions state that the Ministry will select from 2% to 5% of the roadway images for analysis of data quality (*60*). The Ministry uses the same images as those used by the contractor and rates these images themselves according to its standard crack identification protocol. If the bias between the results of its ratings and the results presented by the contractor does not meet the requirements the Ministry stipulates, and no explanation can be furnished, the lot of 100 km will be rejected. The Ministry reserves the right to return the lot to the contractor for reevaluation. The following are the Ministry criteria:

- Cracking index—When the computed index is within ±15% of the Ministry measured index;
- Longitudinal cracking—±10 m/100 m in 100% of the cases and ±5 m/100 m in 80% of the cases; and
- Transverse cracking—±5 cracks/100 m in 100% of the cases and ±3 cracks/100 m in 80% of the cases.

Note that the Ministry recognizes variability and that there will not be a perfect match between Ministry and contractor evaluations of the same images. The acceptance criteria address both a cracking index and its major components. The transverse and longitudinal cracking criteria operate on two levels, with the 80-percentile criteria more stringent than the 100-percentile criteria. The structure of these criteria is reminiscent of the bell-shaped or normal curve, where the majority of the population is close to the mean, yet some results may vary by a relatively large amount from that mean.

British Columbia

The British Columbia Ministry of Transportation and Highway (BCMoTH) has contracted pavement condition data collection for many years and has gradually evolved a QA philosophy. Excerpts are quoted here.

> Since 1993, BCMoTH has contracted out over 40,000 lane-km of automated network level, pavement surface condition surveys on its main highway network. The surveys include surface distress ratings, rut depth and roughness measurements in both wheel-path and video-logs of the right-of-way.
>
> Because the Ministry is committed to open contracting, QA plays a critical role in ensuring that the data [are] accurately collected and repeatable from year to year. The Ministry has developed and implemented comprehensive QA procedures that consist of multiple levels of field-testing.
>
> BCMoTH has worked closely with its contractors in an open effort to ensure the testing is practical and representative of the intended end use of the data for pavement management. Both of these interrelated factors played a key role in the development of the QA procedures. The entire methodology is dependent upon the contractor having real time processing capabilities with onboard computers to not only address and resolve any processing issues arising from the initial calibration process, but also to enable rapid response during the production QA at any time.
>
> Practicality was important for two reasons: firstly the process must provide a realistic test of the contractor's capabilities and, secondly, the process should not present a huge burden to Ministry personnel to implement and monitor. A data QA program that cannot be effectively implemented provides little value in terms of agency understanding and thereby erodes the level of accuracy and acceptance of the survey results.
>
> Similarly, the scope of the QA procedures was driven by the intended end use of the data. This is an important distinction and can sometimes be overlooked in the effort to collect accurate data. In the Ministry's case, automated pavement surface condition data is collected with the clear understanding that it is to be

> used primarily for network level, pavement condition analyses. Hence, the degree of data accuracy and field-testing required is dictated by this fact.
>
> The Ministry's quality assurance program is divided into two phases: initial quality assurance where the contractors' methods and equipment are initially calibrated and production quality assurance where the survey is monitored to ensure continuing compliance (*69*).

The initial QA step serves to qualify the contractor on four QA sites chosen by the Ministry. First, using the standard Ministry rating manual (based in part on the LTPP distress evaluation manual), Ministry personnel conduct manual surface distress, roughness, and rut-depth surveys at the control sites. Then, for video-based surveys, the contractor is required to video record the four sites five times each and do pavement distress index (PDI on a 0 to 10 scale) ratings for each time. The results are provided to the Ministry where the multiple runs serve to test the accuracy and repeatability of the process. For acceptance, the contractor's averages must meet criteria of ±1 PDI unit for accuracy and ±1 standard deviation of the PDI for the five runs for repeatability. The contractor may proceed with production work after the initial QA criteria are met.

For production QA, the contractor's production is measured against blind QA sites randomly located throughout the system and evaluated by agency personnel. The same criteria as used in the initial QA also apply to production. When the contractor satisfactorily completes a blind site QA test, it is authorized to continue the production surveys. However, if the test results fail to meet the criteria, the contractor is required to review the videologs of the blind site and make equipment repairs or modifications and, if necessary, repeat the surveys from the time of the last blind site test.

Finally, BCMoTH places QC responsibility on the contractor. That QC focuses on two areas: data integrity and data continuity. Data integrity relates to making sure that all data fields are complete and accurate and are delivered on time. Data continuity is concerned with ensuring that the data are correctly referenced and that there are no breaks in the data. The contractor is given criteria for establishing QC procedures that are reviewed by the Ministry. These criteria are as follows:

> The contractor's QC program should include, but not be limited to, on-board equipment/sensor confirmation tests, ensuring the correct contract quantities and lane configurations, checking the data for anomalies and reasonableness, cross checking all data with vehicle sensors, and a thorough review of the created file contents and format (*70*).

Mississippi

The Mississippi DOT provided some very general guidelines on the QA and QC program followed with pavement surface distress data (*71*). Surface distress data are checked by using an Image Processing Workstation and video logs for a 5% random sampling of the contractor's work. Distresses checked are cracking, potholes, spalling, and punch-outs. The LTPP distress identification manual is used as the standard for type and severity of distresses. No specific acceptance criteria were given.

Still other agencies are known to do QA work on images, although few details are given in the questionnaire responses or the published literature. Washington State, for example, noted that although QA procedures used on the windshield surveys done previously were "difficult and costly," that QA performed on images is a "straightforward and is a routine process." Iowa is in the process of implementing a new image QA program in cooperation with the University of Iowa. Maryland remarked that QA and QC are "paramount" to producing high-quality cracking data (*49*). Its QA process is discussed more fully in chapter eight.

South Dakota is still developing its QA process for distress surveys as given in attachments to its distress survey manual (*72,73*). In that case, the agency is trying to balance the relevance, reliability, and affordability of the data, and it recognizes that greater reliability means increased costs. It also provided few details of their procedures. Vermont, too, has been actively developing QA procedures.

SENSOR DATA

Sensors measure either longitudinal or transverse pavement profile and, for that reason, it is most convenient to discuss those data in the aggregate, such that roughness (IRI), rut-depth measurements, and joint-faulting measurements are all included in this section. Still, most of the emphasis is on roughness, because that is the parameter measured by almost every agency.

Because of the emphasis on roughness monitoring over the past decade, largely brought about by the HPMS program, there has been a good deal of attention paid to the QA of those data. The HPMS field manual (*5*) recommends the AASHTO roughness quantification standard QA plan consisting of several very general guidelines almost identical to those listed earlier for the asphalt cracking standard (*28*). Again, the guidelines are helpful in describing the steps to be taken, but they provide almost no details, which are left as an agency responsibility. However, some help is available in addressing those details, as described in the following sections.

Profiling Errors

Perera and Kohn (*74*) recently provided guidelines on profiling errors and how to avoid them. They noted that there are three major components to profiling: the height sensor, the accelerometer, and the distance measuring instrument—and that an error in any of these components will affect the quality of the profile data. The authors listed the following procedures for ensuring that inertia profile data are error free:

- Calibrate height sensor(s), accelerometer(s), and distance measuring systems following manufacturers' recommended procedures.
- Clean lenses in sensors and check tire pressure before profiling.
- Perform daily checks on profiler—bounce test and static height sensor check.
- Set sensor spacing to spacing specified in smoothness specification.
- Collect profile data along path specified in smoothness specification. Follow consistent path without lateral wander during profiling.
- Do not collect profile data outside the speed range that is specified for the profiler.
- Maintain a constant speed during data collection. Do not accelerate or decelerate during data collection. If you stop the profiler in a middle of a profiling run, discard the data for that run.
- Have an adequate lead-in distance prior to test section to initialize data collection filters and come up to speed. Strictly follow manufacturers' guidelines.
- Initiate data collection at specified location. If the profiler is equipped with an automated method to initiate data collection (e.g., photocell), use it to initiate data collection.
- Do not profile wet pavements.
- Do not collect data on pavements that have surface contaminants (e.g., gravel, construction debris).
- Evaluate collected profile data for presence of spikes (*74*).

LTPP Work

The LTPP study of the quality and variability of IRI data in the LTPP database addressed all profiles collected between 1989 and 1997 after correction for obvious problems (*10*). Those studies are comprehensive and too voluminous to fully address in a synthesis. However, the profiles and IRI values analyzed represent five replicate runs on each test section for each visit of a profilometer. Although that degree of testing is needed in research work, it clearly would not be feasible for network-level surveys. Nevertheless, some of the major efforts and findings are applicable and are summarized here.

From the LTPP analysis of more than 2,000 test sections where profiles were collected with K.J. Law Model 690DNC optical sensor profilometers "confidence limits were developed for expected variability between repeated profile testing runs and for the expected change in IRI between subsequent visits" (*10*). As noted earlier, if the testing variability exceeded the expected visit-to-visit change in IRI, time series data would be of diminished value.

From the same LTPP study it was found that the run-to-run IRI coefficient of variation is less than 2%. The study further reported significant seasonal impacts on IRI results, especially for PCC pavements. This effect must be quantified and considered when evaluating the significance of day-to-day variations in IRI measurements.

In addition to conducting and documenting the studies described, LTPP has provided a manual for profile measurements that covers all aspects of LTPP profile data collection (with the ICC MDR 4086L3 Road Profiler), including equipment calibration and reporting requirements (*75*). In addition to discussing profiler issues, the document provides guidelines on the use of the Face Company Dipstick, as well as on the use of rod and level surveys. Detailed guidelines are provided on field testing, calibration, and equipment maintenance and repair. The calibration section addresses distance measuring instruments, accelerometers, and lasers. The field testing portion provides a procedure for evaluating the acceptability of the multiple runs on an LTPP site. This procedure employs profile QA software (ProQual) developed for LTPP. Briefly, the procedure is to obtain five error-free runs and then determine acceptability if the average IRI of the left and right wheel paths satisfy the following criteria:

- The IRI of three of the runs are within 1% of the mean IRI of the five runs, and
- The standard deviation of the five runs is within 2% of the mean IRI of the five runs (i.e., if the coefficient of variation is less than 2%).

The two criteria ensure a reasonable degree of accuracy and precision, respectively. Again, five runs are not practical for network-level data collection; however, the LTPP procedures could serve as a starting point for other agencies to use in precision and bias evaluations. The LTPP document as a whole should be a useful guideline for agencies in establishing their own QA procedures.

The Canadian provinces have been active and progressive in the QA of roughness data. An Ontario procedure for acceptance of calibration tests was described in the previous chapter. Three other provinces have made significant contributions to the QA of sensor-collected data. These are described briefly here.

British Columbia

The British Columbia QA process discussed earlier for surface distress is extended to sensor-collected data. For initial QA, the contractor does five profiler runs on the Ministry QA sites, and the approach used is as follows:

> The roughness testing consists of validating the Contractor's automated surveying equipment by field comparisons to the known longitudinal profile at each test site. The survey vehicle completes a series of five runs over each site in order to assess both accuracy and repeatability. The International Roughness Index (IRI) values for each wheel path are generated and compared to the manual values for each as per the acceptance criteria [presented in Table 14].
>
> Because rut depth measurements are fully automated using a multi-laser rut bar, the rut depth QA tests are designed to validate

TABLE 14
BRITISH COLUMBIA ACCEPTANCE CRITERIA FOR SENSOR DATA

Parameter	Roughness	Rut Depth
Measure	IRI	Millimeter
Survey Interval	100 m	10 m
Report Interval	500 m average	500 m average
Unit	Each wheel path	Each wheel path
Accuracy	10% of Class I survey	±3 mm of manual survey
Repeatability	0.1 m/km SD for 5 runs	±3 mm SD for 5 runs

Notes: SD = standard deviation.

> the Contractor's automated surveying equipment by field comparisons to known transverse profiles. The survey vehicle completes five runs over the site to measure the accuracy and repeatability of the rut bar measurements. The average rut depth value is calculated for each wheel path and compared to the manual values as per the acceptance criteria [presented in Table 14].

The QA acceptance criteria for the accuracy and repeatability of the surface distress, roughness, and rut-depth measurements were developed on the basis of Ministry experience and are presented in Table 14.

Again, the contractor may do production testing once the criteria in Table 14 are met. At that time, the Ministry uses the blind sites described under surface distress QA and the criteria in Table 14 again apply. The contractor's QC philosophy as discussed applies to sensor data as well as to surface distress data.

Alberta

Alberta also uses a statistical QM approach for the initial evaluation of its sensor-collected data (*76*). The contractor is required to do on-site calibrations before beginning production work and again before leaving the province.

> The IRI calibration consists of validating the Contractor's automated surveying equipment by field comparisons to the known longitudinal profile at the calibration site. The survey vehicle will complete a series of 3 runs over the site, which is 500 meters in length. The IRI values for each wheel-path shall be calculated and compared to the manual values for each run. The IRI derived through automated data collection must be within 10% of the manual survey and will be considered repeatable if the IRI from each repeated run is within 5% of the mean for the 3 runs.
>
> The rut depth calibration validates the Contractor's automated surveying equipment by field comparisons to the known transverse profiles. The Contractor is required to conduct 3 runs over the site to measure the accuracy and repeatability of the rut bar measurements. This test is performed at one calibration site near Edmonton. The average rut depth over the 500-meter site derived through automated data collection must be within 3 mm of the average rut depth for the manual survey. The automated survey will be considered repeatable if the average rut depth over the 500 meter test section from each repeated run is within ±1 standard deviation of the mean for the 3 runs (*76*).

Alberta also requires the contractor to monitor data accuracy during production (the QC process) using verification sites established by the contractor. Generally, these sites are scheduled every 7 days or 2000 km (1,250 mi) of data collection. The contractor is responsible for submitting these data promptly to agency personnel. Then, the department representative may require the surveys to be halted if an acceptable level of accuracy is not provided. The agency's terms of reference do not define that acceptable level.

Manitoba

Manitoba also applies QA provisions to its sensor-collected data (*77*). In that case, the contractor is required to satisfactorily complete a specified number (contract specific) of "repeat run" sites before the beginning of production work. These sites have been thoroughly analyzed by the province and are used to establish the contractor's equipment capability. The same sites are retested at least once each 3000 km (1,875 mi) of production survey completed. The minimum acceptable equipment standards are given in Table 15.

During production, the province monitors contractor production through the use of blind sites. Immediately after a blind site is run, the contractor is requested to submit the site data to the province staff, where the data are compared with those originally found for the site. The tolerances given in Table 15 again apply. If those tolerances are not met, production is stopped and the contractor is required to recalibrate and to rerun the blind site until the tolerances are met.

During post-processing, the contractor is required to implement a QC process that includes at least verification of quantities and lane configuration, reasonableness of data, and a thorough review of the content and format of files. The contractor is also required to note any sections that were omitted from the evaluation program.

TABLE 15
MANITOBA MINIMUM ACCEPTABLE EQUIPMENT STANDARDS

Attribute	Equipment Standard
Chainage	Distance measuring instrument (±0.1% accuracy)
Roughness	FHWA class II profiler (±10% accuracy)
Rutting, Faulting	Laser or ultrasonic sensors (±2 mm accuracy)

Mississippi

The Mississippi DOT (MDOT) provides some QA guidelines on sensor data collection (*71*). It provides for calibration sites to be set up in each district where contract data collection will take place. Asphalt, jointed concrete, and composite pavements are represented in those sites. MDOT's profiler, rut bar, and Georgia Faultmeter are run on the calibration sites. Then, during production, the contractor calibrates its equipment on these sites at the beginning of each workday.

Baseline production sensor data are collected by MDOT on a 5% random sampling of sites from each pavement type a few weeks before or after the contractor's data collection. Average IRI, rut-depth, and faulting data for each sample are noted and entered into a database to be used for comparison with the contractor's work. For a 2001 contract, it was agreed with the contractor that a calibration site would be traversed at least once each day and that the following acceptance criteria would apply when comparing contract and agency data:

IRI	±0.30 mm/m,
Rut depth	±0.09 in., and
Faulting	±0.07 in.

When data failed to meet those tolerances, the procedure agreed on with the contractor was to disregard any data collected between the failing site and the last passing site. Mississippi's procedures will be discussed in more detailed in the case study in chapter eight.

Louisiana

The LADOT specifies a sensor data QC program for data collection contractors (*58*). This program requires the contractor to administer a plan that will ensure that data are collected accurately and that they reflect actual pavement condition within specified precisions. The contractor's equipment is checked against an agency profiler and a Class I profiling instrument (Dipstick, etc.) before beginning testing. During production, the contractor is required to use QC sections of known IRI, rutting, and faulting values. An interesting aspect is that the sites are permitted to "roll"; that is, the contractor is not required to use the same sites all the time. Rather, the contractor may, on a given day, test a site that was tested 1 week previously. These reruns are evaluated to determine if the profiler is still in calibration. Such tests are documented in writing and delivered to the agency weekly. This feature is helpful in testing over a widespread area, because it is not necessary to do extensive backtracking to do the control sites. Although the questionnaire response provided little information on acceptance criteria, it did address the question of data reasonableness. For example, the maximum reporting value for IRI is given at 10 m/km (632 in./mi).

Other Agencies

As was the case with surface distresses, a few agencies addressed sensor QA issues but provided little information in questionnaire responses. New Mexico and Arizona, for example, cooperate in running IRI control sites, a number of which are listed in New Mexico's response. The general procedure is that each agency runs the same sites and the results are compared. Although on average these comparisons are excellent, there are occasions in which the two sets of data vary widely. The agency does not address how those differences are handled. Oklahoma requires that sensor-collected IRI must be within 5% of measurements made by rod and level dipstick or other Class I profiler (*78*). It further requires repeatability within 5% for three repeat runs. Oklahoma has a unique contract feature that requires the prime contractor to contract with a third party to provide dipstick profiling of 0.80 km (0.50 mi) control sites to be used as "ground truth" for calibration of data collection vehicles.

SUMMARY

Some agencies have done extensive work in and have developed thorough QA requirements or practices. Some of the Canadian provinces have been exceptionally productive in this area and have established procedures that could well provide the foundation for national or international approaches.

There are several general conclusions concerning QA issues, including the following:

- Lower-severity distresses are more difficult to discern from images than from the roadway. Therefore, deduct-based indices done from images often will be higher than those from the roadway.
- The determination of typical variability values for surface distresses (cracking and patching) may be an area needing some future research. Work has been done by LTPP primarily with manual surveys, but more is needed with automated data for network purposes.
- Furthermore, it is necessary to develop data on typical year-to-year changes in pavement distress quantities as well as typical precision and bias statements, such that realistic and meaningful QA provisions can be incorporated into data collection and analysis protocols and contracts.
- There are no widely used acceptance criteria for pavement condition parameters. Because nearly all agencies deal with essentially the same kinds of distresses and data collection issues, it seems that more generally acceptable approaches and criteria would be reasonable and desirable.

