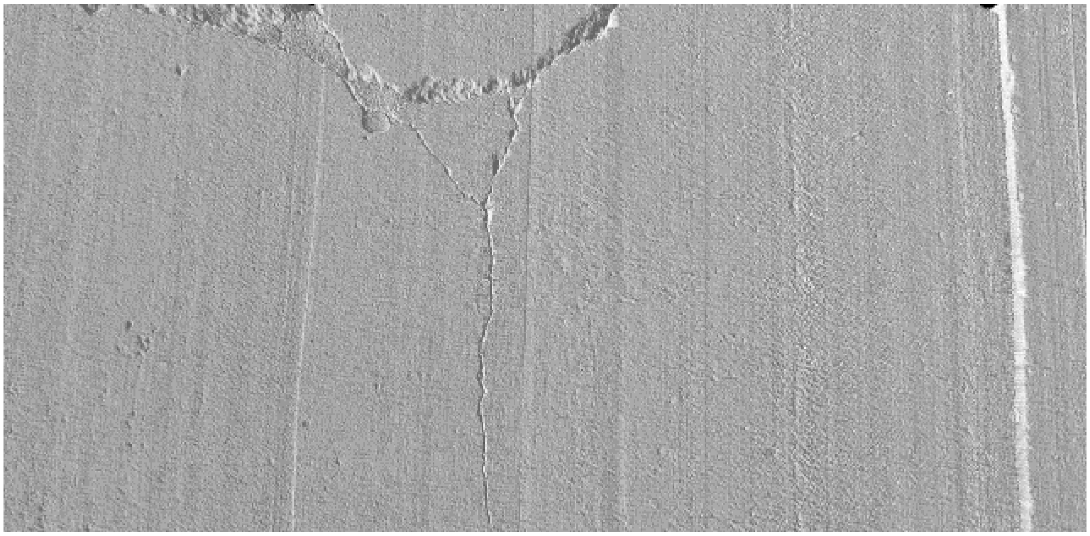
U.S. Department
of Transportation

**Federal Highway
Administration**

Development of Standard Data Format for 2-Dimensional and 3-Dimensional (2D/3D) Pavement Image Data used to determine Pavement Surface Condition and Profiles

Task 2 - Research Current Practices



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16. Abstract

This project was funded by the Transportation Pooled Fund study, TPF-5(299). This report summarizes the contract Task 2 work.

There is a critical need to develop a standard interchangeable data format for pavement surface condition and transverse profile for highway agencies and technology suppliers. When implemented, the pavement image data from various sources can be shared across different analysis software platforms. Other expected benefits include facilitating workable protocols for condition surveys, improving implementation of new technologies, and accelerating the development potential of analysis tools for pavement condition. Through a comprehensive literature review, the current practices within highway agencies for automated pavement image data collection, existing industry image data formats and management of such data sets are assessed and documented. In addition, a questionnaire survey is performed and results are obtained from TPF-5(299) participating State highway agencies, data collection vendors, and technology suppliers. The information are obtained and summarized on surface condition data collection practices, data items collected and their formats, crack data processing and reporting, desired crack data usage in pavement management program, data quality and variations, desired improvement of surface condition data collection practices.