CHAPTER SEVEN

COSTS, ADVANTAGES, AND DISADVANTAGES

Agencies were queried on the costs, advantages, and disadvantages of pavement data collected and processed through automated means. Those responses are discussed and summarized in this chapter.

COSTS OF AUTOMATED DATA COLLECTION AND PROCESSING

The reader is cautioned that the cost data provided are very limited and may be subject to significant errors owing to various logistical, traffic, and geographical variables. Although the agencies were queried on the individual costs of various data items, in most cases that type of information was not available and the reported costs were combined to no more than two separate items: images and sensor data. Only two agencies were able to provide separate costs for roughness, rut-depth measurements, and joint-faulting measurements. Two others did roughness and rut-depth measurements, but no joint-faulting measurements. This is a natural consequence of the way much of the data collection is contracted. Although image collection and sensor data collection are two very different activities, they often are done in one pass by a single vehicle, and they tend to be contracted together.

Table 16 provides a summary of costs reported by the agencies (detailed questionnaire responses are given in Tables B1 through B4 in Appendix B). Note that although not technically a part of this synthesis, the costs of manual surface distress data collection are included for comparison purposes. Generally, costs given in Table 16 do not include agency costs of administering contracts, etc.

In many cases, pavement data collection pricing is combined so that it is difficult to determine the costs of individual data elements. This is especially true for sensor-measured items, because they typically are all collected in one pass of a data collection van. When that is the case, vendors often provide one combined price for IRI, rut depths, and joint faulting. Surface distress (cracking) data are often separated, because collecting them is an entirely different operation—although the surface imaging itself may be done at the same time that the sensor testing is done.

As expected, costs of data collection are very much related to the volume of work in a given location and on how much travel is involved. The Eastern Federal Lands Division of the FHWA, for example, handles data collection for the National Park Service (NPS) on roads that are widely separated and that often involve small quantities at a given location. The combined price the division pays for imaging, image data reduction, and sensor data collection and processing ranges from $200 to $300 per mi depending on the location within the country. Because of the extreme values, Federal Lands' data are not reflected in Table 16.

Another cost variable can be traffic volume. Vermont reported a $20 per mi cost increase for Interstate pavements compared with others. Vermont also reported costs of up to $170 per mi in urban areas for total combined costs of image and sensor data with processing. Other agencies reporting higher than average total costs were Rhode Island at $80 per mile and the District of Columbia at $85 per mile for combined image and sensor data.

An additional variable was introduced by Arkansas and Quebec, where agency personnel collect images and sensor data, but where surface distress data reduction has been done by contract. Arkansas reported $12.50 per mi paid for that service. Quebec has done only a 2002 pilot project in which they paid $45 cdn per km (approximately $50 per mi) for the service. Cost data from those two agencies are not reflected in Table 16.

Finally, very few agencies could provide any costs for data collected by agency personnel. In the few cases where an attempt was made, there were notations such as "includes man hours only," and "no equipment depreciation." The costs of agency-collected data are not reflected in Table 16.

ADVANTAGES AND DISADVANTAGES OF AUTOMATED DATA COLLECTION AND PROCESSING

Although nearly one-half the agencies responding declined to comment on these issues, it is clear that personnel safety and efficiency of data collection are the primary benefits derived from automated collection. Compared with windshield or walking surveys, there is no question that automated collection is much safer, because it is generally conducted at prevailing traffic speeds. This is such an important issue in some states, in Texas for example, that manual data collection is used on lower-volume roads, whereas automated equipment

TABLE 16
SUMMARY OF PAVEMENT DATA COLLECTION AND PROCESSING COSTS: CONTRACT WORK ONLY (U.S. dollars per mile)

		Automated				
		Sensor-Collected Data				
Variables	Visual Surveys Surface Distress	Smoothness/ Roughness	Rut Depth	Joint Faulting	Combined Sensor Data Only	Combined Costs, Images, and Sensor Data
Average	16.00	6.12	1.68	2.23	12.63	50.02
Range	5–18	2.23–10.00	1.11–2.25	2.23	5.57–27.84	24–85
No. of Agencies	3	2	2	1	6	11

Costs per mile refer to lane-miles for automated data and roadway miles for manually collected data.

is used on roads with higher volume. Other noteworthy comments made by various agencies are summarized here.

Arkansas noted, “Automated distress identification allows the Department to use existing staff in other areas.” The agency also saw advantages in owning the data collection equipment and remarked, “Owning an automated roadway analyzer (ARAN) allows flexibility in scheduling and allows its use in project level and research studies.”

FHWA offices responsible for pavement evaluation provided some useful feedback. The Eastern Federal Lands Division is responsible for 8800 km (5,500 mi) of paved NPS roads. They report that NPS wants 100% sampling of every paved road and that “to ensure comparable results from an objective view, we decided that automated crack detection was the only way to complete the analysis.” Roadware Group, Inc., reports that the NPS is making special use of a new ARAN with all digital images and with WiseCrax automated distress analysis and GPS coordinates. In addition to conducting the usual distress surveys, park managers make good use of the digital images in reviewing conditions in remote locations, saving travel time and increasing manager efficiency (*39*).

LTPP personnel also commented, “The biggest benefit with automated (film) distress data collection is that it provides a permanent record of test section condition at a particular time that can be re-evaluated at a future date if needed. Safety is also a factor.”

Florida commented that “the inertial profiler system provides a safer, more efficient and objective way of collecting pavement evaluation data.” Minnesota found that “we get more consistent data when using automated distress data collection. In the past district personnel did manual ratings with much more variability. We currently have the same two people rate the system each year. Having images allows re-checks when questions arise.” Oklahoma reported that automation provides much more data at a detailed level than is possible otherwise. The agency also believes that 100% coverage is beneficial and that it would not be possible for the agency to collect on its own. Vermont and Wisconsin join Minnesota in viewing data consistency as a benefit of automated collection and processing. Vermont also pointed out the advantage of having images to reprocess in the event of revisions made to protocol or processing algorithms.

Virginia hopes for the elimination of the human element if automated distress processing from images is implemented. Washington State finds that with digital images QA and QC are straightforward and routine. The agency reported that QA and QC of previously used windshield data were difficult and costly.

Not all comments were positive; Florida reported that “the results from real time pavement distress analysis from images [are] far from accurate.” Wyoming would like to automate surface distress collection and processing, but sees no way to handle patching and bleeding, which are difficult to do with automated processes.

No agency reported doing a cost–benefit study, although Saskatchewan expects to reduce its data collection costs by approximately 75% when it changes from manual to automated distress surveys and continues to use the same database. Caltrans reported a higher-quality product from doing its own IRI data collection.

SUMMARY

Costs of automated pavement condition data collection and processing vary greatly depending on specific items addressed and on logistics. Full-featured collection and processing will average more than $30 per lane-km ($50 per lane-mi) and may reach \$125 per lane-km (\$200 per lane-mi) or more in urban, high-traffic areas. Distance traveled to collect data is also a significant factor in determining cost.

Some agencies using automated pavement condition data collection cited increased safety as a major reason for doing so. Typically, they maintain that modern traffic volumes are too hazardous for personnel to do manual surveys, and that automated surveys are both safer and more efficient. Other agencies cited shortages of resources as the main reason for automation, especially in data collection.

Not all agencies are satisfied with the results of automation. Some reported that improvements are needed in the quality of images provided, as well as in the data reduced from those images.

CHAPTER EIGHT

CASE STUDIES

This chapter covers cases studies of agencies applying various methods to pavement condition data collection and processing. The studies were performed to provide additional insight into agency practices. The questionnaire responses and the materials appended to those responses by some agencies have been thoroughly reviewed and three agencies meeting the general criteria of doing things in different ways have been chosen. All are state transportation agencies, one of which does everything through the use of agency resources, whereas another does the same things exclusively through contract work. The third accomplishes most of its tasks through a vendor, but with significant input from the agency to accomplish data processing. The studies incorporate work by two of the major North American vendors, the Roadware Group, Inc., in the first two cases, and Pathway, Inc., in the third. All three agencies appear to have been reasonably successful in accomplishing their goals of securing high-quality network-level pavement condition data.

MARYLAND STATE HIGHWAY ADMINISTRATION

Introduction

The Maryland State Highway Administration (MDSHA) provides a case study of an agency that has successfully moved from essentially a manual data collection and analysis process to one that is fully automated. In Maryland, all pavement condition data collection and processing is by agency resources that use purchased data collection equipment, processing hardware and software, and training. Much of the work the agency has done in improving the quality of the data collected has been documented in TRB publications over the past few years. For a case history of automated collection and processing or pavement cracking data, Maryland engineers have provided background in a 2003 TRB paper as summarized here (*49*).

The MDSHA started collecting cracking data on its roadways in 1984. Typically, the data were collected by teams of inspectors, riding in vans. However, with recent reengineering of the agency, the old process began to create resource and logistical problems. In response, over the past few years, the MDSHA pavement management group has developed and implemented a state-of-the-art network-level crack detection process (*49*).

The agency manages some 16,000 lane-mi of highway pavement and spends approximately $100 million annually to maintain and preserve the network. To use the funding wisely, the agency developed and implemented a pavement management system with the appropriate data analysis and performance modeling tools. For there to be suitable performance indicators, pavement cracking is an important input to those models.

Data Collection

In 1995, the state purchased an ARAN device and software that enabled the capture of pavement images and the analysis of pavement cracking for the network. “After a period of experimentation and development, an efficient, accurate, and repeatable process evolved” (*49*).

Ride, rutting, and cracking data are all collected with the ARAN by running one lane in each direction or the curb lane for multilane roads. As a result, some 10,000 lane-mi per year are collected. The report describes the ARAN as follows:

> The ARAN vehicle is equipped with state-of-the-art equipment to collect information about Maryland’s highway infrastructure. The combination of high resolution digital video, ultrasonic sensors, accelerometers, gyroscopes, Global Positioning Systems (GPS), and a distance measuring device are used to collect data at highway speeds. As it travels, it collects information on rutting and roughness, grade, and curve radius. It also collects right-of-way digital video. Digital photographs of the pavement view are taken by two rear-mounted, downward looking cameras (*49*).

The profiling capabilities of the Maryland ARAN exceed the requirements for a Class II profiling device. A 37-sensor rut bar measures transverse pavement profile and determines the amount and severity of rutting. In addition, digital pavement images are collected and stored on removable hard drives. These images are processed by agency personnel at an off-line work station.

Maryland indicated that its data collection procedures have matured to become a robust part of its business process. The agency noted

> Many customers within and outside the State use this data and it is now integrated with the Geographic Information System (GIS). By pushing a button within the GIS, a full database of inventory, performance, and right-of-way data can be accessed.

> The use of digital right-of-way images has now been rolled-out statewide and, as a result, the Pavement Division has seen a large increase in the number and variety of customers who are utilizing this information.

Maryland engineers noted that the automated procedures described here apply only to flexible pavements because visual surveys are done on PCC pavements.

Image Processing

Each week the ARAN crew brings the pavement images into the office on removable hard drives. The files are archived and the following tasks as given in the report are performed (*49*):

- Data management,
- Pre-processing,
- Processing,
- Quality control,
- Quality assurance,
- Classification and rating, and
- Data reduction.

Data Management

Paper log sheets containing location-reference information and other collection information are entered into a database and serve as important measures of progress in covering the system. The data are cross checked with inventory to make sure that the appropriate road sections are being collected. Still another tool, described in the data reduction portion of this document, along with this database, monitors crack detection progress. The present database is updated continuously during data collection and processing.

Pre-Processing

Pre-processing begins with loading data from archived videotapes into the WiseCrax processing computer. These data are a control file containing location-reference information and providing a tie-in between roadway locations and pavement images. The file is segmented into 0.016 km (0.01 mi) increments. The corresponding images are stored as JPEG digital files. No data could be processed without the control file. To speed processing and review, pavement history files are reviewed to identify new overlays. Those no more than 2 years old are assumed to have zero cracking and are not processed. The WiseCrax program is then started and the control file and images are loaded. Images are then reviewed by the operator to ensure that they are of a suitable quality to be processed. This review consists of making sure that images are clear and that the lighting is even. Following this review, a series of adjustments are made to the software to ensure that crack detection input parameters are acceptable. MDSHA engineers noted "*This is the most important part of the crack detection process* and it involves a great deal of experience by the operator to perform well" (*49*). Although the details of this part of the process are not given by the agency, the MDSHA does report that "the manufacturer's user's guide and training ensure that operators are skilled to perform this task." The MDSHA engineers continued

> As part of this process, the operator performs trial crack detection on a variety of stations within the road section. During this process, the automated crack detection results are compared to a manual review of the data on the computer screen. This is done to ensure that crack detection is occurring correctly. Parameter settings are sensitive to changes in pavement color and texture so, in the end, a compromise set of parameters that best apply to the entire section is usually chosen. It is also possible to choose separate crack detection parameters for individual sections within a pavement, but this option is not normally performed in MDSHA due to time and efficiency constraints. Identification of 80 percent or greater of all visible cracks is the benchmark used to determine if crack detection is adequate (*49*).

Processing

Processing is done in the automatic mode of the WiseCrax program, which processes the images at an equivalent speed of 21 to 27 km/h (13 to 17 mph), depending on processor speed, the amount of cracking, and other factors. Because no human intervention is required, most processing is done overnight.

Quality Control

QC of the processed files is very important and usually is carried out by the person who started the program for a given run. It is done as soon as the run is completed and consists of three reviews: completeness, section-level data, and data management. The completeness review ensures that all files have been processed. The section-level review is done to determine whether or not the program is detecting most cracking, and it is accomplished through both subjective evaluation by an experienced operator and through direct comparison of detected cracking to superimposed images. Approximately 50% of the 0.016-km (0.01-mi)-long stations are reviewed, because this high level of QC has been found to be feasible and warranted to produce good cracking data. The goal of the process is to achieve 80% crack recognition, for this level has been found to be sufficient for network-level surveys. Finally, the data management review is conducted to ensure that the data have been saved to the WiseCrax computer hard drive and then to the network. Table 17 summarizes the QA requirements applied by Maryland.

Quality Assurance

The Maryland QA process is of particular interest because it demonstrates the concern that the agency has for securing good-quality data and the extent to which one must go to achieve that objective. A QA auditor (QAA) does a weekly or

TABLE 17
MARYLAND PROCESSING QC RATING MATRIX

QC Procedure	Good	Fair	Poor
Stations Processed	100%		<100%
>80% Cracks Detected	>90% of stations	70%–90% of stations	<70% of stations
Saved to Hard Drive	Yes		No
Saved to Network	Yes		No

biweekly review of the process to ensure that the QC has been properly conducted. For a given group of sections, the QAA must be someone other than the person who ran the original WiseCrax on the sections. The QAA inspects the previous week's documentation and then selects a 10% sample of the data for QA review. Maryland engineers do not cite a random sampling requirement for this 10%. An equal number of files for each different operator are evaluated. The main review consists of conducting the QC process as described and assigning QC ratings as shown in Table 17. For files rated "Fair" in Table 17, disposition is at the discretion of the QAA. Any ratings not in agreement with the originals are noted. Two evaluation criteria are then applied:

- If more than two discrepancies are found within one file, 50% of the file must be reviewed for the possibility of a systematic crack detection problem; and
- From that 50%, if more than 10% have discrepancies, consideration is given to throwing out all data and repeating the WiseCrax process for the files represented.

All rating discrepancies are discussed with the appropriate operators and a consensus is reached as to the final rating to be assigned. Finally, the QAA ensures that all data have been backed up to the network daily and archived to a tape drive once a week. MDSHA engineers clearly consider those data to be very valuable and worthy of a sound QA program, and of solid backup and archival procedures.

Classification and Rating

Upon completion of data QC and QA, the next step is to classify and rate the cracking detected. WiseCrax performs this process automatically at a rate of approximately 1300 km/h (800 mph) once the operator enters the proper commands. Longitudinal and transverse cracks are classified while their location on the pavement (outside wheel path, inside wheel path, center, left edge, or right edge) and widths are determined. Proprietary algorithms perform this procedure. Finally, the cracks are rated as low, medium, or high severity through application of the AASHTO cracking standard (*17*). The final result is a text file of location-reference and cracking data. MDSHA produces about 1 millions rows of such data each year.

Data Reduction

The raw data from the classification and rating process are used in the computation of a PCI. MDSHA uses a combination of the AASHTO cracking protocol (*17*) and the PCI developed by the U.S. Army Corps of Engineers (*19*) to compute the condition index.

Performance Indicators

MDSHA engineers noted that the ultimate use of the cracking data is as an overall performance indictor to be used in performance models. They anticipate that an overall condition index combining roughness, rutting, and cracking eventually will be developed. To date they have not developed that index because reliable cracking data have only recently become available through the new WiseCrax process.

Lessons Learned

Maryland engineers cited a number of lessons learned from their work with the automated crack detection and classification program. In the belief that these lessons are of special value to those considering automated distress collection and data reduction, they are listed here exactly as given in the report (*49*):

- Automated crack detection is a viable technology that is "ready for primetime."
- Performing (the process) in-house is a large resource commitment in terms of equipment purchase, personnel training, and operator time.
- The key to quality cracking data is to take a phased approach to implementation. Take each step slowly and work out all bugs before proceeding to the next step.
- Rigorous QC and QA are paramount. Large amounts of effort should be devoted to this cause.
- Partner with the manufacturer of equipment you use. Learn from them and allow personnel to attend training offered by the vendor. More was learned in two days with the vendor than in 10 weeks on our own.
- Secure commitment from above. The implementation process is time and resource intensive and progress sometimes appears to be slow.
- Validate your data and your process at each stage of implementation. "Ground-truth" resulting data as much as possible in the field by comparing office generated data with actual field conditions.
- Keep it as simple as possible.

Related Research

In work related to cracking data collection and reduction, MDSHA did an evaluation in 2002 of the AASHTO protocol on quantifying cracks in asphalt pavement surface (*79*). The work spanned more than a year and consisted of a pilot study of feasibility, a survey to ensure that the results were compatible with expert opinion, and a production study to determine standard utility at the network level. It was concluded that the protocol is suitable for use at the network level. However, the MDSHA process as described previously is not entirely compliant with the AASHTO standard owing to hardware, software, and even policy issues. However, MDSHA engineers deemed their procedure to be "well within the spirit" of the AASHTO protocol.

Conclusion

The MDSHA has done a comprehensive study of the application of the WiseCrax method of pavement cracking identification and classification and finds the procedure to be ready for use on a network basis. The agency concedes that the process must be undertaken deliberately, that personnel must be fully trained through partnering with the equipment provider, and that a full agency commitment is necessary. Conclusions from the Maryland work include the following:

- A rigorous QA process is a must for automated surface distress collection and processing;
- WiseCrax cannot accurately detect cracks on Maryland concrete pavements or bridge decks, generally because the striations in the relatively coarse texture are detected as cracks; and
- A crack recognition level of 80% has been found to be sufficient for network-level surveys.

LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

Introduction

Another agency chosen as a case study is the LADOTD. Essentially all of LADOTD pavement condition data collection and processing are done by contract, a sharp contrast with Maryland. Although the LADOTD has not published a comprehensive study of its work, as Maryland did with the WiseCrax work, the agency has provided extensive operational and contractual data that make up the overall case history.

LADOTD began the current effort concurrent with the release of The Road Information Program (TRIP) report, showing that Louisiana had the second worst pavement conditions in the nation, with 27% of the state's major roads rated as poor (*80*). Although the TRIP report was done for the Louisiana Associated General Contractors, Inc., it relied on FHWA data for its assessment. Although contract and other LADOTD documents do not refer to the TRIP report, there is little question that the agency was under considerable pressure to do its own objective and efficient assessment of pavement conditions. LADOTD issued an RFP in January 2000 and received a proposal from Roadware Group, Inc., on March 7, 2000. The subsequent contract, discussed here, was an outgrowth of that proposal.

General Contract Provisions

The 2001 contract was awarded on October 25 and encompassed 32 000 lane-km (20,000 lane-mi) of comprehensive data collection and analysis. Following a period of experience with the original contract, including some renegotiation of contract provisions and pricing, a supplementary agreement was executed in June 2002. The work covered all nine districts administered by LADOTD. Included were GPS data, digital right-of-way and pavement images, IRI, faulting and rutting measurements, and pavement distress evaluation (*58*). Furthermore, a workstation for agency review of images and validation of distress data was to be provided at an LADOTD office. Other general contract provisions addressed the following:

- A QC program,
- A master progress schedule,
- The collection and processing system configurations, and
- Specific data requirements.

The QC program requires the contractor to administer a plan that will ensure that data are accurately collected and that they reflect the actual pavement condition within specified precisions. The contractor's equipment is checked against an agency profiler and a Class I profiling instrument (Dipstick, etc.) before beginning testing. During production, the contractor is required to use verification sites of known IRI, rutting, and faulting values. These sites are permitted to "roll"; that is, the contractor is not required to use the same sites all the time. Rather, the contractor may, on a given day, test a site that was tested 1 week previously. These reruns are evaluated to determine if the profiler is still in calibration. Such tests are documented in writing and delivered to the agency weekly. This feature is helpful in testing over a widespread area, because extensive backtracking is not necessary to do the verification sites.

The master progress schedule was to address scheduling of data collection over the nine districts beginning within 90 days of the notice to proceed. The contractor was to deliver data for at least one and no more than two districts per month beginning in November 2002, with all nine to be delivered by May 15, 2003. The contract did not address the reason for the two district maximum, but it is presumed to relate to the time required for LADOTD evaluation of deliverables. Liquidated damages of $100 per day were to be assessed for each day that data for the required number of districts were not delivered on time and $500 per day for each day the data for all nine districts were not delivered on time. Finally, damages of $300 per day were to be assessed for each day that the final report was not on time.

Specific sensor data requirements are given in Table 18. Additional requirements were for at least three transverse laser sensors on a bar not to exceed 2.4 m (8 ft) in length for rut depth measurements, for continuous faulting measurements 0.3 to 0.9 m (1 to 3 ft) from the outside edge, and for statistical parameters (averages and standard deviations for both wheel paths) of IRI measurements.

The agreement called for the collection of pavement distress data in accordance with LADOTD protocols (*81,82*) based on the LTPP distress identification manual (*18*). These protocols include the distresses given in Table 19. The maximum and minimum values of each of these distresses are to be determined in Task I of the data collection portion of the contract discussed here.

PCI Data Collection, Quantification, and Reporting

This portion of the contract called for work to be done in four tasks as summarized here:

TABLE 18
LOUISIANA SENSOR DATA COLLECTION REQUIREMENTS (*58*)

Variables	Roughness	Rut Depth	Faulting
Scope	All pavements	Asphalt surfaces	Jointed concrete
Definition	Longitudinal profile, both wheel paths	Rutting of each wheel path	Elevation difference across joint (trailing slab lower)
Sampling	Max., 0.3 m (1 ft)	Max., 3 m (10 ft)	All transverse joints
Calculation and Statistics	IRI, each wheel path and average of both wheel paths	Each transverse profile of both wheel paths, for section report average	Wheel path absolute elevation difference averaged for each joint, for section report average
Units	Inches/mile	Inches [nearest 2.5 mm (0.1 in.)]	Inches [nearest 1 mm (0.04 in.)]
Equipment Configuration	Lasers and accelerometers, both wheel paths	Min., 3 laser sensors	Lasers in right wheel path
Standards	ASTM E950, HPMS Field Manual Class II	None given	None given
Precision and Bias	Max. error of 5% bias or 0.3 m/km (20 in./mi), whichever is less	Contractor to provide	Contractor to provide
Initial Verification	Section comparison of longitudinal profile with Class I profiling instrument and LADOTD's SD laser profiler	Test section comparison with field measurements provided by LADOTD	Test section comparison with field measurements provided by LADOTD
Ongoing Quality Monitoring	QA/QC sections	QA/QC sections	QA/QC sections
Special Requirements	Correct/report low-speed sections; capability of monitoring data collection in real time in the data collection vehicle	Capability of monitoring data collection in real time in the data collection vehicle	Capability of monitoring data collection in real time in the data collection vehicle
Reporting Frequency	0.16 km (0.10 mi)	0.16 km (0.10 mi)	0.16 km (0.10 mi)

TABLE 19
LOUISIANA SURFACE DISTRESSES TO BE COLLECTED

Variable	Asphalt Pavements	Jointed Concrete Pavements	Continuously Reinforced Concrete Pavement
Cracking	Alligator, block, longitudinal, transverse, reflection	Longitudinal, transverse	Longitudinal, transverse
Miscellaneous	Patching, patch deterioration, potholes	Patching, patch deterioration	Patching, patch deterioration, punch-outs

- Task 1—Preliminary activities in which the contractor did additional calibration testing, calibrated raters in identifying and classifying typical distresses, and delivered the LADOTD workstation.
- Task 2—Data collection by district in which clear digital pavement images of all roads were required. These images were required to be location-reference identified to the nearest 0.0016 km (0.001 mi) and to provide resolution sufficient to identify cracks 3 mm (0.125 in.) wide. These images were to be loaded weekly into an approximately four terabyte server provided by the contractor in Task 1. Raw sensor data were also to be included in the Task 2 deliverables. This portion of the contract specified that roadway locations with unacceptable image quality were to undergo data collection again at no additional cost to the agency.
- Task 3—Distress quantification in which distresses were evaluated and reported in 0.16 km (0.10 mi) increments and tied to the LADOTD's location-reference system. LTPP protocols and the Louisiana distress identification manual were specified for this distress data reduction. In that section of the contract, the agency reserved the right to review images and data quantification on the provided workstation and to require the contractor to resolve any problems with the quantified distress data. No specifics of this process are given. The D-Rate procedure discussed in chapter three was to be used for distress quantification.
- Task 4—Final documentation of the project including a summation of the project detailing problems, solutions, and final outcome. Final documentation was also to include a final QC report and a report of proposed and actual schedules of work accomplishment.

Conclusion

The Louisiana contract is ongoing and no assessment of its' success or failure has been released. The LADOTD estimated the cost of delivered data at approximately $32 per km ($54 per mi) and did not note any special problems with the contract in response to the synthesis questionnaire.

Although the responses to the questionnaire provided little information on acceptance criteria, it did in part address the question of data reasonableness. For example, the maximum reporting value for IRI is given at 10 m/km (632 in./m), whereas the minimum for joint faulting is 5 mm (0.20 in.) as provided by the AASHTO provisional standard. Furthermore, discussion with the agency management systems engineer (S.M. Ismail, LADOTD, personal communication, August 2003) revealed that data have been delivered in compliance with contract requirements. Digital images are delivered weekly for the agency to check quality. Once each month, and according to the delivery schedule, the contractor delivers data for one district, including digital images and distress data. The agency has 2 weeks in which to review the delivery. Anything considered not acceptable is rejected, and the contractor must correct the deliverable even if it is necessary to recollect the data.

At least two features of the Louisiana case are worthy of additional comment. The first is the use of rolling sensor data calibration sites, the concept being that a site production tested one week may be tested as a calibration check the following week. Use of the rolling site does not replace a calibration requirement; rather, it is intended as a screening activity to determine if a recalibration is needed. In view of the large systems managed by some agencies, this approach may be a reasonable interim QM tool.

A second feature is the provision for the definition of maximum and minimum values of distress data items during the preliminary phase of the contract. This type of requirement is not unusual, and points to the lack of solid pavement databases reflecting typical data variabilities and extreme values. The issue is very much related to the broader issue of how pavement data items can and should be characterized. As found throughout the development of this synthesis, there is a great need for a focused study of pavement data items to determine typical variabilities such that defensible contract provisions, especially in the QA area, can be developed.

MISSISSIPPI DEPARTMENT OF TRANSPORTATION

Introduction

MDOT was chosen as the third case study, where data collection and processing activities are done by a vendor, but with specific protocols provided by the agency. Whereas both of the previous case studies depended on equipment and processes provided by one vendor, this third case represents the use of a competing vendor. Mississippi provided contractual and procedural attachments in responding to the synthesis questionnaire.

Background for the Mississippi work is provided by the pavement management overview given in a research report found on the agency's website (*83*). In 1986, MDOT contracted with the University of Mississippi to implement a pilot pavement management system in one district. Included was a rudimentary database containing distress and roughness data for the entire state-maintained system for the district. Later, the products of the university-developed pilot were used by MDOT to establish a statewide pavement management system. At that time, the database was expanded to include location reference, lane widths, roadway lengths, county and route information, and inventory and historical information (original construction as well as overlays). Presently, a contractor collects data every 2 years to assess the overall condition of the state's highways. Data collected include the IRI, a pavement condition rating (PCR), rut depth, joint faulting, and texture. Cracking, potholes, patching, punch-outs, and joint deterioration data are collected on two 150-m (500-ft)-long samples per mile within each analysis section.

Data Collection

A contractor has collected pavement condition data in Mississippi every 2 years since 1991 (*83*). GPS receivers collect coordinate data on laser-equipped profilers, collecting pavement profile data that are used to generate IRI, rutting, and faulting values. Roughness, rutting, and faulting data are collected on 100% of the state-maintained system and on the HPMS roadways in the state. The vans also carry five video cameras used to capture images of the shoulders, wheel paths, and front perspective views. Images of the pavement surface require a minimum shutter speed of 4,000 frames per second that will provide clear, crisp resolution for distress analysis purposes.

The present contract provides for the collection of inventory videologging and longitudinal profiling of approximately 34 700 km (21,700 mi) of state-maintained and non-state-maintained roadway (*84*). The non-state-maintained roadways inventoried are part of the state's HPMS mileage, and the contract serves as a means of meeting FHWA requirements for reporting on those roadways. Data are obtained from the outside lane in both directions for divided highways and in an easterly or northerly direction for undivided highways.

Sensor data are collected for 100% of the length of highways being surveyed at a maximum sampling frequency of 25 cm (10 in.). A South Dakota-type profiler equipped with three laser height sensors and real-time graphical display is required for sensor data collection. The agency does not specify rut-measuring methodology, but it reserves the right of approval of sensor orientation before the start of work.

The contractor is required to maintain a library of field data tapes in a fireproof enclosure until completion of the contract, when they will be provided to the agency. An additional set is furnished to the agency as soon as available. The agency provides the contractor with established file formats for the capture of all data items. These formats must be adhered to by the contractor, but they may be supplemented with additional files as needed by the contractor.

Data Review and Processing

In addition to providing sensor data for the 8100 km (13,000 mi) of state-maintained roadways, the contractor provides distress data reduction from the interpretation of digital images. The various distresses applicable to each pavement type are separately evaluated for location, severity, and extent. Although either automated or manual processing is acceptable, the contract stated, "automated distress interpretation shall require, as a minimum, ninety-five (95) percent reliability and must have prior written approval by the COMMISSION before use." Without stating a methodology, the contract indicated that "the COMMISSION reserves the exclusive right to make the determination of whether an automated distress interpretation scheme attains the ninety-five (95) percent reliability level" (*84*).

In the execution of the current contract, the data reduction process involves having individuals identify the various distresses from digitized video images; that is, a manual method is used. In this process, images are digitized at a frequency of approximately one every 15 m (50 ft). A distress evaluation whereby cracks, potholes, punch-outs, etc., are measured is then performed on the digitized images. The sampling technique used ensures that approximately 20% coverage of the state-maintained system is achieved in the distress evaluation.

Quality Control and Quality Assurance

The Mississippi data collection contract (*84*) provides that an overall QC plan for the verification of the accuracy of reduced data shall be presented for agency review and approval before the start of field surveys. Additional requirements were that the contractor shall provide accuracy and precision data from previous work and that the QC plan address both roughness and distress data.

In the current contract, QC procedures consist of vendor units traversing approved calibration sites in the district where work is ongoing (*84*). Such sites are strategically located in the districts. To develop a baseline for the district, any vendor unit must test all sites before beginning data collection. Agency IRI, rutting, and faulting statistics for the calibration sites are derived from manual data using an agency South Dakota profiler, a rut bar, and the Georgia Faultmeter, respectively.

After initial approval in a district, each unit is required to make a traverse of one calibration site before the beginning of data collection for each day. Precision thresholds for sensor-collected data for each traverse are

IRI = ±0.30 mm/m (±19 in./mi),
rutting = ±0.23 cm (±0.09 in.), and
faulting = ±0.18 cm (±0.07 in.).

The procedure agreed to by the contractor and the agency is to disregard any data between an unacceptable calibration site traverse and the previous acceptable traverse. Because of the daily traverse requirement, no more than 1 day's work should be lost through this procedure.

Agency review of distress data basically involves an individual positioned at a video workstation who conducts a QA on randomly selected samples. A 5% sampling of each pavement type and of all one-half mile or shorter sections are examined (*85*). Distresses checked are cracking, potholes, spalling, and punch-outs. The LTPP *Distress Identification Manual* (*18*) is used as the standard for type and severity of distress levels.

At this time, the agency does not provide written acceptance criteria for distress data determined from image evaluation. Instead, there is a contract provision stating, "It is understood that the work required of the CONSULTANT under this contract shall meet the normal standards of the state-of-the-art and state-of-the-practice for distress and roughness information and shall be performed to the satisfaction and approval of the COMMISSION." Because those standards are not spelled out, it is likely that the state would use more specific acceptance criteria if databases to support appropriate limits and variabilities of data existed.

Data Reporting

The state requires Excel spreadsheets for the overall PCR, the distress rating, and the roughness rating for each section by district. Excel files that list and quantify incremental distresses in each section with location, severity, and extent also are required. The format for those files is given in the contract.

Conclusion

MDOT is implementing a comprehensive PMS that requires the data described in this case study. The agency has taken great strides in just a few years to meet its data needs through contracted data collection and processing. Although the reduction of pavement distresses from pavement images is not yet automated in practice for the state, such automation is desired and is a contract option at this time. The agency requires the contractor to develop and execute a QC plan while the state exercises some degree of QA on the delivered data. However, data acceptance procedures are not clearly spelled out in the current contract, suggesting that there is a need for additional research in the QC/QA area.

Mississippi uses pavement condition data to compute three indices: roughness rating, distress number, and general PCR consisting of a combination of roughness and surface distress. The focus of the data is at the network level, so that the data are used primarily to show the condition of the system as a whole or of a particular class of roads. Data are also used to monitor performance of pavements over time and for long-term budgeting. Other uses include life-cycle cost analyses of various pavement types and of pavement rehabilitation and maintenance treatments. The data are sometimes used at the project level, but mainly as a tool to plan projects and evaluate performance to more efficiently expend allocated funds.

Two other important uses of pavement condition data identified by the agency are the following (*83*):

1. MDOT has let its first warranty job contract, which was aided by pavement management data. Standards for job acceptance based on pavement condition were developed, and a CD-ROM was made showing typical distress features and severity levels. This CD-ROM will be used to illustrate to contractors what is and is not acceptable for warranty jobs in the future.
2. The chief engineer uses PMS data to show how pavement condition declines over time if maintenance is not done, to request funding for the state's four-lane system. In that way, PMS data support the concept of pavements being a long-term investment.

SUMMARY

The three case histories on automated pavement data collection and processing show that various agencies approach the matter in very different ways. Maryland prefers to do all collection and processing in-house, whereas Louisiana has similar work done totally by a vendor. Mississippi also has most of the work done by a vendor, but it uses different procedures and software.

One of the contrasts between Maryland and the other two agencies is the enormous amount of work that Maryland has put into the maturing of the processes in the state. It has taken the state years (since 1995 with the current equipment) to grow the technologies to where it is now very confident of the data received, provided that a rigorous QA program is used. It is reasonable to anticipate that other agencies can learn much from the Maryland experience. It is also reasonable to expect that the other two agencies highlighted are fairly early in the learning process. Although Louisiana has a QA process in place, it does not have a great deal of experience with how it works, although it has invoked some contractor penalties. Mississippi is developing its QA program as it proceeds with the work. The agency also has not developed a set of specifications on deliverables. It is depending heavily on the vendor to provide high-quality data in a timely manner. Only time and experience will determine if experiences in Louisiana and Mississippi will be as positive as that of Maryland.

CHAPTER NINE

ART VERSUS PRACTICE

This chapter addresses the state of the art versus the state of the practice for automated pavement distress collection techniques. The distinction is important because of the real and perceived differences in what is achievable and what is being achieved in the areas within the scope of this synthesis. Clearly, many of those differences are because the applicable technologies are rapidly evolving and will continue to do so for the foreseeable future. This chapter attempts to capture the sense of how that evolution is taking place and how it will continue. Several conclusions point out technical areas where it might be advantageous for user agencies or vendors to move closer to the state of the art.

PAVEMENT IMAGING

It is likely that the area of pavement imaging and the interpretation of those images present the largest gap between art and practice. It is clear that much of the work going on in research studies show the great potential of automated real-time collection of pavement surface distress (cracking, etc.) data. However, many of the agencies using the applicable technologies at the time the project questionnaire was circulated did not have great confidence in the quality of the data collected, processed, and delivered to them by either vendors or by agency personnel. Therefore, it is safe to say that there is a relatively wide gap between art and practice for image-related data.