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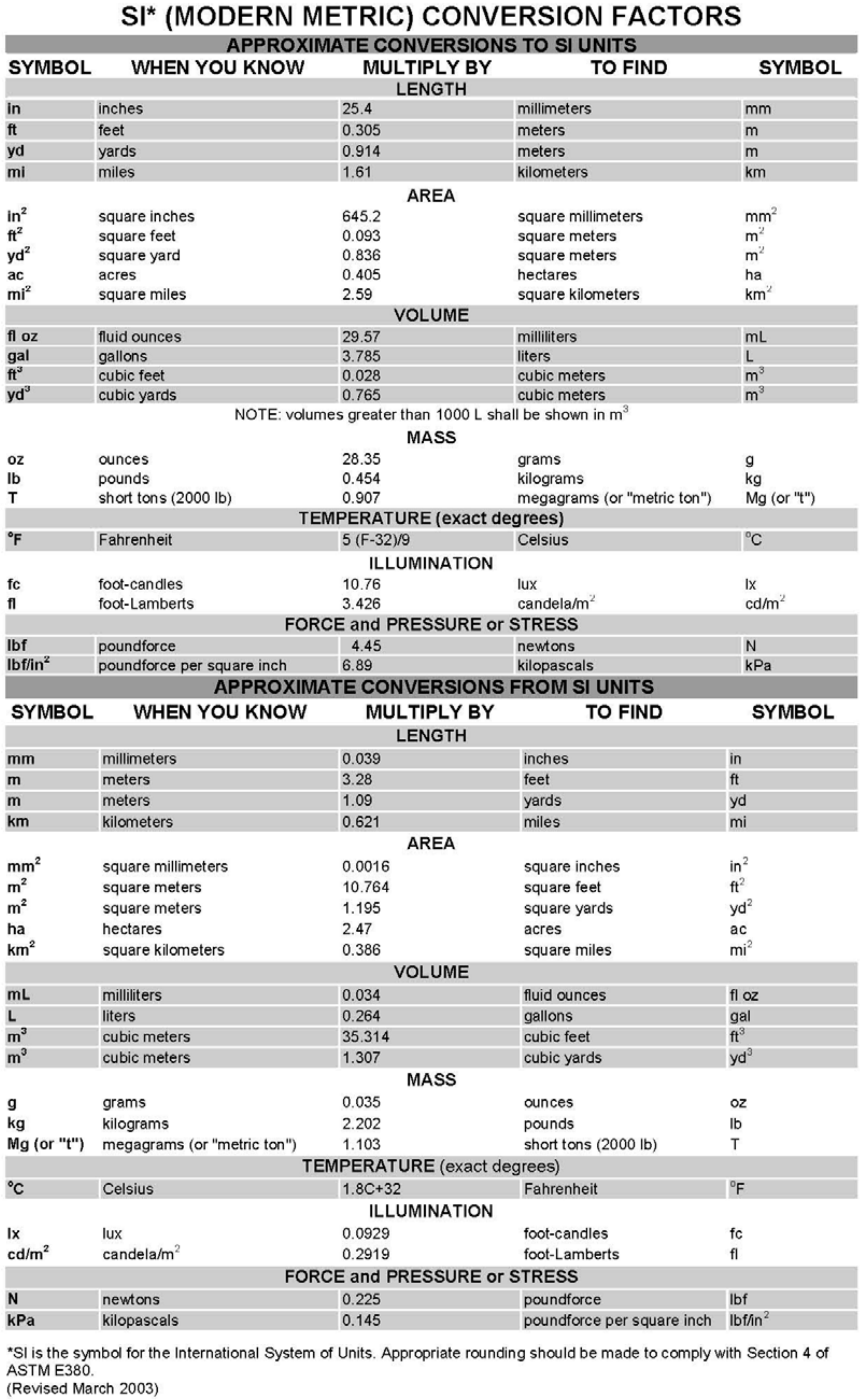

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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1. INTRODUCTION

Background

Transportation asset management plans and pavement performance measures are required by the *Moving Ahead for Progress in the 21st Century Act* (MAP-21) (FHWA, 2012). Central to fulfilling objectives for asset management and performance measures are data collected and housed by State and local agencies and reported to the Federal Highway Administration (FHWA) in various pavement, bridge, safety, and other management systems. In particular, most State and local agencies have a pavement management system (PMS), which includes inventory, condition and distress data collected at regular intervals. This pavement condition data enables the characterization of current network conditions, triggering of pavement preservation and rehabilitation treatments and/or strategies, and prediction of future conditions. Network condition data, combined with inventory, traffic, and cost data, allows a PMS to analyze and compare pavement sections to find the most cost-effective and beneficial combination of sections and treatments (Pierce et al., 2014; Flintsch and McGhee, 2009; McGhee, 2004).

However, there is considerable variety in the ways that agencies collect, process, and report the PMS data. Some agencies collect data in-house, while others hire collection contractors. Some agencies use manual, semi-automated, or fully-automated distress collection. Some agencies use distress data attributes outlined in the *Long-Term Pavement Performance (LTPP) Distress Identification Manual* (Miller and Bellinger, 2003). Further, differing technologies are used by highway agencies and contractors. For example, measurement of cracking, rutting, roughness, and faulting may be performed using point, line and scanning lasers, or combinations of these (Pierce et al., 2014; Wang and Smadi, 2011). In recent years, three dimensional (3D) imaging systems have gained their popularity, while there is currently no general purpose, open standard for storing such data (Wang, 2011). As a result, vendors and users develop and rely on proprietary software and ad-hoc formats to process, display, and report collected data, and face the challenge of meeting transportation agencies' different data requirements. Information stored in proprietary formats can be difficult to access, and ad-hoc formats increase software development costs and are not easily extended to widespread usage.