One of the reasons for an apparent reluctance to accept data at face value may be the relative dearth of workable and accepted QA procedures. Although such procedures were discussed earlier and some are in use, it is evident that much more needs to be done. The research must be conducted before it will be possible for data collection and processing protocols to contain the appropriate QA requirements and guidelines. Until then, there may be little hope of significantly narrowing the gap between art and practice for those data.

Another area requiring further development is in the achievement of truly acceptable pavement images from equipment operating at highway speeds. Although some vendors and some agency-owned equipment appear to deliver adequate images under some conditions, it can be noted that those conditions too often do not prevail, such that the images delivered are at best borderline in quality. The result is that users again do not have confidence in the data derived from those images.

One limitation of the current state of digital imaging and automated processing of distresses is in the area of shadows on images. In the absence of special lighting to reduce shadows, it is very difficult to obtain usable images under many conditions, such as shady roadways and in the presence of vehicle-cast shadows. Another limitation is with coarse-textured surfaces such as chip-sealed surfaces, tined surfaces, and sealed cracks. Although researchers are confident that high-resolution images will overcome this limitation, the art has not yet been developed.

The whole area of laser imaging, essentially 3-D profiling of the pavement surface, is an emerging technology that will require some maturing before it comes into practical use. At present, the limitation appears to be in the resolution that is reported by some to be too low for effective crack detection (*20*).

SENSOR-RELATED DATA

There is a wide variation in how art and practice relate with regard to sensor data, depending on the data item considered. The separate items are discussed briefly here.

Roughness

For roughness, there appears to be little gap between art and practice. No doubt this relates to an emphasis placed on IRI determination by the HPMS program, requiring agencies to test the National Highway System at least every other year. That emphasis means that all agencies are doing at least longitudinal profile testing. The need for more equipment and faster delivery of IRI data has caused equipment manufacturers and vendors to place greater emphasis on updating their equipment. As a result, almost all are using the fastest sensors (high-speed lasers) available and the supporting hardware and software. The absence of agency resources to do roughness monitoring with older equipment has led almost all agencies to either purchase or hire the latest equipment as it becomes available.

Rut-Depth Measurement

An entirely different matter prevails with rut-depth measurement, where there is a broad gap between the practice and the art as propounded by vendors. As discussed in chapters two and six, there is a wide variation in how agencies are specifying rut-depth measurement. Protocols in use provide for from 3 to 37 points of measurement along the transverse profile and a wide variation of how the data are to be used to determine rut depth. One researcher (*38*) makes a case for using at least nine sensors to determine rutting, whereas at least two vendors are promoting transverse scanning lasers capable of providing thousands of incremental measurements on that transverse profile (*26,40*). Presumably, that wealth of data would permit an extremely accurate determination of rut depth at almost any longitudinal frequency desired. However, the protocols to do that type of measurement still need to be developed. The gap here will remain broad until such protocols are available.

Joint-Faulting Measurements

The automation of joint-faulting measurements has attracted so little attention that there is virtually no agreement on what is required. Although there is a provisional AASHTO standard, very few agencies report its use, because most simply take what vendors provide or use protocols suggested by vendors. The result is that there really is little definition of either art or practice. That situation will prevail until someone undertakes to clarify what is really needed to do automated joint-faulting measurements.

Slab Warping and Curling

Areas related to joint faulting are warping and curling of concrete pavement slabs. Although no agency mentioned these concerns in survey responses, the FHWA has a project underway to apply inertial profiling as the measuring tool in a major warping and curling research study (*86*). The FHWA cites recent advances in inertial profiling technology developed at FHWA's Turner–Fairbank Highway Research Center and advances in computer technology as making it possible to reliably measure the shape of very large numbers of PCC pavement slabs over a short period of time and to perform analyses of these data. Products of the research would include written and computer-based guidelines that will focus on the effects that design and construction decisions will have on slab curvature and ultimate long-term performance. Successful completion of such a project would no doubt stimulate agency interest in applying similar technologies.

AASHTO PAVEMENT DATA COLLECTION PROVISIONAL STANDARDS

Many respondents to the questionnaire professed to no knowledge of the AASHTO provisional standards. Several even asked for copies or a web address where the standards might be accessed. It is not clear whether this situation reflects breakdowns in internal agency communications or a problem at the national level. On the other hand, discussion revealed that at least the roughness standard is being widely used, but it is often given some other designation such as SHRP, LTPP, or ASTM.

Only four agencies reported using the AASHTO cracking standard or some modification thereof (see Table B1 in Appendix B). The reason most often given for not using it relates to banks of legacy data that agencies fear might no longer be useful if too many changes in the collection standards are adopted. C. Grogan, pavement management engineer, MDOT (personal communication, August 2003), provided this perspective:

> We are not using the AASHTO provisional protocols at this time since we have been adhering to the SHRP Manual and feel that this meets our needs. Also, there is the problem of converting legacy data, at which task we spent years getting it into our present information system, TMIS (Transportation Management Information System), which is a custom-built data warehouse application that includes a pavement management subsystem. We are also trying to get our Pavement Analysis Package (PAP), which is an optimization program, up and running. More historical data conversion would involve huge coding changes to TMIS, and would keep us from moving forward toward more actual use of the data. We also like the specific nature of the SHRP Manual interpretation of distress.

Some agencies reported using AASHTO provisional standards with local modifications. For example, Wang et al. (*87*) described a crack detection protocol developed for the Arkansas State Highway and Transportation Department based primarily on the AASHTO provisional standard. Changes were in the definitions of transverse and longitudinal cracking to meet Arkansas needs. Again, Maryland (*78*) described its crack detection process as not totally compliant with but "well within the spirit" of the AASHTO provisional standard

On the other hand, many agencies appear to use the roughness standard or something very closely related (see Table B2 in Appendix B). Twelve agencies listed the AASHTO standard, while 19 cited either ASTM, FHWA, or LTPP guidelines. Although these results suggest that there is not a firm understanding of the standard and its origins, again they probably reflect a natural outgrowth of HPMS requirements and the accompanying ASTM standards.

As discussed, there is little real agreement on what is really required for either rut-depth or joint-faulting measurements. Although several agencies listed the AASHTO standard for rut-depth determinations, most either left the question blank or cited a vendor or agency protocol for joint faulting (see Appendix B, Tables B3 and B4). It is unlikely that AASHTO provisional standards will be put to much use until a better understanding of the automation issues has evolved.

SUMMARY

The issue of state of the art versus state of the practice for automated pavement condition data collection and processing is cause for concern. Although there appears to be little gap in roughness measurement, there is a significant one for both cracking and for rut-depth measurement. For joint-faulting measurements, the automation issues are not well enough defined to determine either the state of the art or state of the practice.

It is unlikely that the AASHTO provisional standards will be put to widespread use for other than roughness monitoring until some of the issues discussed in art versus practice are resolved.

CHAPTER TEN

CONCLUSIONS

Questionnaire responses in conjunction with the related literature permitted the identification of several problems common to a number of the agencies practicing automated distress data collection. Although not all problems are serious, all have caused at least some loss of productivity in data capture or processing, or some compromise in the quality of data collected or in the final results obtained from collection and processing combined.

The whole process of automated distress data reduction from images is evolving and is extremely complex, with significant technical demands, from the points of view of both equipment and personnel. Major issues have been the inability to reliably identify certain distresses, the resolution of cracking (the size of crack identifiable), and the rate of production of high-quality information. As well, real-time, onboard, distress data processing often cannot be carried out at anywhere near the speeds of prevailing traffic, although the collection process can take place at those traffic speeds.

Shadows on images are a significant problem for both manual and automated processing of surface distresses from images. Shadows make it very difficult to discern distresses in the shadowed area, and if such areas are large and frequent, they can significantly affect the results of both extent and severity determinations for a given roadway. Some agencies and vendors use lighted cameras to overcome the shadowing problem, especially on rural roads with narrow rights-of-way and where surrounding foliage and other factors are a problem. Furthermore, the survey vehicle and camera layout must be configured properly to minimize shadows from the vehicle itself. Even under the best of other conditions, the position of the sun may make satisfactory imaging without strobe lights almost impossible.

There is very little consensus on the methodology of automated rut-depth measurement except that the more sensors used the better the results. The AASHTO provisional standard provides for a minimum of five sensors, although a number of agencies still use three. On the other hand, one researcher is promoting at least nine. Some of the vendors have moved to 37 sensors, whereas some are promoting more than 1,000 data points collected by a scanning laser. Automated rut-depth measurement is an area needing additional research to arrive at an optimum testing scheme and protocols.

Automated joint-faulting measurement is an area that has not been addressed by many agencies. That is demonstrated by the relatively few agencies actually collecting the data through automated means. Some of those that do use automated means profess to have little confidence in the data collected. If others collect the data at all, most are using manual methods, such as simple straightedges or the Georgia Faultmeter. Although the faultmeter appears to have a good reputation among users, its greatest disadvantages are that it is still manual, extremely time consuming, and primarily limited to project-level work. Again, there is need for a serious look at how to proceed with automated joint-faulting measurements.

Closely related to all of the perceived problems are the AASHTO Provisional Standards on Pavement Data Collection. There appears to be sufficient adoption of the roughness measurement standard and considerable interest in the one on rut-depth measurement. In the latter case, the community needs to decide what is needed before a realistic standard can be devised. Both the cracking and joint-faulting standards are similar to that for rut depth, for there is not much agreement on what is needed. However, the cracking standard has an additional problem in that agencies have existing databases built on agency protocols and comprising pavement performance histories. Because the agencies often do not want to abolish the old databases they are reluctant to adopt a new protocol. A few are incorporating the AASHTO standards into agency standards.

Several areas in the field of automated distress data collection could be the subject of further research.

First, with the exception of the International Roughness Index, there is clearly a need for further work with data collection protocols. The current generation of cracking, rut-depth measurement, and joint-faulting standards was developed primarily for a manual testing environment and later revised to apply to automated data collection. User agencies are not readily adopting those standards.

A study should examine AASHTO, ASTM, and other standards to determine their applicability to the rapidly evolving field of automated collection. Such a study could further examine the reasons that agencies are hesitant to adopt existing standards and identify what changes would promote adoption. The impact on legacy data would be expected to be a major issue in any changes. The expected results would include recommendations of necessary revisions, including the means of consolidating various standards. Another element of data collection standards needing some attention is in the area of portland cement concrete pavements. There appear to be few standards in use for those pavements, although they constitute a significant portion of the highway inventory.

Several methods of reducing pavement surface distress (principally cracking and patching) from analog or digital images are currently in use. These have been developed and are being implemented by industry or academia. A research study could examine the relevant technologies, identify the features needing standardization, and provide recommendations on the development of appropriate standards. Processing standards themselves would be developed under a separate project as needed.

In addition, survey results show that there is an urgent need for the development of quality management programs for automated pavement data collection and processing. Some agencies, especially those in Canada, have made significant progress in developing quality management programs and procedures, whereas others depend totally on vendors to provide the quality of data needed. That level of quality itself is not well defined except in very general terms, such as requiring that the data to be of sufficient quality to feed pavement management program algorithms.

TRB Committee A2B06, Pavement Monitoring, Evaluation and Data Storage, has recognized the need for a research project to address data quality management. The committee developed a research needs statement with the objective of establishing guidelines that highway agencies can use to develop or improve their quality management practices for contract pavement distress data collection. The guidelines should include the following:

- Recommendations on appropriate levels of accuracy, precision, and resolution, as well as how an agency can determine these values for its local pavement management system decision process;
- Required elements of a contractor's quality control plan;
- How to structure the highway agency's quality assurance program;
- Ways to evaluate and select contractors;
- Appropriate uses of qualification test sections for contractor selection, certification, and quality assurance;
- How to compare and evaluate vendor test measurements against reference values;
- How to measure contractor performance;
- Appropriate award and penalty structures for contractor performance;
- Progressive data delivery schedules to permit ongoing assessment during the contract period so that corrections can be made;
- When to terminate a contract for poor performance;
- The magnitude of agency resources required for alternate quality management approaches; and
- Pitfalls to avoid in development of requests for contractor services.

Additional study could address the inherent variabilities of the processes, including the sources of those variabilities. There are several critical elements that could be captured and quantified to facilitate the development of better standards and contract provisions including:

- Surface distress measurement variability—How repeatable are the various manual, semi-automated, and automated means of data reduction?
- How repeatable are the sensor measurements of rut depth and joint faulting?
- What are the sources of variability of such aspects? For example, with image-collected data, how much of the variability is associated with imaging, how much with manual and automated means of data reduction, and how much with data manipulation and computation? Also, are there other sources of variability? If image-reduced data are to be compared with manually collected data, what are the variability properties of those data and how well should the two types of data compare? Similar questions could be asked for the sensor-collected data.

Agencies wishing to use automated data collection and processing have many choices to review and decisions to make. Development of a "toolbox" addressing those choices is an important research need. Such a toolbox would address the various issues, what factors to consider, and the potential tools to address those issues. It is expected that the toolbox would contain information on hardware, software, and procedures for both the collection and processing of pavement condition data, including that collected from images and from sensors. The toolbox would also be expected to contain information on the establishment and implementation of rudimentary data quality management of pavement conditions.

In addition, there is an overall need for the development of standards for pavement distress data. Although there are numerous data formats and handling procedures in use in the pavement data collection arena, nothing has been standardized. This means that essentially every vendor can use different formats and procedures and that customers and others can be at a loss as to how a given data system works. Standards would offer another tool that agencies and others could use in the development of data procurement contracts. It would be much easier to specify that a data management system meet a certain standard than as is now done with spelling out specific formats, equipment, etc. Another important justification for data standards is to provide for data documentation to ensure against the loss of data utility whenever key personnel are no longer available.

Finally, the general term applied to information about data is "metadata," or data about data. Simply put, metadata are the background information that describe the content, quality, condition, and other appropriate characteristics of the data. It is expected that the standards developed would address at least data format, data storage, data access, data transfer, and data documentation. It is further expected that the standards would address data at both the systemwide and elementary levels. Examples are analysis models for crack detection and classification, and linear referencing of image location, respectively.

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GLOSSARY

Where applicable, sources are provided (in parentheses) from the references used in this synthesis report.

Alligator cracking—See fatigue cracking.

Crack—Fissure or discontinuity in the pavement surface not necessarily extending through the entire thickness of the pavement (*63*).

Digital image—Image that is stored in numerical form.

Digitize—Process of converting analog images to digital.

Fatigue cracking—Series of small, jagged, interconnecting cracks caused by the failure of the asphalt concrete surface under repeated traffic loading (also called alligator cracking) (*11*).

Fault—Difference in elevation between opposing sides of a joint or crack (*11*).

Flexible pavement—Pavement structure that maintains intimate contact with and distributes loads to the subgrade and that depends on aggregate interlock, particle friction, and cohesion for stability.

Global Positioning System (GPS)—Worldwide radio navigation system formed from a constellation of 24 satellites and their ground stations.

International Roughness Index (IRI)—Pavement roughness index computed from a longitudinal profile measurement using a quarter-car simulation at a simulation speed of 50 mph (80 km/h) (*63*).

JPEG—Joint Photographic Experts Group standard for compressing data.

Longitudinal cracking—Cracks in the pavement predominantly parallel to the direction of traffic (*63*).

Longitudinal profile—Perpendicular deviations of the pavement surface from an established reference parallel to the lane direction, usually measured in the wheel tracks (*63*).

Mile point—Location reference used in highway work, usually expressed as a logged mileage along a specific route from a political boundary or roadway intersection.

Mile post—Physical marker of a mile point.

Network-level data—Data supporting pavement management decisions on a roadway network or system basis.

Patch—Portion of pavement surface that has been replaced or additional material that has been applied to the pavement after original construction (*63*).

Pavement condition—Qualitative representation of distress in pavement at a given point in time (*63*).

Pavement distress—External indications of pavement defects or deterioration (*63*).

Pavement performance—Ability of a pavement to fulfill its purpose over time (*63*).

Photologging—Process of capturing roadway or pavement images by photographic methods.

Present serviceability—Current condition of a pavement (traveled surface) as perceived by the traveling public (*63*).

Profiler—Equipment used to measure the profile of the traveled surface.

Profilometer—Equipment used to measure traveled surface roughness (*63*).

Project-level data—Data supporting pavement management decisions on a discrete project or roadway segment basis.

Rideability—Subjective judgment of the comparative discomfort induced by traveling over a specific section of highway pavement in a vehicle (*63*).

Roughness—Deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics and ride quality.

Rutting—Longitudinal surface depressions in the wheel paths (*11*).

Transverse cracking—Cracks in the pavement that are predominantly perpendicular to the direction of traffic (*63*).

Transverse profile—Vertical deviations of the pavement surface from a horizontal reference perpendicular to the lane direction (*63*).

Wheel track—Line or path followed by the tire of a road vehicle on a traveled surface (*63*).

WEBSITE DIRECTORY

Amskan Ltd.—www.amskan.com
  SPIRIT laser profilometry equipment
CGH Pavement Engineering, Inc.—www.cgh-pavement.com
(Now a division of ARA/ERES)
  Laser profilers
Dynatest Consulting, Inc.—www.dynatest.com
  Dynatest Model 5051 Mk II RSP—Road surface profiler
GEO-3D, Inc.—www.Geo-3D.com
  Geographic Information Technologies software and services
GIE Technologies—www.gietech.com/
  Lasers, 3-D measurement of pavements
IMS-Terracon—www.ims-terracon.com
  Pavement management programs
INO—www.ino.ca
  Laser systems, digital systems
International Cybernetics—
  www.internationalcybernetics.com/
  Laser profiler, evaluation software
LMI Selcom—www.lmint.com
  Laser sensor suppliers
Mandli—www.mandli.com
  Digital imaging, digilog scanning
MHM Associates, Inc.—www.mhmassociates.com
  Automated Road Image Analyzer—ARIA
Pathway Services, Inc.—www.pathwayservices.com
  Pathrunner profiler, digital video logging, distress data processing, sign, signal, guardrail inventory
Phoenix Scientific Inc.—www.phnx-sci.com
  Scanning lasers, 3-D measurement of pavements
Roadware—www.roadware.com/
  Automatic Road Analyzer (ARAN)
  WiseCrax (WX) crack recognition software
ROMDAS—www.romdas.com
  Profiling and video imaging
Surface Systems and Instruments—www.smoothroad.com
  Laser profiler

APPENDIX A

Survey Questionnaire

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

AUTOMATED PAVEMENT DISTRESS COLLECTION TECHNIQUES

QUESTIONNAIRE

You are being asked to help in developing a synthesis on Automated Pavement Distress Collection Techniques by providing information on your agency. We are confident that the synthesis will become a valuable resource document for you and others contemplating the collection and management of pavement condition data. The synthesis will focus on automated pavement condition collection techniques, specifically for pavement cracking, roughness, rutting, and faulting. The objective is to document how agencies conduct automated data acquisition and processing. This questionnaire has been simplified to the extent possible given the nature of the material. In some instances it may be best that the consultant, Ken McGhee, talk with individuals within your agency. For that reason, there are several cases where you are asked to provide additional contacts, if appropriate. In other instances, copies of protocols, standard operating procedures, contracts, or other documents may be the best response, and the questionnaire often suggests that option. Please call or e-mail the consultant if you have trouble with the questionnaire. The consultant will call or e-mail you if he needs additional information.

Respondent Information

Please provide the information requested below for the person completing this questionnaire (if you received the questionnaire and someone else is in a better position to respond, please forward the document to that person).

Agency: ____________________
Name: ____________________
Title: ____________________
Street address: ____________________
City: ____________________
State: ____________________
Zip code: ____________________
Telephone: ____________________
Fax: ____________________
E-mail: ____________________

Return Information

Please return the completed questionnaire by e-mail, fax, or by land mail with any supporting documents by February 10, 2003 to:

Kenneth H. McGhee
HCR 05, Box 100
Madison, VA 22727
Telephone: 540-948-4754 Fax: 540-948-3101
E-mail: khmcghee@ns.gemlink.com

PART I—PRELIMINARY QUESTIONS

1. Does your agency collect pavement distress data? [Includes any of the following: surface distress (cracking), pavement ride quality (IRI), pavement rutting, or joint faulting.]

   Yes ☐ No ☐

   If the answer is "Yes," please proceed to the next question. If the answer is "No," please return the questionnaire as directed above and thank you for your time.

2. Does your agency use or plan to soon use automated pavement distress collection technologies? (For the purposes of this questionnaire, automated is defined as data collected by imaging or by non-contact sensor equipment.)

   Yes ☐ No ☐ Soon ☐

   If the answer is "Yes," please proceed to Part II. If the answer is "No," please return the questionnaire as directed above and thank you for your time. If the answer is soon, please proceed to the next question.

3. The agency plans to implement automated pavement condition data collection within the following time frames (please check):

   Distress data <1 year ☐, 1–2 years ☐, 2–5 years ☐, >5 years ☐

   Smoothness <1 year ☐, 1–2 years ☐, 2–5 years ☐, >5 years ☐

   Rut depth <1 year ☐, 1–2 years ☐, 2–5 years ☐, >5 years ☐

   Joint faulting <1 year ☐, 1–2 years ☐, 2–5 years ☐, >5 years ☐

   Please return the questionnaire as directed above and thank you for your time.

PART II—DETAILED AGENCY RESPONSE

Please check the appropriate response or provide a written description as needed.

1. Surface distresses (cracking, etc.)

   a. Methodology used to collect surface distress data:
   Manual ☐
   Film ☐
   Video ☐
   Digital imaging
      Line scan ☐
      Full image ☐
   Protocol/SOP used: AASHTO, ASTM, FHWA, agency, etc. (If agency-specific protocols are used, please attach or e-mail copies.)

   b. Location—Referencing used:
   Mile post ☐
   Link-node ☐
   GPS coordinates ☐
   Other ☐ Brief description or attach protocol/SOP

   c. Monitoring frequency (months):

   d. Sampling techniques/frequency (1/10 mi, 1 km, etc.; please describe, cite protocol, or attach protocol).

e. Data management (please describe data management procedures including type of data capture and storage media; e.g., optical disks, hard drives, tapes, etc.).

f. Data processing (reduction of distress data, especially from images):
Manual ☐
Automated ☐
If automated, please describe technology.

g. Are distress data collected by
Agency personnel ☐
Contractor ☐
Both ☐

h. Costs of automated surface distress data collection and processing.
Collection: Units Cost $ (Not known) ☐
Processing: Units Cost $ (Not known) ☐
Total (if not separated): Units Cost $ (Not known) ☐

2. Smoothness

a. Smoothness (IRI) data are collected (please check):
Concurrent with surface distress data ☐
Separately ☐
By agency personnel ☐
By contract ☐
By both agency and contract ☐
Not at all ☐

b. Methodology used to collect smoothness (IRI) data:
Lasers ☐
Ultrasonics ☐
Other ☐ Please describe:

c. Wheel path collected: Left ☐ Right ☐ Both ☐

d. Location—Referencing used
Mile post ☐
Link-node ☐
GPS coordinates ☐
Other ☐ Brief description or attach protocol/SOP

e. Monitoring frequency (months):

f. Sampling techniques/frequency (1/10 mi, 1 km, etc.; please describe, cite protocol, or attach protocol).

g. Data management (please describe data management procedures including type of data capture and storage media; e.g., optical disks, hard drives, tapes, etc.).

h. Costs of smoothness data collection: Units: Cost: $ (Not known) ☐

Describe or list IRI protocol used:
(If agency specific protocols are used, please attach or e-mail copies.)

3. Rut Depth

a. Rut-depth measurements are made (please check):
Concurrent with surface distress data ☐
Concurrent with smoothness data ☐

Separately ☐
By agency personnel ☐
By contract ☐
By both agency and contract ☐
Not at all ☐

b. Methodology of rut-depth measurements (please check):
Three sensor ☐ Sensor type: Laser ☐
Five sensor ☐ Ultrasonic ☐
Multiple sensor (>5) ☐ Please describe:
Other technology ☐ Please describe:

c. Location—Referencing used
Mile post ☐
Link-node ☐
GPS coordinates ☐
Other ☐ Brief description or attach protocol/SOP

d. Monitoring frequency (months):

e. Sampling techniques/frequency (1/10 mi, 1 km, etc.; please describe, cite protocol, or attach protocol).

f. Data management (please describe data management procedures including type of data capture and storage media; e.g., optical disks, hard drives, tapes, etc.):

g. Costs of rut-depth measurements: Units: Cost: $ (Not known) ☐

Describe or list rut-depth protocol used:
(If agency specific protocols are used, please attach or e-mail copies.)

4. Joint Faulting

a. Joint-faulting measurements are made (please check):
Concurrent with surface distress data ☐
Concurrent with smoothness data ☐
Separately ☐
By agency personnel ☐
By contract ☐
By both agency and contract ☐
Not at all ☐

b. Methodology of joint-faulting measurements (please check):
Sensor ☐
Other technology ☐ Please describe:

c. Location—Referencing used
Mile post ☐
Link-node ☐
GPS coordinates ☐
Other ☐ Brief description or attach protocol/SOP

d. Monitoring frequency (months):

e. Sampling techniques/frequency (1/10 mi, 1 km, etc.; please describe, cite protocol, or attach protocol).

f. Data management (please describe data management procedures including type of data capture and storage media; e.g., optical disks, hard drives, tapes, etc.):

g. Costs of joint-faulting measurements: Units: Cost: $ (Not known) ☐

Describe or list joint faulting protocol used:
(If agency specific protocols are used, please attach or e-mail copies.)

5. Peripheral Data (right-of-way images, sign inventory, other items)

a. Are peripheral data collected concurrent with surface distress data, i.e., in a single pass?

Yes ☐ No ☐

b. Types of data collected (check):
Right-of-way images ☐
Sign inventory ☐
Drainage inventory ☐
Other inventory ☐
Please describe:

c. Methodology of peripheral data collection (please check):
Additional cameras ☐ Please describe:
Other technology ☐ Please describe:

Describe or list any protocols used:
(If agency specific protocols are used, please attach or e-mail copies.)

6. Contracting Procedures

a. Contracts are awarded on what basis?
Request for qualifications ☐
Request for proposal ☐
Advertised contract (bids) ☐
Other ☐ Please describe:

b. Do contracts contain warranty provisions? Yes ☐ No ☐ If "Yes," please briefly describe:

c. Please describe or attach typical contract documents if possible.

d. Typical contract time period is: years.

Typical bid items (images, IRI, rut measurements, etc.), please list with typical quantities or attach typical contract documents:

e. Are there quality control/quality assurance provisions in contracts? Yes ☐ No ☐

f. Are there price adjustment clauses for timely/untimely deliveries? Yes ☐ No ☐

If "Yes," please briefly describe price adjustment procedures:

7. Quality Control/Assurance

Distress data verification: Frequency: days
Method—Test sites ☐
Standard images ☐
Other ☐ Please explain:

Profiler verification: Frequency: days
Method—Test sites ☐
Vehicle internal ☐
Other ☐ Please explain:

DMI calibration Frequency: days
Method—Test sites ☐
Internal ☐
Other ☐ Please explain:

8. Benefits/Advantages of Automated Processes

Please provide any available documentation of benefits or advantages your agency has found with automated distress data collection and/or processing. For example, please provide information on any cost–benefit studies done either on agency-owned equipment or in comparing agency to contracted work.

9. Other Issues—Problems Identified

a. Please provide any available documentation of major problems identified by your agency with regard to automated distress data collection and/or processing.

b. Has your agency been able to resolve most problems with automated data collection?
Yes ☐ No ☐

c. Please comment on any major changes foreseen for the agency in the area of automated pavement data collection (attachments are welcomed).

10. Other Contact Persons

If applicable, please identify other persons within your agency who might be good sources of information on:

a. Contract issues: Name:

Phone:

E-mail:

b. Quality control/quality assurance:

Name:

Phone:

E-mail:

c. Cost of automated data collection and processing:

Name:

Phone:

E-mail:

We appreciate the time you have taken to provide this information and thank you very much for your help with this important undertaking.

APPENDIX B

Responses to Survey Questionnaire

Table B1 **Page 1**

Automated Pavement Distress Collection Techniques -NCHRP Synthesis Topic 34-04

Pavement Cracking & Patching Automated Data Collection Questionnaire Responses

			Method of Capture									Monitoring Frequency			
	Automated	Manual			Digital			Location-Referencing Method				(months)		Sampling/Reporting	Data Management
Agency	Collection	Collection	Film	Video	Linescan	Area Scan	Protocol	Milepost	Link-node	GPS	Other	Interstate	Other Roads	Frequency	Storage
Alabama	y	y				y	Caltrans/FHWA	y				12	24	100%, summarize @ 1/100 mi.	HD, CD, DVD
(cont.)															
(cont.)															
Arizona		y						y				12	12	1000sf/MP	Flat file
Arkansas	y			y			LTPP	y		y		12	24- NHS	100%, summarize @ 25 m	S-VHS tapes
British Columbia	y					y	Stantec	y					24-48	100%	Hard Drives
(cont.)															
California		y					Agency	y				12	12	100% rigid, report @ 1mi.	Laptop & tranferred by zip disks
(cont.)														Flex. - 0.5 to 20 mi. depending upon distress	
Colorado	y			y			LTPP	y				12	12	100%, reported @ 1/10 mi.	S-VHS, data on CD
Connecticut	y					y	Agency-Aran	y		y		12	12	100%	Stored on portable hard drives during collection
Dist. Of Columbia													12	100%	Hard drives - servers
Delaware		y					Agency	y				12	12	Various Segments	Uploaded to PMS
FHWA															
E.Federal Lands	y					y				y			36	100% samplinga at the 0.02 mi.	Removable hard drives & forwarded to FHWA server.
(cont.)															
LTPP	y	y	y				SHRP-LTPP	y		y[4]		24	24	100% of 500 ft. long section	Film to hard drive to LTPP via disk after QC review
Florida		y					Agency	y				12	12	100%,	Floppy-tape-mainframe
Georgia		y					Agency	y				12	12	100ft./mi.	Laptops to server
Idaho	y					y		y				12	12	0.5 mi. To 5 mi.	Hard drive
Illinois	y					y	Agency	y		y		12	24	1/10 mi.(Interstate), Segment (Others)	Removable hard drives to workstation
(cont.)															
Iowa	y					y	Roadware			y		24	24	100%, summarized @ 10 m	Agency gets only QA/QC images on DVD
Kansas		y					Agency	y				12	12	3- 100' long random secions per mile	ICC equipment w/data collection panel- hard drive
(cont.)															
(cont.)															
(cont.)															
(cont.)															
(cont.)															
Kentucky		y					Agency	y				Variable	Variable	All Interstate & Parkway, 10% of others	Client based pavement management system
Louisiana	y					y	Agency			y	Log mile	24	24	100%, Summarize @ 1/10 mi.	Digital images stored on hard drives.
(cont.)															
Maine	y					y	AASHTO		y			24	24	100%, Summarize @ 1/10 mi.	Digital images stored on hard drives, backed up on tapes.
Manitoba	y	y		y			GIECRK		y(1)			12	12	100%, every 4 inches	16 3-D lasers, hard drive to 4 mm backup tapes.
(cont.)															
Maryland	y					y	Mod. AASHTO	y		y		12	12	100%	
(cont.)															
Massachusetts		y					AASHTO	y				36	36	100%, summarize @ 200 m	Hard drive
Michigan	y			y			Agency	y				24	24	100%	Videotape images, distress data delivered on JAZ or disks.
(cont.)															
Minnesota	y			y			Agency	y				24	24	500 ft/mi	Video images, hard drive workstation, ORACLE server.
Mississippi	y			y			Mod. LTPP	y				24	24	2- 500' sections per mile	Managed under contract by vendor
Missouri	y					y	Agency				Log Mile	12	12	100%, summarized @ 0.02 mi.	On hard drives to Oracle data base.
(cont.)															
Nebraska	y					y	Agency	y		y		12	12	Images @ 0.025 mi.	Captured as jpeg, saved on removeable hard drive,
(cont.)															uploaded to DOT network.
New Brunswick		y									Control Section		1/3 per year	500 m intervals	Collected on laptops and transferred by diskettes.
(cont.)															
New Jersey		y					Agency/ARAN	y		y		24	24	Collected @ 1/100 mi, reported @ 1/10 mi	ARAN to disk, CD or hard drive then to office PC.
New Mex		y					Agency	y				12	12	1/10 mi.	Collected visually with pen based units and laptops
New York		y						y				12	12	100%	Pentablet to Access database to Oracle
Nova Scotia	y														
Ohio		y					Agency				Log mile	12	12	100%, reported at 1 mi.	Laptop to Sybase on mainframe.
Oklahoma	y			y			Mod AASHTO				*See notes*	24	24	100%	Data loaded in ODOT database shell and delivered on CDs.
(cont.)															
Ontario		y							y		LHRS[2]		1/2 per year	100% by section (there are 1600)	Laptops to corporate database to PMS
(cont.)															
Oregon		y					Agency	y				24	24	NHS, sample @ 0.1 mi., Non-NHS windshield	Collected on laptops, transfer to office for processing.
Penn.	y				y	y	Agency			y	*See notes*	NHS -12	24	By segment of approx. 1/2 mi. length	Collecte to removable hard drives via 'FireWire'
PE Island		y													
Quebec	y			y			Mod. AASHTO	y					1/2 per year	30 m at each 100 m	video, numeric tapes(Panasonic DVC Pro) to CD
(cont.)															
Rhode Island	y			y			Agency	y		y		24	24	100 m	CD, hard drives
(cont.)															
Saskatchewan		y							y				12	Sample 50 m per segment of 500 m to 20 kms.	Recorded on paper then keyed into a database.
S. Carolina		y				y[3]	Agency	y				NHS -12	36	100% by windshield	Windshield is married to sensor data in real time.
(cont.)															
S. Dakota		y						y				12	12	100%	Laptop hard drive copied weekly to noetwork drive.
Texas	High traffic	most		High Traffic			Agency	y				12	12	100% worst lane	From laptops to mainframe.High traffic videos to TEXDOT.
(cont.)															
Vermont	y					y	Agency-Wisecra	y				24	24	100% summarize @ 1/10 mi.	Deighton dTIMS CT used for data management after delivery.
(cont.)															
Virginia		y		y	y	y	Agency	y		y		12	12	Automated -25% randomized, windshield 100%	Removable hard drives
(cont.)															
Washington	y					y	Agency	y			Route mile	12	12	100% one lane or one lane per direction for	JPEG files to van hard drive, to server by removable disks.
(cont.)														for divided.	
W. Virginia	y			y			LTPP	y				24	24	100% summarize @ 1/10 mi.	DVD and servers for images.
Wisconsin	y			y			Agency		y			24	24	5% of each 1 mile segment	Tapes, hard drives to main frame.
Wyoming	y			y			Agency/PCI	y				24	24	10%, 1000 ft.each 2 miles	VHS Tapes
Total Agencies	30	24		14	2	17		35	5	13	8				

(1) Control section very similar to link-node

(2) Linear Highway Reference System

(3) Images used for quality control, data reporting, and loaded in Pholog Viewer

(4) GPS coordinates are used to fix a test section on a map. Mileposts are used to pinpoint exact location of 500 ft. long section