Therefore, there is a critical need to develop a standard interchangeable data format for pavement surface condition and transverse profile for highway agencies and technology suppliers. Commonly agreed-upon data standards would yield substantial benefits. When implemented, the pavement image data from various sources can be shared across different analysis software platforms. Other expected benefits include facilitating workable protocols for condition surveys, improving implementation of new technologies, and accelerating the development potential of analysis tools for pavement condition. In addition, this format would potentially be used for the development of future pavement condition data viewer software, aiding in data sharing between agencies and vendors, as well as Highway Performance Monitoring Systems (HPMS) (FHWA, 2010) reporting to the FHWA and setting national, State, and local performance goals to meet the MAP-21 requirements.

As stated, the overall objective of this project is to establish a recommended standard data format for 2 dimensional (2D) and/or 3 dimensional (3D) pavement image data. This objective is supported by the following sub-objectives:

- Collect information through a literature review regarding common pavement image, condition, and distress data formats;

- Conduct a survey of a representative sample of the Transportation Pooled-Fund Study TPF-5(299) participating highway agencies, data collection vendors, and technology suppliers on their current practices in terms of image data collection, format and needs;
- Evaluate data items collected for pavement surface condition and profiles and determine the inclusion of data items into the common pavement image data format;
- Assess existing image data format standards to meet transportation agencies' different data requirements;
- Develop and document metadata/data format that is used to determine pavement surface condition and profiles; and
- Prepare and submit draft proposed standards for AASHTO, ASTM, or other standards organizations as directed by the TPOC.

Particularly, there are four tasks to address all the activities and fulfill the objective of this project:

- Task 1 —Kickoff Meeting
- Task 2—Research Current Practices
- Task 3—Evaluate Data Items and Formats
- Task 4--Develop Metadata and Proposed Standards.

Report Outline

This report documents the work performed by the research team for Task 2 of this project. In this Task, a comprehensive literature review regarding common pavement image, condition, and distress data formats are conducted. In addition, a survey and review of the current practices of the participating highway agencies of the Transportation Pooled-Fund Study TPF-5(299), data collection vendors, and technology suppliers are performed with a focus on data format and related matters. The review has laid a foundation for the assessment of existing data items collected and data formats of pavement image data (Task 3) and the development of a standard data format to determine pavement surface condition and profiles (Task 4). The report is organized as follows:

- Chapter 1 outlines the background, objective, and tasks of this project;
- Chapter 2 reviews the current practices of various methodologies and equipment available within highway agencies to automate the collection of pavement image data, and the data formats and management of such data sets;
- Chapter 3 reports the survey and results from TPF-5(299) participating State highway agencies, data collection vendors, and technology suppliers to determine the current state-of-the-practice in their automated distress collection techniques and data management;
- Chapter 4 gives a brief summary of Task 2 of this report.

2. PAVEMENT IMAGE DATA COLLECTION AND DATA MANAGEMENT

Introduction

Pavement condition data is a critical component of a pavement management system. As the needs and uses of network-level condition data evolve, so has the technology to collect it. This Chapter discusses the evolution of this effort and the ensuing technology through a comprehensive literature review on common pavement image data collection and data formats. The research utilizes materials from online libraries and publication directories of various highway agencies, industry organizations, academic institutions, and relevant papers from conference proceedings and research journals.

Pavement Image Data Collection Technology

There are two primary methods of collecting pavement surface condition data: manual and automated (Pierce et al., 2014; Flintsch and McGhee, 2009; McGhee, 2004), used by State highway agencies as shown in Figure 2.1. Manual surveys are generally considered to be visual assessments of field conditions conducted by one or more individuals who inspect the pavement surface through the windshield of a vehicle or by walking along the pavement. The windshield survey provides very general data since it is unlikely that the observer will see, recognize, and record distresses in a consistent manner (McGhee 2004). The walking survey is generally used to acquire "reference" values, or ground truth conditions, for quality control, comparison purposes, and equipment validation (Pierce et al., 2014; Wang and Williams, 2010; Flintsch and McGhee 2009). Some agencies have chosen to use manual surveys on lower traffic volume roadways and automated approaches on higher volume roadways, where safety is a greater concern (Smith et al., 1998).

More recently, States are moving toward automated surveys to record surface characteristics and images. Image data can be collected with various means, such as analog or digital, 2D camera system, or 3D laser imaging based acquisition system (Wang, 2011; Wang and Smadi, 2011; Flintsch and McGhee, 2009; McGhee, 2004). Analog refers to the process 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 image data in digital format is then transferred electronically to computing devices for processing or reproduction purposes without the traditional digitizing process for analog based devices. In recent years, a common data collection method is to use a combination of lasers and digital cameras to capture 2D and/or 3D images. Particularly, 3D laser scanning and imaging has rapidly gained popularity (Wang, 2011).

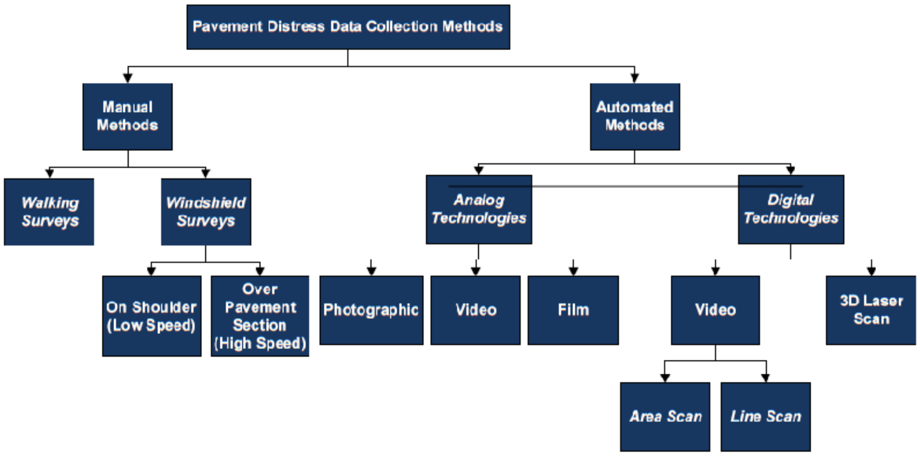


Figure 2.1 Pavement distress data collection methods (McGhee 2004)

Automated System Components

Figure 2.2 illustrates the basic system concept of an automated distress survey system, consisting of data acquisition, data storage, and data display and processing subsystems (Wang and Smadi, 2011). In addition, a database system is used for archiving and retrieving the processed data.

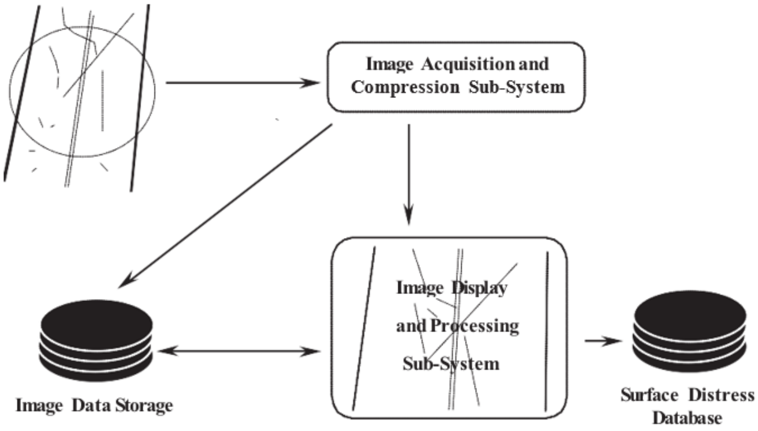


Figure 2.2 System concept of automated pavement distress survey (Wang and Smadi, 2011)

Analog Method

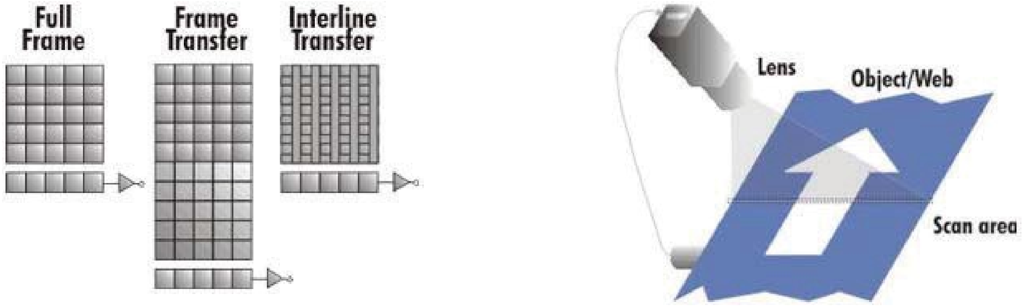
The predominant approach to using the analog method in pavement image acquisition is based on videotape or 35-mm film (Wang and Smadi, 2011; McGhee, 2004). Since analog-based data is not computer friendly, they are less frequently used in recent years due to maturity of digital technology. Even though 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 analog video signal is also relatively low compared to some digital alternatives. Therefore, today's highway users of video tapes have largely transitioned into using computer-based digital technology.