Table B1 **Page 2**

Automated Pavement Distress Collection Techniques -NCHRP Synthesis Topic 34-04

Pavement Cracking & Patching Automated Data Collection Questionnaire Responses

							Cost of Distress Data				
	Data Collected By		Data Processed By		Data Processed		$/Mile			Not Known	
Agency	Agency	Vendor	Agency	Vendor	Manually	Automated	Collection	Processing	Total	Not Given	Comments
Alabama	y	y		y	y	y			$51.36		Processing through proprietry software (Wisecrax) used by vendor, manual intervention
(cont.)											sometimes necessary. Price includes collection and processing of distress,
(cont.)											IRI, rut depth, faulting and peripheral data.
Arizona	y		y		y		$5.00	unk			Note manual collection and processing.
Arkansas	y			y	y		$12.50				
British Columbia		y		y	y				$20-30		Distress is noted as data collected with distress type and severity assigned.
(cont.)											Contractor is Stantec.
California	y				y						See comments under item 9.
(cont.)									$5.00		$250,000 given for 5 (?units) approx 50000 lane miles
Colorado		y		y	y				$44.00		Data collected continuously in right lane, reported in 1/10 mi. segments
Connecticut	y		y			y			$100.00		Cost is for total data collection
Dist. Of Columbia									$85.00		
Delaware		y		y	y					y	Note manual collection and processing. No cost data given.
FHWA											
E.Federal Lands	y	y		y		y			$200-$300		Cost depends upon location within the country.
(cont.)											ARAN using high resolution digital camera, processed with WiseCrax
LTPP		y		y	y				$1000/section		See footnote 10.
Florida	y		y		y				$33.00		Note manual collection and processing.
Georgia	y		y		y					y	Note manual collection and processing. No cost data given.
Idaho	y		y		y					y	
Illinois	y		y		y					y	Images collected each 6 ft. for pavement views. Processing by district rating
(cont.)											teams to view severity and extent of distress and assign ratings.
Iowa		y		y		y			$40.00		Processing by Wisecrax. Cost includes cracking, IRI, rut, fault
Kansas	y		y		y				$13.50		Part IV of KDOT Field Operations Manual Attached, cost includes IRI, rut
(cont.)											depth, joint faulting. KDOT is very comfortable using their own matured
(cont.)											automated data collection techniques. They are not happy with AASHTO
(cont.)											cracking protocol since they use a definition of cracking that includes
(cont.)											associated roughness. They have a research project underway with Kansas
(cont.)											State to evaluate AASHTO protocols. (See Mustaque Hossain 2003 TRB).
Kentucky	y		y		y					y	
Louisiana		y		y	y				$54.00		Cost includes IRI, rut depth, joint faulting, peripheral data. Operations
(cont.)											manual attached.
Maine	y		y			y				y	Wisecrax for data processing. Deighton for program analysis.
Manitoba		y		y		GIE			$9.23		Data processing by vendor's hardware, the GIECRK system used to extract
(cont.)											cracks from images.
Maryland	y		y			y				y	Wisecrax detection software (Roadware), Processing and data reduction
(cont.)											including QC/QA in house.
Massachusetts	y		y		y					y	Data processing through agency PMS software.
Michigan		y		y	y		$19.98	$23.49			Costs: Collection - distress, IRI, Rut, Faulting, perspective view. Processing
(cont.)											- distress only.
Minnesota	y		y		y				$25.00		This cost cover labor, but not vehicle/equipment depreciation.
Mississippi		y		y	y				$32.00		Costs: Collection - distress, IRI, Rut, Faulting, perspective view. Processing
											State attached extensive contract and protocol documentation.
Missouri	y		y		y					y	*Call state for costs - they indicated they included everything in distress cost,*
(cont.)											*but didn't show it.*
Nebraska					y						
New Brunswick											
(cont.)	y		y		y					y	Processing to compute Surface Distress Index, Dbase III+n*ot considered*
											automated processing).
New Jersey	state rds.	co. rds.	y	y	y					y	*Index determination called automated by state, not in context of synthesis.*
New Mex.	y		y		y					y	
New York	y		y		y		$5.25	$1.25	$6.50		
Nova Scotia					y						
Ohio	y		y		y					y	
Oklahoma		y		y	Drate				$32.50		Consultant (Roadware) rates distresses from video using Drate software that
(cont.)											measures area or length of distress, but not type or severity.
Ontario	y		y		y					y	Processing to compute Distress Manifestation Index (DMI) and PCIn*ot*
(cont.)											*considered automated processing).*
Oregon	y		y		y				Approx. $25		
Penn.		y		y	y				$47.50		Cost includes distress, ride, rut depth, and faulting.
PE Island											Collect data manually only, no other information given.
Quebec	y			y	y				$50.00		Cost from 2002 pilot project - note collection is by agency, distress data
(cont.)											reduction by contract.
Rhode Island		y		y		y			Aprox $80		Processing is vendor based. Cost includes distress, ride, rutting, peripheral
(cont.)											data.
Saskatchewan	y		y		y					y	*The sampling technique is different. See notes.*
S. Carolina	y		y		y				$44.00		Cost includes windshield, IRI, rut depth, joint faulting, digital images, GPS,
(cont.)											processing, analysis.
S. Dakota	y		y		y						$68,000 per year is spent on the manual distress survey.
Texas	most	high traffic	y		y		$18.13				Cost for manual only. High volume videos are manually rated by operator.
(cont.)											
Vermont	some	most		y		y			$35.00		Costs include cracking, ride, rutting, processing. Interstate - $55/mi,
(cont.)											State - $35/mi., Urban - $170/mi.
Virginia	manual	automated	manual	automated	y				$75.00		Last contract front loaded on collection and included distress, IRI, rut depth,
(cont.)											frontal view. Contract terminated due to technical problems delaying delivery.
Washington	y		y		y				see comment		Collection $81K/yr, processing $90k/yr, images, IRI,rutting, faulting,
(cont.)											processing of distress data.
W. Virginia		y		y		Wisecrax			see comment		$206,000 not separated by distress, but by surface type and # of lanes.
Wisconsin	y		y		y					y	*Data collection manual was attached.*
Wyoming	y	y	y		y		$9.47	$15.00			
	34	20	28	20	40	10					

Table B2

Automated Pavement Distress Collection Techniques -NCHRP Synthesis Topic 34-04

Pavement Roughness (Smoothness) Measurement Questionnaire Responses

		Roughness Data Collected																Monitoring Frequency						
	Data	With			Data Collected By			Technology Applied			Wheel Path Collected			Location Referencing Used				Months		Sampling	Data	Cost		
Agency	Collected	Distress	Separately	Protocol(s)	Agency	Contract	Both	Laser	Ultrasonic	Other	Left	Right	Both	Milepost	Link-node	GPS	Other	Interstate	Other	Frequency	Management	$/mile	Not Given	Combined
Alabama	y	y		AASHTO PP37-99			y	y					y	y				12	24	100%, summarize @ 16 m (1/100 mi.)	Hard drive, CD, storage on DVD			See Table B-1
Alaska	y		y	ASTM E-950			y	y						y		y		12	12	100%, summarize @ 16 m (1/100 mi.)	Hard drive, CD, DB	$27.84		w/ Rut
Alberta	y		y	ASTM E950		y		y					y			y				100%, Summarize @ 50 m.	Delivered in CSV format on CDs.	$10.00		
Arizona	y		y	ASTM E-950	y					Infared			y	y				12	12	100%, summarize @ 1.6 m (1 mi.)	Captured in ASCII, imported to Foxpro and Access DB	$8.00		
Arkansas	y			Agency	y			y					y	y		y		12	24-NHS	100%, summarize @ 25 m (83 ft)	Hard drive collection, transferred via high capacity floppy		y	
British Columbia	y	y		Agency		y		y			y			y					24-48	100%, Summarize @ 50 m.	Hard drives			See Table B1
California	y		y	ASTM E-950	y			y					y	y				12	12	100%, report as needed	Portable hard disks, managed by Microsoft Explorer	($100,000)		
Colorado	y	y		AASHTO		y		y					y	y				12	12	1/10 mi.	CD Rom			See Table B-1
Connecticut	y	y		ARAN	y			y					y	y		y		12	12	100% of network	Stored on portable hardrives during collection			See Table B-1
Dist. Of Columbia	y			Vendor		y											blocks	12	12		Hard drive to server		y	
Delaware	y		y	ARAN		y		y					y	y				12	12		Data uploaded to pavement management system		y	
FHWA																								
E.Federal Lands	y	y					y	y					y			y			36	100% sampling at the 0.02 mi.	Removable hard drives, then processed by vendor then to FHWA			See Table B-1
LTPP	y		y	SHRP-LTPP		y		y					y	y		Table B-1		12	12	100% of 500 ft. test section	Hard drives	$500/section		
Florida	y	y		ASTM E-950/1926	y			y					y	y				12	12	100%, 12"recording, report by section	HD-Floppy-Tape- Mainframe			See Table B-1
Georgia	y		y	Agency GDT 126	y			y					y	y				12	12	1/4mi(PCC) - 1/2 mi.(AC)	Collected in field and uploaded to central database.		y	
Idaho	y	y		AASHTO PP37-99	y			y					y	y				12	12	1/10 mi.	Hard drives		y	
Illinois	y	y			y			y					y	y		y		12	24	1/10 mi.(Interstate), Segment (Others)	Hard drive to Zip disks to workstations		y	
Iowa	y	vendor	agency	ASTM E-950			y	y					y	agency		vendor		24	24	Vendor- 100%, summarize to 10 m	Stored on hard drives.			See Table B-1
(Cont.)																				Agency-100%				
Kansas	y		y	Agency	y			y					y	y				12	12	100%	Readings aggregated to 3" and stored on hard drive, zip.			See Table B-1
Kentucky	y		y	AASHTO	y				y				y	y				12	12	100%, summarize @ 1/10 mi.	Data stored on mainframe, moving to PMS.		y	
(Cont.)																				data is collected every inch, averaged over 12" running average and recorded every 6") and summarized over 0.1 mile.				
Louisiana	y	y		1/2 car		y		y					y			y		12	12	100%, summarize @ 1/10 mi.	Laser measurement stored on hard drives.			See Table B-1
Maine	y	y		ARAN	y			y					y		y			24	24	100%, summarize @ 1/10 mi.	Hard drives		y	
Manitoba	y		y	Standard MRB7-09		y		y					y		y(1)				12	4 inches, see Table B-1	See Table B-1	10.09		
Maryland	y	y		AASHTO	y			y					y	y		y		12	12	nple @10 cm (4"), summarize @ 16 m (0.01	Collect on 70 GB removable hard drive, transfer to office.		y	
Massachusetts	y	y		AASHTO	y			y					y	y				36	36	100%, summarized @ 200 m.	IRI collected on hard drives.		y	
Michigan	y	y		MDOT RQI		y		y					y	y				24	24	100%	Collected on hard drive, delivered on JAZ or CD.	7.29(2)		
Minnesota	y	y		IRI converted to PSR	y			y					y	y				12	12	100%	Hardrives to network conn. Or Zip to ORACLE server.			See Table B-1
Mississippi	y	y		Agency		y		y					y	y		y		24	24	100%	Vendor managed			See Table B-1
Missouri	y	y		AASHTO	y			y					y				Log mile	12	12	100%, summarized @ 32 m (0.02 mi.)	On hard drives to Oracle data base.			See Table B-1
Nebraska	y			ASTM E-950	y			y					y	y				12	12	3" sampling, summarized @ 1/10 mi.	ICC software, hard drive, transferred by Zip disks.	$1.00		
New Brunswick	y		y	ASTM E-950	y				y				y				Control section		24	Sampled @ 300mm, reported @ 50 m	Collected and stored on Zip disks		y	
New Jersey	y	y		ARAN	state rds.	co. rds		y					y	y		y		24	24	Collected @ 1/100 mi, reported @ 1/10 mi	ARAN to disk, CD or hard drive then to office PC.		y	
New Mex.	y		y	AASHTO	y					Infrared			y	y				12	12	100%	Hard drive		y	
New York	y		y	PP43-00, ASTM E950	y			y						y				12	24	100%, reported by 1/10 mi.	From Access in van by removable HD to Oracle		y	
Nova Scotia	y																							
Ohio	y		y	Mod. AASHTO	y			y		Some infrared			y	y				12	24	100%, summarize @ 1/10 mi.	Removable hard drives and zip drives	$10.00		
Oklahoma	y	y		AASHTO PP 37-00		y		y					y				*See notes*	24	24	100%	Provided by consultant in data base shell on CD	$10.00(3)		
Ontario	y		y	ASTM E950		y		y					y		y				12	100% in outer NB & WB lanes	Summarized by 50 m, 1km, and section in digital file.		y	
Oregon	y		y		y			soon	y				y	y				12	24	Continous, sample every 0.1 mi.	Stored on Zip disks and sent to office for processing.	$15.00		
Penn.	y	y		ASTM E-950			y	y					y			y	*See notes*	NHS-12	24	By segment of approx. 1/2 mi. length.	Collected to hard drives via "FireWire".			See Table B-1
Quebec	y	y		ASTM E950	y					Infrared			y	y					1/2 per yea	Recorded @ 150 mm, IRI @ 100 m.	Summarized by mean of 100 m's in section(approx 2 km)		y	
Rhode Island	y	y		ASTM E950-GIE		y		y					y	y		y		24	24	100 m	CD, hard drives			See Table B-1
Saskatchewan	y		y	TAC	y			y					y		y	y			12	100% with IRI @ 25 mm to a 50 m interval.	Hard drives (fixed and removable) then into network.		y	
S. Carolina	y	y	y	ASTM E-950	y			y					y	y				NHS-12	36	100% @ 12" , reported @ 1/10 mi.	Removal hard drives to network for Dept. wide access.			See Table B-1
S. Dakota	y		y	ASTM E-950	y			y					y	y				12	12	100%sample, IRI @ 1/10 mi.	Manual under development.			$11/mi.(4)
Texas	y		y	ASTM E-950	y			y					y	y				12	12	100% of worst lane, summarize @ 1/10 mi.	Summarized in van for uploading to mainframe	$3.00		
Vermont	y	y		ASTM E-950	some	most	y	y					y	y				24	24	100%, summarize @ 1/10 mi.	Deighton dTIMS CT used for data management after delivery			See Table B-1
Virginia	y		y	AASHTO PP37-99	y			y					y	y				12	12	100%, summarize @ 1/10 mi.	Hard drives to floppy disks			See Table B-1
Washington	y	y		Agency	y			y					y	y			Route miles	12	12	0% one lane or one lane per direction for divi	Profiles to van hard drive, to server by removable disks.			See Table B-1
W. Virginia	y	y		ASTM E-950		y		y					y	y				24	24	100%, summarize @ 1/10 mi.	DVD and servers			See Table B-1
Wisconsin	y	y		AASHTO	y			y			Reported		y		y			24	24	100%	Tapes, hard drives to main frame.		y	
Wyoming	y	y				y		1					y	y				24	24	100%	JAZ Disks. CD Rom	$2.23		
Total Agencies	52	28	22		31	17	6	45	3	4	2	0	47	38	5	15	6						18	

(1) Manitoba uses a control section system very similar to link-node

(2) Michigan cost includes ride and rut processing and determination of Michigan Ride Quality Index (RQI).

(3) Oklahoma cost includes all sensor data , IRI, rut depth, faulting, geometrics.

(4) South Dakota cost includes IRI, rut depth, and joint faulting.

Table B3

Automated Pavement Distress Collection Techniques -NCHRP Synthesis Topic 34-04

Rut Measurement Questionnaire Responses

	Data	Rutdepth Data Collected			Data Collected By			Technology Applied			Methodology				Location Referencing Used				Monitoring Frequency Months		Sampling	Data	Cost		
Agency	Collected	With Distress	With Smoothness	Separately	Agency	Contract	Both	Laser	Ultrasonic	Other	3 Sensor	5 Sensor	>5 Sensors	Protocol	Milepost	Link-node	GPS	Other	Interstate	Other	Frequency	Management	$/mile	Not Given	Combined
Alabama	y	y	y				y	y			Agency		37	Roadware	y				12	24	100%, summarize @ 1/100 mi.	Hard drive, CD, storage on DVD			See Table B-1
Alaska	y		y				y	y					7	Agency	y		y		12	12	100%, summarize @ 1/100 mi.	See Table B-2			See Table B-2
Alberta	y		y			y			y				y	Agency			y				100%, Summarize @ 50 m	Delivered in CSV format on CDs.	2.25		
Arizona	y		y		y					Infrared	y			Agency Spl.	y				12	12	100%, summarize @ 1 mi.	Captured in ASCII, imported to Foxpro and Access DB			See Table B-2
Arkansas	y	y	y		y				y				37	Agency	y		y		12	24	100%, summarize @ 25 m	Hard drive collection, transferred via high capacity floppy		y	
British Columbia	y	y	y			y			y			y		Agency	y					24-48	100%, Summarize @ 50 m	Hard drives			See Table B-1
California	y		y		y			y			y			ModAASHTO	y				12	12	100%, report as needed	Portable hard disks, managed by Microsoft Explorer			See Table B-2 ual rutting and report >3/4"
Colorado	y	y				y		y				y		Agency	y				12	12	See Table B-1	CD Rom			See Table B-1
Connecticut	y	y	y		y				y				37	Agency-Aran	y		y		12	12	100% of network	Stored on portable hard drives during collection			See Table B-1
Dist. Of Columbia	y		y			y												Blocks	12	12	100%	Hard drives - servers			
Delaware	y		y			y		y			y			Roadware	y				12	12	100% report by segment	Uploaded to pavement management system			
FHWA																									
E.Federal Lands	y	y					y	y					y				y			36	100% at the 0.02 mi.				See Table B-1
LTPP	y	y				y				y[3]				SHRP-LTPP	y		Table B-1		24	24	100% of 500 ft. test section	Hard drives	$250/section		
Florida	y	y			y			y			y			Agency	y				12	12	100%, summarize @ 1/100 mi.	HD to 3.5" disk to tapes for mainframe, 40 year protection			See Table B-1
Georgia	y	y	y		y					Manual				Agency	y				12	12	100ft./mi.	Collected in field and uploaded to central database.		y	
Idaho	y		y		y			y				y			y				12	12	1/10 mi.	Hard drives		y	
Illinois	y	y	y		y			y			older	now		Agency	y		y		12	24	1/10 mi.(Interstate), Segment (Others)	Hard drive to Zip disks to workstations		y	
Iowa	y	y					y	y	y			y			agency		vendor		24	24	Vendor- 100%, summarize to 10 m	Hard drives.			See Table B-1
Kansas	y		y		y			y			y			Agency 3 pt.	y				12	12	100%, summarize @ 12"	Laser readings aggregated to 12" intervals and stored on hard drive with zip backup.			See Table B-1
Kentucky	y		y		y				y			y		AASHTO	y				12	12	100%, summarize @ 1/10 mi.	Stored on mainframe.		y	
(Cont.)																					data is collected every inch, averaged over 12" running average and recorded every 6") and summarized over 0.1 mile.				
Louisiana	y	y	y			y		y			y			Agency			y		24	24	100%, summarize @ 1/10 mi.	Laser measurement stored on hard drive.			See Table B-1
Maine	y	y			y				y				37	Agency		y			24	24	100%, summarize @ 1/10 mi.	Data collected on hard drive. Backed up on tape.		y	
Manitoba	y		y			y		y				4 lasers		See Table B-1		Table B-1				12	Table B-1				Table B-2
Maryland	y	y	y		y				y				37	Agency/ARAN	y				12	12	sampled @ 10.5', summarized @ 0.01 mi.	Collect on 70 GB removable hard drive, transfer to office		y	
Mass.	y	y			y				y				37	AASHTO/ARAN	y				36	36	100%, summarize @ 200 m	Rut depth in mm		y	
Michigan	y	y	y			y		y				y		Pathways	y				24	24	100%	Collected on hard drive, delivered on JAZ or CD	Table B-2		
(cont.)																					Avg depth per mi., % of section >1/2 in.				
Minnesota	y		y		y			y				y		Agency	y				12	12	100%	Hardrives to network connection or Zip to ORACLE server. >1/2" rut used in index.			See Table B-1
Mississippi	y	y	y			y		y			y			Mod. LTPP	y		y		24	24	100%	Vendor managed *(contract and protocols were attached to questionnaire)*.			See Table B-1
Missouri	y	y	y		y				y				32	ARAN				Log mile	12	12	100%, summarize @ 0.02 mi.	Collected on hard drives to Oracle data base			See Table B-1
Nebraska	y		y		y			y			y			ICC	y				12	12	Sampled @ 3", summarized @ 1/10 mi	ICC software, hard drive, transferred to mainframe by Zip disks			See Table B-1
New Brunswick	y		y		y				y			y		ICC				Control section		24	Sampled @ 300mm, reported @ 50 m.	Collected and stored on Zip disks.		y	
New Jersey	y	y	y		State rds.	co. rds.			y			use 3		ARAN	y		y		24	24	Collected @ 1/100 mi, reported @ 1/10 mi.	ARAN to disk, CD or hard drive then to office PC		y	
New Mex.	y	y	y		y					Infrared		y		Law	y				12	12	100%	Hard drives. Collected by Law T6600 profilometer and visually.		y	
New York	y		y		y			y				y		PP 38-00	y				12	24	100%, reported by 1/10 mi	From Access in van to Oracle by removable hard drives.		y	
Oklahoma	y	y	y			y			y				up to 37	PP 38-00				*See notes*	24	24	100%	Provided by consultant in data base shell on CD			See Table B-2
Ontario	y			y	y				y				37	ARAN stringline		y				12	Sampled at 10 m, report @ 10 m, 50 m, section.	Retrieve on CD, view program on hard drive, final report archived on CDs.		y	
Oregon	y			y	y					rutbar					y				24	24	NHS only, sample every mile.			y	
Penn.	y	y	y			y		y			y			Agency			y	See notes	NHS-12	24	By segment of approx. 1/2 mi. length.	Collected to hard drives via "FireWire"			See Table B-1
Quebec	y	y	y		y					INO[1]				ASTM	y					1/2 per yea	Tran,. Profile @ 10 m ea. WP	Report max value between WPs @ 100 m. Summarize @ 2 km section. CD storage.		y	
Rhode Island	y	y	y			y		y						Not given	y		y		24	24	100 m	CD, hard drives			See Table B-1
Saskatchewan	y		y		y			y		INO[1]				Agency		y	y			12	Sample @ 2 m, summarize @ 50 m	Combination of fixed and removable hard drives.		y	
S. Carolina	y	y	y		y			y			y			ICC Van	y				NHS-12	36	Each 1/10", 100% @ 12", reported @ 1/10 mi.	Removal hard drives to network for Dept. wide access.			See Table B-1
S. Dakota	y		y		y			y			y			Agency	y				12	12	100%, rut depth reported @ 1/100 mi.	Manual under development.			See Table B-2
Texas	y		y		y			1 unit	15 units			y		6" bar	y				12	12	100% of worst lane, summarized 1/10 mi.	100% of worst lane, summarized @ 1/10 mi. *Also see notes.*			See Table B-1
Vermont	y	y	y				y	y					30+/-	Roadware	y				24	24	100% summarize @ 1/10 mi				See Table B-1
Virginia	y		y		y			y			y[2]			Agency	y				12	12	each 10 ft.	Hard drives to floppy disks			See Table B-1
Washington	y	y	y		y			y			y			Agency	y			Route miles	12	12	100% one lane or one lane per direction for divide	Profiles to van hard drive, to server by removable disks			See Table B-1
W. Virginia	y	y	y			y		y				y		ARAN	y				24	24	100% summarize @ 1/10 mi.				See Table B-1
Wisconsin	y		y		y			y				y		AASHTO		y			24	24	100%	Tapes, hard drives to main frame.		y	
Wyoming	y	y				y		y			y				y				24	24	100%	JAZ disks, CD Rom	$1.11		
Total Agencies	50	29	40	2	30	16	5	30	15	7	16	16	14		37	5	14	6						17	