Digital Imaging

The employment of digital cameras is becoming the preferred method of pavement imaging. Digital imaging of pavements provides the opportunity to reduce distress data from those images through automated methods and the availability of random access to the data. Charged couple device (CCD) has been the dominant sensor type used in digital imaging, while better performing complementary metal oxide semiconductor (CMOS) based cameras have recently gained their popularity.

There are two types of cameras currently used to digitally image a pavement surface: the “area scan” and the “line scan” methods (Wang, 2011; Wang and Smadi, 2011; McGhee, 2004,). Area scanning uses a 2D array of pixels in a conventional sequence of snapshots. The three basic types of area array are full frame, frame transfer, and interline transfer (ILT), shown in Figure 2.3 (a). Line scan imagers use a single line of sensor pixels to build up a 2D image. The second dimension results from the motion of the object being imaged. The 2D images are acquired line by line by successive single-line scans while the object moves (perpendicularly) past the line of pixels in the image sensor, shown in Figure 2.3 (b). Line scan image capture has many benefits, including (1) very high spatial resolution image capture; (2) dynamic range that can be much higher than alternative image capture methods; (3) pixel fill-factor (typically 100%) to maximize sensitivity; and (4) smear-free images of fast moving objects without strobing or shuttering. The trade-offs in line scan imaging usually relate to lighting and optics. Illumination must be high and remain reasonably uniform over the entire field of view. Optical lens need to accommodate large image circle diameter required for lines due to their high resolution.

After years of relying on area-scan cameras for collecting pavement images, line-scan cameras in recent years became a standard in collecting 2D pavement images (Wang, 2011; Wang and Smadi, 2011). An advantage for using line-scan camera is the ability to illuminate the pavement surface with a line laser. The resulting images are normally of high quality without the influence from sun-light or shadow. With laser illumination, a highly focused narrow laser beam scans a surface in the lateral direction of the movement. The reflections of the laser beam on the surface are then collected with a line scan camera and formulated as a line when one lateral scan is completed. The collected lines are then compiled into a 2D surface.



(a) Area Scanning (b) Line Scanning

Figure 2.3 Scanning Methods in Digital Imaging (Wang and Smadi, 2011)

2D Method Using Line-Scan Camera

The Time Delayed Integration (TDI) camera is a high-sensitivity line-scan sensor widely used for capturing images of high speed moving objects at low lighting applications, such as pavement surfaces (Wang, 2011). The TDI sensor is similar to a traditional line-scan charge-coupled device (CCD) which uses a single line of photo-sensitive elements to capture one image strip of a scene. A line-scan CCD needs to have high light levels, however, in order to register the light quickly before the motion causes smearing of images. The TDI camera overcomes the illumination limitation by having multiple rows of elements which each shift their partial measurements to the adjacent row synchronously. The TDI provides high sensitivity for moving images unobtainable using conventional CCD arrays or single-line-scan devices.

In any line-scan application, the system designer must consider both the resolution across the object's movement (transverse resolution) and the resolution along the path of the object's movement (longitudinal resolution), as demonstrated in Figure 2.4. The transverse resolution is limited only by the number of line pixels in the camera. Longitudinal resolution is a function of the speed of movement, or the data vehicle's speed, and the scan rate of the camera. The speed encoder generates and sends the speed data to the camera at real-time. With the speed known and the resolution fixed, scan rate of the camera can be dynamically adjusted to satisfy the requirement of uniform resolution for both transverse and longitudinal directions.

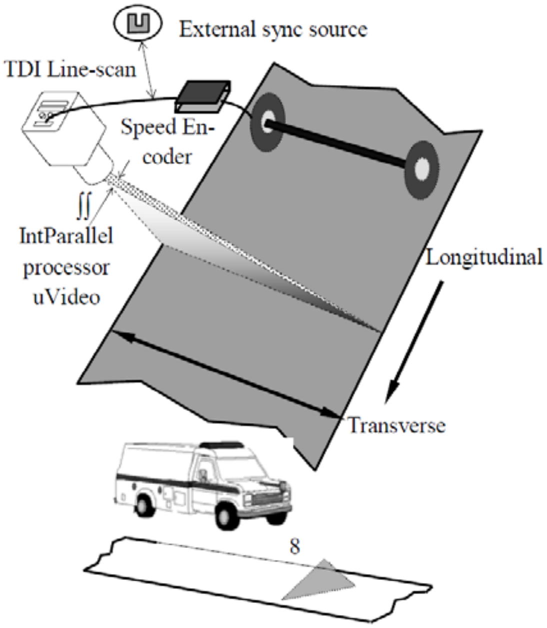


Figure 2.4 Line-Scan Camera Based Pavement Surface Inspection (Wang, 2011)

In order to capture clean images with a TDI camera, tight synchronization with the moving vehicle is required. Side-to-side motion can also affect the image uniformity when photo-elements in the same column may capture unnecessary pixels (Wang, 2011). The effect of side to side motion on image quality can also be controlled through adjusting the number of stages. Based on integration needs, the number of stages may be adjusted or selected for certain TDI cameras.

Figure 2.5 illustrates a system design for an inspection system for pavement surface distress with a TDI camera (Wang, 2011). The speed of the data vehicle is monitored in the encoder to determine the synchronization with the camera. The timing control unit generates necessary camera clock signals based on the data from the encoder. Lines from the camera are formatted in the Video Formatting step in the camera interface device. The formatted digital lines are then fed into a parallel processor for image processing. All the interfacing devices and the parallel processor are housed in the host computer, which also controls disk array for the storage of the images and related data sets. In addition, a global positioning system (GPS) receiver is connected to the host computer to log location data for the collected images.

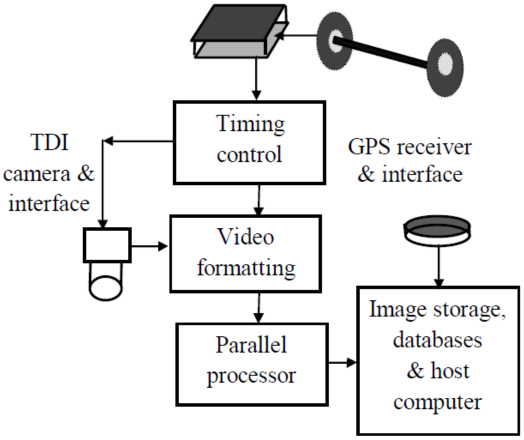


Figure 2.5 Elements of TDI based surface inspection system (Wang 2011)

3D Data Collection Techniques

Deployment of the 2D image method has been used for many years to collect pavement cracking data and estimate pavement distress. However, due to the mechanism of 2D data acquisition, the performance of crack detection and measurements is severely hampered in the presence of shadows, lighting effects, non-uniform crack widths, and poor intensity contrast between cracks and surrounding pavement surfaces. As a result, various 3D pavement crack detection techniques have been developed in recent years (Wang, 2011). Since a 3D technology uses range (elevation) information to describe pavement surface, it has several advantages compared to traditional 2D techniques, especially when laser illumination is used. The range data based on a 3D laser profile is hardly influenced by different lighting conditions. Poor intensity contrasts and contaminants like oil stains will not interfere with the crack detection using the acquired range data.

There are several techniques to collect 3D surface data. A conventional method is based on the photogrammetric principle, widely used in highway engineering dating to the use of analog film. The NCHRP-IDEA 88 project "*Automated Pavement Distress Survey through Stereovision*" uses photogrammetric principle to establish 3D pavement surfaces (Wang, 2004). The research produced good results. However, a limitation of this technique is the lighting requirement for the pavement surface. The illumination of a pavement surface to the required intensity level under direct sunlight is nearly impossible, which is required for photogrammetric image acquisition. Figure 2.6 illustrates the photogrammetric principle used in the NCHRP research and the resulting software to match a pair of 2D images with common points to generate a 3D surface model of pavement.