(1) INO technology, reference www.ino.ca.

(2) Virginia considers 3 sensor measurement to not be really meaningful and will change to 5 or more in future.

(3) Rutting measured by FACE dipstick and by transverse profile film image analyzed manually.

Table B4

Automated Pavement Distress Collection Techniques -NCHRP Synthesis Topic 34-04

Joint Faulting Measurement Questionnaire Responses

		Joint Fault Data Collected								Monitoring Frequency							
	Data	With	With		Data Collected By			Technology Applied		Months		Sampling	Data	Cost			
Agency	Collected	Distress	Smoothness	Separately	Agency	Contract	Both	Sensor	Other	Interstate	Other	Frequency	Management	$/mile	Not Given	Combined	Protocol
Alabama	y	y	y				y	Contract	Agency (1)	12	24	100%, reported @ 1/100 mi.	Hard drive, transport on CD, storage on DVD			y	Roadware
Arizona	y		y		y			y		12	12	100%, summarize >0.1" @ 1 mi.	Faults >0.1 in., ASCII to Foxpro and Access DB			See Table B-2	Agency, looks like AASHTO
Arkansas	y		y		y			y		12	24	100%, summarize @ 25 m	Hard drive collection, transferred via high capacity floppy		y		Agency
California	y		y		y			y		12	12	100%, report as needed	Portable hard disks, managed by Microsoft Explorer			See Table B-2	ModAASHTO
Delaware	na																
FHWA																	
LTPP	y	y				y			y(1)	24	24	100% of 500 ft. test section	Collected manually and entered into LTPP database hard d	$250/sect.			
Florida	y	y			y				Agency (1)	12	12	1st 5 jts./section	HD to 3.5" disk to tapes for mainframe, 40 year protection			See Table B-1	
Georgia	y	y			y				Agency (1)	12	12	Every 8th slab	Data collected on hard copy and entered to central DB.		y		
Idaho	y		y		y			y		12	12	Variable	Hard drives.		y		
Illinois	y	y	y		y			y		12	24	1/10 mi.(Interstate), Segment (Others)	Hard drive to Zip disks to workstations		y		Agency
Iowa	y	y				y		y		24	24	100%, summarize to 10 m sections	Hard drives.			See Table B-1	
Kansas	y		y		y			y		12	12	Profile data base, 3" intervals	Profiles aggregated to 3", sorted on hard drive, zip backup.			See Table B-1	Agency
Kentucky	y			y	y				Visual	12	12	Visual			y		
Louisiana	y	y	y			y		y	Agency	24	24	1/10 mile	Laser measurements stored on hard drives.			See Table B-1	
Manitoba			y			y		2 laser			12	See Table B-1	See Table B-1			See Table B-2	
Michigan	y	y	y		y	y		y	Pathways	24	24	100%	Collected on hard drive, delivered on JAZ or CD	1.89(2)			
Minnesota	y		y		y			y	Agency	12	12	500 ft/mi, % section > 1/4 in.	Hardrives to network connection or Zip to ORACLE server.			See Table B-1	
Mississippi	y	y				y		y		24	24	100%	Vendor managed *(contract and protocols were attached.)*			See Table B-1	
Nebraska	y		y		y			y	ICC Software	12	12	Sampled @ 3", reported @ 1/10 mi.	ICC software, hard drive, transferred to mainframe by Zip.			See Table B-1	ICC
New Jersey	y	y			y				Visual	24	24	Collected @ 1/100 mi, reported @ 1/10 mi	ARAN to disk, CD or hard drive then to office PC.		y		
New Mex.	y	y	y		y			y	Infrared	12	12	100%	Hard drives.Collection with K.J.Law T6600 and visually.		y		
New York	y		y		y			y		12	24	100%, report by 1/10 mi.	From Access in van to Oracle by removable hard drives.		y		PP 39-00
Ohio	y	y			y				Manual	-	-	Pavement section	Hard drives to floppies		y		Agency
Oklahoma	y	y				y		y		24	24	100%	Provided by consultant in data base shell on CD			See Table B-2	PP 39-00
Ontario		y		y	y	y			Manual		various	project & as part of bi-annual survey			y		
Penn.	y	y	y			y		y		NHS-12	24	By segment of approx. 1/2 mi. length.	Collected to hard drives via "FireWire".			See Table B-1	Agency
S. Carolina	y	y	y		y				windshield	NHS-12	36	Windshield	Profiler to 80 mb portable drives to office to network			See Table B-1	
S. Dakota	y		y		y			y		12	12	100%	Manual under development			See Table B-2	Agency
Washington	y	y	y		y			y		12	12	% one lane or one lane per direction for divi	Profiles to van hard drive, to server by removable disks.			See Table B-1	Agency
W. Virginia	y	y	y			y		y		24	24	1/10 mi.(Interstate), Segment (Others)	DVD and servers.			See Table B-1	ARAN
Wisconsin	y		y		y			y		24	24	100%	Tapes, hard drives to main frame.		y		·
Wyoming	y	y	y			y		y		24	24	100%	JAZ disks, CD Rom	$2.23			
Total Agencies	30	19	21	2	21	11	1	23	14						11	17	

(1) Fault Gauge

(2) Michigan cost is for processing of faulting data, collection cost include with distress.

Table B5

Automated Pavement Distress Collection Techniques -NCHRP Synthesis Topic 34-04

Peripheral Data Collected During Distress Data Collection (Agencies Collecting Automated Data)

	Is Peripheral Data Collected With DistressData?		Collected by	Type of Data Collected				
			Vendor or	ROW	Sign	Drainage		
Agency	Yes	No	Agency	Images	Inventory	Inventory	Other	Method of Collection
Alabama	y		Both	y				Top of vehicle camera.
Arkansas	y		Agency	y				Single right-of-way camera.
British Columbia	y		Vendor	y				Additional cameras
California	y		Agency				y	Potolog of front highway view collected by a forward facing camera mounted within the vehicle.
Connecticut	y		Agency	y			railroad	Additional sideview camera
FHWA								
E. Federal Lands	y		Vendor	y	y	y	y	Three digital cameras on roof with 160 degree ROW view.
Florida	y		Agency	y	y		y	One ROW , one sign inventory camera.
Idaho	y		Agency	y				Additional cameras
Illinois	y		Agency	y	y			Additional cameras, center, left & right shoulder, rear
Iowa		n	Both					DOT operates own van for peripheral data, 2 yr cycle
Louisiana	y		Vendor	y	y		y	3 cameras, guide rail, bridges, advertising signs.
Maine	y		Agency	y				3 cameras top of van, ahead, right, left.
Maryland	y		Agency	y				1300 x 1030 digital camera
Massachusetts	y		Agency	y				Additional camera, will soon use 3 cameras (ARAN).
Minnesota	y		Agency	y			Shoulders	Front and right looking cameras. Report shoulder paved or unpaved and god-fair-poor condition rating.
Mississippi	y		Vendor	y			Shoulders	5 video cameras capture wheel paths, perspective,shoulders.
Missouri	y		Agency	y				3 ROW cameras in ARAN surveyor inventory package.
Nebraska		n	Agency			y	y	Digilog (picture @ 1/10 mi), VDES (voice data entry system)
New Jersey	y		Both	y				ROW video to document pavement condition at time of survey.
New York		n	Agency	y				Additional cameras
Oklahoma	y		Vendor	y				Additional cameras
Ontario	y		Vendor				Shoulders	Manual
Pennsylvania	y		Both	y			Geometry	3 forward facing cameras, gyroscope
Quebec	y		Agency	y	y	y	shoulders	3 additional cameras
Rhode Island	y		Vendor	y				Stereo imaging
South Carolina	y		Agency					Digital used for QC, data reporting, photolog viewer.
South Dakota		n	Agency					Will soon collect ROW images with additional cameras.
Texas			Agency					Currently adding digital ROW cameras to profilers.
Vermont	y		Both	y				Forward facing video for QC and reference.
Virginia	y		Agency	y				ROW, forward facing
Washington	y		Agency					Front & shoulder digital images by additional
(Cont.)								cameras, not currently used except in distres ratings.
West Virginia	y		Vendor	y				
Wyoming	y		Vendor	y	y			Additional VHS cameras

Table B6

Automated Pavement Distress Collection Techniques -NCHRP Synthesis Topic 34-04

Contracting Procedures Questionnaire Responses

Agency	Basis For Award			Contracts Contain Warranty Provisions		Performance Bond Required		Typical Contract Time Period	Contracts Contain QC/QA Provisions		Contracts Contain Price Adjustment Clauses		Comments
	Request for Qualifications	Request for Proposal	BIDS	Yes	No	Yes	No		Yes	No	Yes	No	
Alabama	y	y			n			2 years	y			n	Contractor pays all costs attributable to delay, state may eliminate from approved list.
Alaska		y		y				2 years	y			n	Checked and certified meeting ASTM E 950, Class 1
Alberta		y			n			1 year	y		y		$1000Cnd per each day beyond the specified date. Terms of reference attached.
Arkansas			y		n	y		1 year	y			n	
British Columbia	y	y			n			3 years	y			n	Bristish Columbia puts out an RFP, shorts lists, then awards a contract. An overview document
(cont.)													was attached.
California													
Colorado		y						1yr, 5yr option to renew	y		y		Penalty for each day late
Dist. Of Columbia	Pending call												
Delaware	y	y		y				3 years	y			n	No comments
FHWA													
E.Federal Lands			y		y			3 years	y		y		Will provide contract documents on request.
LTPP		y			y			5 years	y			y	Contract is standard fixed price for film, distress data collection, and processing. All others are
(cont.)													cost plus award fee (labor, materials, travel, overhead).
Florida													Only peripheral is done by a consultant. At this time no contract are applicable
Illinois													No contractual information given although Pathways does work.
Iowa					n			2 years		n	y		Current technology evaluated by inviting vendors to collect data and compare results on same pavements.
Kansas													For timing and consistency reasons the agency collects its own data.
Kentucky													Not applicable.
Louisiana			y		n			1.6 years	y		y		Copy of contract was attached to questionnaire.
Manitoba			y		n			2 years	y			n	A typical contract was attached and is referenced in text.
Michigan	y	y			n			2 years	y		y(1)		Bid items, collection, processing of distress, ride, rut, faulting, display software, maintenance. About 6000 mi./yr.
Mississippi	y				n			3 years - 2 surveys		n		n	Distress, ride, rutting, faulting collected under contract. Contract attached.
New Jersey		y			n			2 years		n		n	For requirements, refer to NJDOT web site/Doing Business/Procurements/Professional Services
Ohio		y		y				No response	y		y		Liqudated damages based on a per day basis.
Oklahoma		y			n			2 years	y			n	Attachment of typical contract provided.
Ontario			RF Quotes	y				1-2 years	y		y		Only IRI data is contracted out (approx. 18000 km). Penalties for failing to meet delivery deadlines
(cont.)													have been invoked. An example Terms of Reference was attached.
Oregon													
Penn.		y			n			2 years	y		y		Contractor is paid per mile delivered (54,000 mi.). Items are distress, rutting, roughness, geometry, panoramic images.
Quebec		y		y				1 year	y		y		Cracking data reduction only is contracted. *Typical contract was attached.*
Rhode Island		soon	y		n			1 year	y		y		Now awarding by low bid, moving to RFP in future. Items are distress, ride, rutting, ROW images.
Texas			y		n			2 years, renewable for 2	y			n	Bid item is pavement surface distress data collection (manual). RFP on hand.
Vermont		y			n			4 years	y			n	Cost includes distress, ride, rutting, forward video. Contract attached.
Virginia		y			n			3-5 years	y		proposed		Last contract terminated due to failure to deliver on time. Next would have liquidated damages.
W. Virginia		y			n			1 year	y			n	Lump sum for IRI, distress, and images.
Wyoming	y	y	y	y				2 years		n		n	QA/QC done internally by vendor, Items are images, roughness, faulting, rutting, texture, geometrics.
Total Agencies	7	18	8	6	19	1	0		22	4	12	14	

(1) Michigan charges a fixed penalty dollar amount for each week a scheduled delivery is late.

Table B7

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Quality Control/Assurance Procedures Questionnaire Responses

	Distress Data Verification				Profiler Verification				DMI Calibration			
		Verification Method				Verification Method				Calibration Method		
Agency	Frequency (days)	Test Sites	Standard Images	Comments	Frequency (days	Test Sites	Vehicle Internal	Comments	Frequency (days)	Test Sites	Internal	Comments
Alabama				Stratified random sample (l/10 mi.) - 200 ft. checked manually from each sample.	5		y	Stratified random sample, 1 mi, with agency profiler.	5	y		
Alaska						y		Daily bounce test		y		
Alberta				NA	5	y			5	y		
Arizona	Varies		y	To QA manual surveys	30	y	y		Varies	y		
Arkansas			y	Vendor receives S-VHS tapes from agency, sample sections are compared using in-house verification.								
British Columbia	1	y			1	y			1	y		
California	60			Supervisor verification of manual ratings by comparison ratings.	30	y	y		30	y		
Colorado		y	y			y						
Connecticut	30	y			30	y			30	y		
Dist. Of Columbia												
Delaware		y										
FHWA												
E.Federal Lands		y		No further info given		y		No further info given		y		No further info given
LTPP	daily		y	Calibration board used to check camera images.	daily		y	Use laser sensor	monthly	y		See profile manual
Florida	365			Verification by Districts following annual survey.	30	y		Verified each month at marked sites.	30	y	y	Calibration at special site once a month.
Georgia				Segments with ratings below a trigger value are re-evaluated by senior personnel.	90	y	y		90	y	y	
Idaho			y	No further information given.	7	y			y	y		
Illinois				No distress QA information given.	30	y		Man power constraints limit QA.	30	y		
Iowa		y				y						
Kansas				Pre-survey training, 5%redundant data collection, 1% QA independent checks.	4	y			7	y		Use test sites and the Kansas 1-mi. road grid system.
Kentucky				No comments.								
Louisiana	7	y		Reference field manual.	7	y		Reference field manual.	7	y		Reference field manual.
Maine		y		Not yet in place	varies	y			varies	y		
Manitoba				*A standard was attached and is referenced in the text.*				*A standard was attached and is referenced in the text.*				*A standard was attached and is referenced in the text.*
Maryland				Agency method, including QC/QA - 2003 TRB Paper				Annual calibration by vendor.				Annual calibration with profiler.
Massachusetts	1/ year	y	y	Once per year or as needed	2/year	y	y	Twice per year or as needed	30	y		
Michigan	continuous			Random sampling QA performed on all submitted data.	7	y		Compared to in-house vehicle measurements	7	y		Meet manufacturer's stated tolerance for measured mile.
Minnesota				Informal process.	yearly			Certification	Yearly			Manufacturers recommendation.
Mississippi	continuous			5% random sampling of state maintained system	daily	y		528' long calibration site run daily	daily	y		528' long calibration site run daily
Missouri			y	Random sampling.		y	y	Have not yet developed standard	14	y		
Nebraska	30	y			30	y	y	Internal twice daily in testing season.	30	y	y	Internal monitored regularly while testing.
New Brunswick				Manual QA measurements take every eigth segment for various distresses.	7	y			7	y		
New Jersey		y				y				y		
New Mex.								Compare to identical sections as Arizona.				
New York				No QC/Qa Procedures Given				Using Kansas oversampling as model				No QC/Qa Procedures Given
Ohio				NA		y	y	Compare measured to sites		y		Compared to road inventory to nearest 1/100 mi.
Oklahoma				Agency screens for data out of normal range. Then, 5% is visually compared with vendor ratings.	7	y						Contractor responsibility
Ontario				Post survey verification.		y		*Acceptance criteria were attached and are referenced.*				See attached materials
(Cont.)								A quality control must be submitted by the contractor.				
Oregon	14		y	Comprehensive training, cross-checks with experienced raters, query for unexpalined discrepancies.	7		y		30	y		
Penn.		y		No procedure given		y		No QC/Qa Procedures Given		y		No procedure given
Quebec	7		y	Ministry sends 500 km lot to contractor for analysis and return in lees than a month. After approval of	7		y		30	y		
(Cont.)				this lot the contractor can proceed with production work. Then, 2 % to 5% of submitted work will be								
(Cont.)				evaluated by the Ministry and accepted when the cracking index is within +/- 15% of the manually								
(Cont.)				measured index. Also accepted when long cracking is within +/- 10m/100m in 100% of the cases or								
(Cont.)				+/- 5m/100m in 80% of the cases and trans cracking is within +/-5 cracks/100m in 100% of the cases								
(Cont.)				or +/- 3 cracks/100m in 80% of the cases.								
Rhode Island	7	y			7	y						Not done
Saskatchewan	annual	y		Do spot quality assurance where raters are cross referenced on special sites.	3	y	y			y		An ongoing process against construction and control logs.
S. Carolina		y		Data compared to previous years data to ensure repeatability, accuracy.				*See attachments, notes.*	3000 mi.	y		
S. Dakota		y			5	y			30			Distress weekly, profile monthly
Texas				Approx, 6% of sections chosen by TEXDOT, compared to vendor results.		y	y	*See attachments, notes.*	7	y	y	Measured mile used for verification and calibration.
Vermont		y		3-5% of network randomly sampled & compared to delivered data, also 5 sites for pre-collection tests.		y		Five IRI sites are checked.				Beginning and end of contract.
Virginia		y	y	Check at startup and during production	30	y			30	y		
Washington				No QA procedures reported.				No QA procedures reported.				No QA procedures reported.
W. Virginia		y		*No description provided.*		y		*No description provided.*		y		*No description provided.*
Wisconsin	7		y	*No description provided.*	7		y	*No description provided.*	30	y		*No description provided.*
Wyoming	5% sample			Random review of PCI surveys	annual	y		Compare with previous cycle, statistical analysis	1			Contractor QC program
Total Agencies		19	11			35	14			33	4	