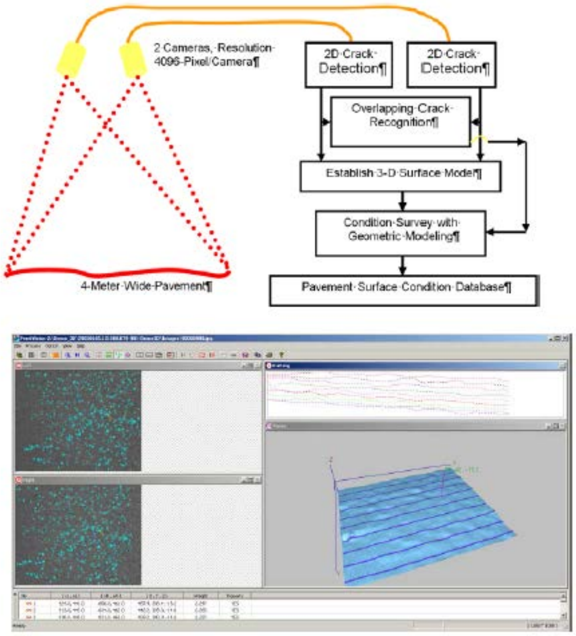
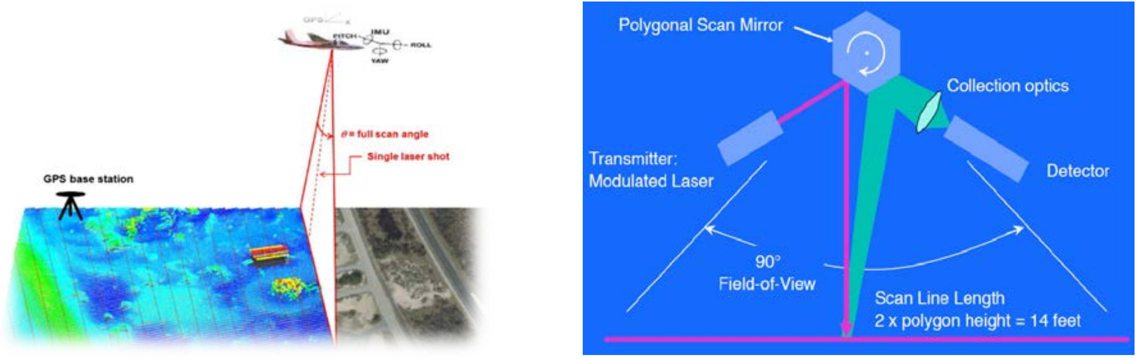


Figure 2.6 Stereovision and 3-D reconstruction (Wang, 2004)

Another technique for 3D surface modeling is Light Detection And Ranging (LIDAR), also referred to as laser altimetry which was initially used to geo-reference terrain features. A LIDAR system shown in Figure 2.7(a) is composed of a laser scanning system, GPS, and an inertial measuring unit (IMU) (NOAA, 2012). The laser scan data is collected using a scanning mirror that rotates transverse to the direction of motion. The LIDAR signal is not a point but rather an area beam. The beam is narrow, but it does get wider as it moves away from the source. Moreover, it also becomes distorted, taking on an ellipsoidal shape, as it travels along the scan (Burtch, 2002).

Based on LIDAR principle, Figure 2.7(b) shows a rotating laser system for pavement survey developed in the 1990's by Phoenix Scientific (Herr, 2001). Another company, GIE Technologies Inc. (http://www.gietech.com/) in Canada developed the LaserVISION system to model the 3-D surface of pavements. Four stationary lasers are used to cover full lane-width primarily for roughness and rutting survey. Due to the difficulties in making significant improvements to the resolution of the system, its usage has been limited for pavement surface imaging (Wang, 2011).



(a) LIDAR (NOAA, 2012) (b) Rotating Laser System (Herr, 2001)

Figure 2.7 Other Example 3D Techniques

The 3D laser triangulation imaging technology has been widely applied for inspection of manufactured products. Figure 2.8 illustrates the general principles of using 3D laser triangulation to capture surface characteristics on the conveyer belt (Wang, 2011). By illuminating a surface using a line laser and shooting 2D images using an area camera from the side (an angle) targeting at the narrow area of the laser line, the surface variation in the vertical direction can be analyzed by examining the laser line features in the captured 2D picture. When 2D images are captured in a sequence, the laser lines in the sequential 2D pictures can be extracted and combined sequentially to form a digital 3D surface. Since pavement surface defects all have unique 3D characteristics of various scales in both the x and y dimension (surface), and the z dimension (depth), such 3D laser triangulation techniques can be applied to pavement surface imaging. With high power laser line projectors, custom filters and a camera as the detector, 3-D laser imaging technique certainly has shown its capability for comprehensive and fully automated survey of pavement condition, and has been used by several vendors to develop a 3D system for pavement surface data collection with height information at pixel points (Wang, 2011).

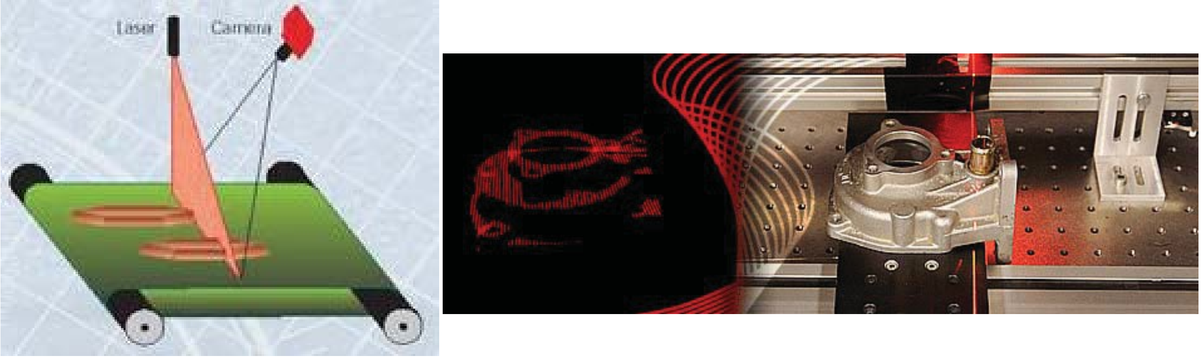


Figure 2.8 Line Laser and Triangulation for 3D Imaging (Wang, 2011)

Currently Available 3D Systems

Traditionally special lighting is often used to illuminate any shadows on the pavement surface (Fukuhara et al., 1990; Wang, 2000; Wang, 2011). After several decades' struggle in acquiring high-quality pavement images without the influence of sunlight and shadows, a laser illumination based technology became available in late 2005 by INO (http://www.ino.ca/en/) of Quebec, Canada using Laser Road Imaging Systems (LRIS), and/or Laser Crack Measurement System (LCMS). Figure 2.9 demonstrates the working principles of the laser imaging system, which allows image acquisition without the influence of sun light and shadows and can work during the day or at night, as long as the pavement surface is dry. The resolution of the acquired pavement surface images is about 1 mm in both transverse and longitudinal directions. The implemented data collection speed is from slow moving to over 100 kilometers per hour (km/h). The system is based on two illuminating lasers and two digital line cameras with about 200 watts of power consumption, versus thousands of watts of traditional lighting systems (Wang and Smadi, 2011). The INO Laser Imaging System provides the hardware and software library for integrators or vendors, which allow vendors to write software programs to acquire line images from the two cameras triggered by vendor-specific electronics based on a signal from the vehicle's speed encoder.

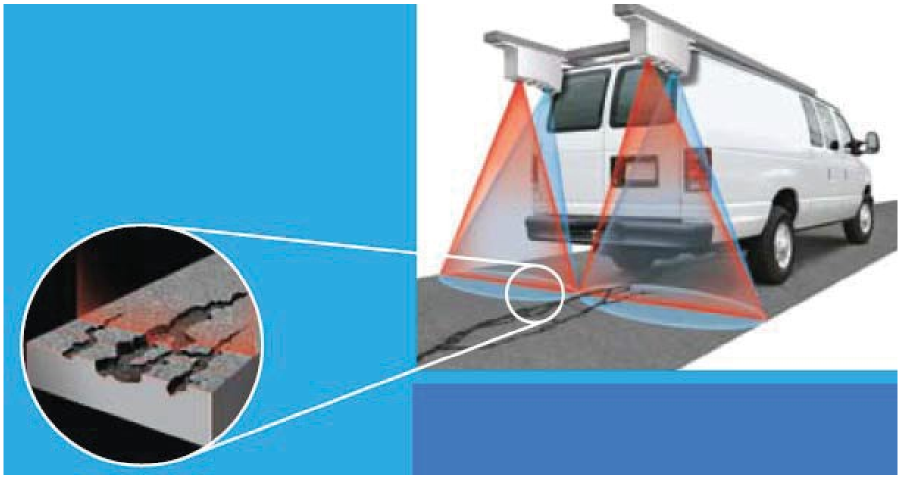


Figure 2.9 INO Laser Imaging System (Courtesy of INO)

Nowadays, most of the automated systems if not all are using laser illumination based technology (Wang, 2011). There are handful of vendors and technology suppliers that have been practicing the collection of pavement imaging data over the past several decades using the INO sensors (now partnership with Pavemetrics), including Applus, ARRB Group, Dynatest, Fugro Roadware, International Cybernetics, and Mandli. The vendors mostly offer integrated solutions of Pavemetrics/INO LCMS sensors and software for the imaging of pavement surfaces (http://www.pavemetrics.com/).