Table B8

Automated Pavement Distress Collection Techniques -NCHRP Synthesis Topic 34-04

Benefits/Advantages of Automated Processes

Agency	Benefits/Advantages of Automated Processes Cited by Agency
Alabama	No comments
Alaska	No formal studies done.
Alberta	No comments
Arizona	No comments
Arkansas	Distress identification allows the Department to utililize existing staff in other areas.
	Owning an automated roadway analyzer (ARAN) allows flexibility in scheduling to
	allow it's use in project level and research studies.
British Columbia	No comments
California	Briefly, Caltrans has seen a higher quality product for IRI collection by doing the work ourselves.
Colorado	No comments
Connecticut	We have no documentation regarding the benefits of agency owned equipment for automated distress
	collection and/or processing.
Delaware	Too new of a contract to provide any advantages or disadvantages at this time.
FHWA	
E. Federal Lands	The FHWA is responsible for all National Park Service(NPS) road inventories throughout the US covering
(Cont.)	5500 miles of paveed roads. The NPS wants 100% sampling of every paved road. Therefore to ensure
(Cont.)	comparable results from an objective view, we decided that automated crack detection was the only way
(Cont.)	to complete the analysis.
LTPP	The biggest benefit we see with the automated (film) distress data collection is that it provides us with
(Cont.)	a permanent record of the test section condition at a particular point in time that can be reevaluated at a
(Cont.)	future date if need be. Safety is also a factor. We also collect manual distress data so there is no savings
(Cont.)	in time and the safety problem of having technicians working on the roadway exists. The biggest advantage
(Cont.)	to automated profiled data collection is the speed at which it can be done (50-60mph) and the safety factor.
Florida	Inertia profiler system provides a safer, more efficient and objective way of collecting pavement evaluation
(Cont.)	data. The results from "real time" pavement distress analysis from images is far from accurate.
Georgia	No comments
Idaho	No comments
Illinois	No comments
Iowa	No comments
Kansas	No comments
Kentucky	No comments
Louisiana	No comments
Maine	No comments
Manitoba	Data base of road characteristics is necessary for our pavement management system.
Maryland	No comments.
Massachusetts	No comments
Michigan	Increased uniformity
Minnesota	We find that we get more consistent data when using automated distress data collection. In the past
(Cont.)	district personnel did manual ratings with much more variability. We currently have the same two people
(Cont.)	rate the system each year. Having the images allows rechecks when questions arise.
Mississippi	No comments
Missouri	No comments
Nebraska	No comments
New Brunswick	No comments
New Jersey	No comments
New Mexico	No Comments
New York	No comments
Ohio	No comments
Oklahoma	Automated distress data collection and processing procedures provide ODOT with much more data at a
(Cont.)	detailed level than would be possible otherwise. 100% coverage is beneficial and not possibe for the
(Cont.)	agency to collect on its own.
Ontario	No comments
Oregon	No comments
Pennsylvania	The change to aumated collection from manual collection was made to ensure more consistent objective,
(Cont.)	objective data, and to reduce the safety hazard of slow moving survey vehicles. While it would be less
(Cont.)	expensive to perform automated collection in-house, this is not an option because of the lack of manpower
(Cont.)	to reduce the data.
Quebec	No comments.
Rhode Island	No choice other than contract due to staff limitations.
Saskatchewan	Will be totally automated over next two years. The cost of manual is about $1.2 million annually. WIth
(Cont.)	the automated system we feel we can collect the data for about $0.3 million annually including depreciation.
(Cont.)	That figure is for collection only. Processing will be another cost. Same data base as for manual will be used.
South Carolina	To data the SCDOT has not participated in a a cost-benefit study. The state is a self data collector.
South Dakota	No comments.
Texas	No comments.
Vermont	Advantages include consistency when processing data, ability to reprocess collected images to meet new
(Cont.)	or revised protocols and classification algorithms.
Virginia	Raters work in safer environment, van moves at highway speeds, not lane closures or othe traffic control.
(Cont.)	Also, elimination of human variable from data interpretation would be a big help.
Washington	Prior to automated collection windshield surveys were used. Logistically, it was costly and difficult to QA/QC
(Cont.)	windshield data. With digital images, QA/QC is straight forward and routine. The front, shoulder
(Cont.)	and pavement digital images with 100% coverage are available for other DOT sections such as bridge
(Cont.)	preservation and maintenance.
West Virginia	No comments
Wisconsin	Better quality data, more consistency of data, safer data collection (vs. windshield), permanent visual
(Cont.)	record of actual road conditions.
Wyoming	We currently do not use an automated processing system because we require patching and bleeding
(Cont.)	information. Additionally, we have no cost-benefit studies on the switch to automated distress data
(Cont.)	collection.

Table B9

Automated Pavement Distress Collection Techniques -NCHRP Synthesis Topic 34-04

Issues/Problems Identified

Agency	Comments on Experiences With Automated Processes
Alabama	Agency attempting to resolve some problems with automated processes, need finer crack resolution (2 mm).
Alaska	Handled problems encountered.
Alberta	No comments
Arizona	Have had no problems.
Arkansas	A research project is underway with the University of Arkansas and the Mack Blackwell Rural Transportation
	Center to determine the accuracy of an automated crack detection system.
British Columbia	Have been able to handle problems. Side roads recently included in surveys.
California	Before Caltrans considers automated distress collection technology must be able to
(Cont.)	detect the distress types seen on California roads and allow for automated identification
(Cont.)	according to the CT proprietary protocol.
Colorado	No comments
Delaware	No comments
FHWA	
E. Federal Lands	Handled problem encountered. We found that using the hioghest resolution cameras
(Cont.)	for the pavement provided the best crack detection.
LTPP	Handled problems encountered. In the future we plan to start requiring deliverables (test
(Cont.)	section images and distress maps) of distress data to be in a digital format. We have
(Cont.)	also been looking at the possibility if collecting faulting data automatically, but have
(Cont.)	been unsatisfied with the accuracy of automated faulting devices.
Florida	Handled problems encountered. Do plan to upgrade to multi-function automated system w/ profiler, linescan, ROW, sign inventory, cross slope, grade, and curvature measurement capabilities.
Georgia	Handled problems encountered. In vestigating use of 5 laser rut bar to use with smoothness testing.
Idaho	Handled problems encountered.
Illinois	Handled problems encountered.
Iowa	In process of developing new QC program through analyzing vendor images manually and with crack identification software developed with the U. of Iowa. These results will be compared with vendor raw data to assess accuracy of their work.
	raw data to assess accuracy of their work.
Kansas	Stated they would not use a manual interpretation of images if can be avoided.
Kentucky	No comments
Louisiana	No comments
Maine	Handled problems encountered.
Manitoba	Experience is too limited to determine accuracy, repeatability, applicability yet.
Maryland	No comments
Massachusetts	Handled problems encountered, in process of buying new ARAN.
Michigan	Working on resolution of some problems with location reference, relational database.
Minnesota	Plan to go to fully automated distress collection and reduction over next 5 years.
Mississippi	No comments
Missouri	No comments
Nebraska	No comments
New Brunswick	Handled problems encountered.
New Jersey	Problems with calibration of IRI equipment. Problems with protocols affecting LTPP continuity of data.
New Mexico	Interested in automated data collection of pavement distress data.
New York	No comments
Ohio	No comments
Oklahoma	Expressed concerns with sensor data quality (variable rut bar length) and with distress
	data (gaps in data), inconsistency between raters, difficulty rating wide sealed cracks
	A new RFP will be issued in 2003. Prospective contractors will be invited to participate
	in trial runs of control sites. May also separate data collection and distress rating.
Ontario	No comments
Oregon	No comments
Pennsylvania	It was difficult to implement the automated collection program; no vendor had experience
(Cont.)	surveying a network as large as PENNDOTs and we had approximately 15 years of
(Cont.)	manually collected historical data that we strived to maintain consistency with. Have
(Cont.)	been able to resolve most problems encountered.
Quebec	The Ministry of Transportation of Quebec carried out several pilot projects for automated
(Cont.)	pavement distress data collection and processing. We do not have an official report on
(Cont.)	those projects. An experimental track having cracks simulated by sawcuts was built to
(Cont.)	evaluate the equipment performance. Many problems can be generally solved with
(Cont.)	human intervention and a very elaborate quality control plan.
Rhode Island	No comments
Saskatchewan	Has been able to address problem encountered.
South Carolina	Many of the secondary routes have two attributes that make accurate data collection
(Cont.)	difficult. These are (1) data is often collected at speeds less than 15 mph, and (2)
(Cont.)	numerous secondary routes are less than 1/10 mi. in length. These problems are
(Cont.)	being addressed by a data consultant.
South Dakota	Foresee having to change distress severity and extent definitions when they change
(Cont.)	from manual over to automated distress surveys because of collecting off of digital images

(Cont.)	rather than the road.
Texas	We are planning to add realtime automated visual distress rating system over the next
(Cont.)	2-3 years to fleet of profiler/rut systems. This will eliminate contracts and audits. We
(Cont.)	are also adding texture lasers to system to obtain realtime skid estimates.
Vermont	Handled problems encountered. A new contract will be developed soon, few changes.
Virginia	Problems with timely delivery of acceptable data led to termination of the most recent
(Cont.)	contract and reversion to data collection through windshield surveys. While the agency
(Cont.)	has demonstrated the ability to collect distress data in-house it does not really have the
(Cont.)	resources to extract the data from digital images at this time.
Washington	A major problem in moving to automated was in maintaining continuity between historical
(Cont.)	windshield data and the new. The concern was the affect on performance models of any
(Cont.)	differences. We found that, on the average, the two types were consistent. Now, with
(Cont.)	four years of automated there is less concern. The agency plans to update the automated
(Cont.)	survey vehicle next year with 5 sensor rut measurements and higher resolution digital cameras.
(Cont.)	Not yet using AASHTO cracking protocol because of a large historical data using agency
(Cont.)	protocol. Some incompatibility issues need to be resolved before a switch can be
(Cont.)	made. The agency does plan to adopt the AASHTO in the future. Using AASHTO
(Cont.)	for IRI and going to AASHTO 5 point rutting next year.
West Virginia	Expansion of data collected is foreseen.
Wisconsin	Major problems: 1. Adjusting equipment and procedures to account for WISDOTs
(Cont.)	historical 2-lane survey, 2. Handling large volume of data generated by image files.
Wyoming	While the state can't use automated processing because of patching and bleeding
(Cont.)	they have experienced no major problems with automated data collection since they
(Cont.)	switched to laser sensors. Earlier they had problems with rut sensors that did not
(Cont.)	significantly affect the data. They have been able to handle the problems encountered.
(Cont.)	They may switch to digital imaging and possible automated processing in the future.

APPENDIX C

Responding Agencies and Contact Information

Agency	Contact Position	Address
Alabama	Acting Pavement Mgmt. Engineer	3700 Fairgrounds Rd., Montgomery, AL 36110
Alaska	Pavement Management Engineer	5750 E. Tudor Rd., Anchorage, AK 99507
Arizona	Pavement Management Engineer	1221 N. 21st Ave., Phoenix, AZ 85284
Arkansas	Pavement Management Engineer	10324 Interstate 30, Little Rock, AR 72209
California	MM1	P.O. Box 942873, Sacramento, CA 94273-0001
Colorado	Pavement Management Assist.	4201 E. Arkansas Ave., Denver, CO 80222
Connecticut	Transportation Supervising Engineer	280 West St., Rocky Hill, CT 06067-3502
District of Columbia	Chief, Pavement Mgmt. Branch	2000 14th St. N.W. 7th Fl., Washington, DC 20009
Delaware	Pavement Management Engineer	P.O. Box 778, Dover, DE 19901
Florida	Pavement Evaluation Engineer	5007 Northeast 39th Ave., Gainesville, FL 32609
Georgia	State Pavement Engineer	15 Kennedy Drive, Forest Park, GA 30297
Idaho	Pavement Management Engineer	P.O. Box 7129, Boise, ID 83707-1129
Illinois	Pavement Technology Engineer	126 East Ash St., Springfield, IL 62704
Iowa	Pavement Management Engineer	800 Lincoln Way, Ames, IA 50010
Kansas	Asst. Geotechnical Engineer	2300 Van Buren, Topeka, KS 66611-1195
Kentucky	TEBM	705 State Office Building, Frankfort, KY 40622
Louisiana	Management Systems Engineer	8900 Jimmy Wedell St., Baton Rouge, LA 70807
Maine	Pavement Management Engineer	16 State House Station, Augusta, ME 04333-0016
Maryland	Asst. Division Chief	2323 W. Joppa Rd., Lutherville, MD 21093
Massachusetts	Pavement Management Engineer	10 Park Plaza, Boston, MA 02116
Michigan	Operations Engineer, PM Unit	8885 Ricks Rd., Lansing, MI 48909
Minnesota	Pavement Management Engineer	1400 Gervais Ave., Maplewood, MN 55128
Mississippi	Asst. State Research Engineer	P.O. Box 1850, Jackson, MS 39215-1850
Missouri	Systems Analysis Engineer	P.O. Box 270, Jefferson City, MO 65102
Nebraska	IT Business Systems Analyst	P.O. Box 94759, Lincoln, NE 68509-4759
Nevada	Asst. Chief Materials Engineer	1263 S. Stewart St., Carson City, NV 89712
New Jersey	Supervising Engineer	P.O. Box 600, Trenton, NJ 08625-0600
New Mexico	Pavement Management Engineer	P.O. Box 1149, Santa Fe, NM 87501
New York	Pavement Manager	1220 Washington Ave., Albany, NY 12232
Ohio	Pavement Management Engineer	1980 West Broad St., Columbus, OH 43223
Oklahoma	Pavement Management Engineer	200 NE 21st St., Oklahoma City, OK 73105
Oregon	Pavement Management Engineer	800 Airport Rd., Salem, OR 97301
Pennsylvania	Division Chief	907 Elmerton Ave., Harrisburg, PA 17110
Rhode Island	Chief Civil Engineer	2 Capitol Hill, Providence, RI 02903
South Carolina	Pavement Management Engineer	901 Park Street, Columbia, SC 29202
South Dakota	Pavement Management Engineer	700 East Broadway Ave., Pierre, SD 57501-2586
Texas	Senior Pavement Engineer	125 East 11th St., Austin, TX 78701-2483
Vermont	Pavement Management Engineer	National Life Building, Drawer 33, Montpelier, VT 05633
Virginia	Pavement Management Engineer	1401 E. Broad St., Richmond, VA 23219
Washington	Pavement Management Engineer	P.O. Box 7365, Olympia, WA 98504-7365
West Virginia	Highway Engineer	1900 Kanawha Blvd., East, Charleston, WV 25305
Wisconsin	Pavement Engineer	3502 Kinsman Blvd., Madison, WI 53704
Wyoming	Staff Engineer Pavement Mgmt.	5300 Bishop Blvd., Cheyenne, WY 82009
Eastern Federal Lands	Road Inventory Program Coor.	21400 Ridgetop Circle, Sterling, VA 20166
LTPP	Senior Engineer	6300 Georgetown Pike, F-209, McLean, VA 22101
Alberta	Road Surface Data Coordinator	4999-98 Ave., Edmonton, Alberta, Canada, T6B 2X3
British Columbia	Chief Materials & Pavement Engineer	4B-940 Blanshard St., Victoria, BC, Canada, V8W 9T5
Manitoba	Pavement Design Engineer	215 Garry St., Winnipeg, Manitoba, Canada, R3C 3Z1
New Brunswick	Senior Systems Planning Engineer	440 King St., Fredericton, NB, Canada, E3B-5H1
Nova Scotia	Technical Services Specialist	107 Guysborough Rd., Falls River, NS, Canada, B2T 1J6
Ontario	Manager, Pavements Section	1201 Wilson Ave., Downsview, Ontario, Canada, M3M 1J8
Prince Edward Island	Engineering Tech.	P.O. Box 2000, Charlottetown, PEI, Canada, C1A7N8
Quebec	P. Eng.	930, Sainte-Foy Road, Quebec City, QC, Canada, G1S 4X9
Saskatchewan	Area Manager	126–105th St. E., Saskatoon, SK, Canada, S7N 1Z3
Yukon	Manager, Geotech Services	461 Range Rd., Box 2703, White Horse, Yukon, Y1A 2C6
Transport Canada	Airfield Pavement Engineer	330 Sparks St., Ottawa, Ontario, Canada, K1A 0N8

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation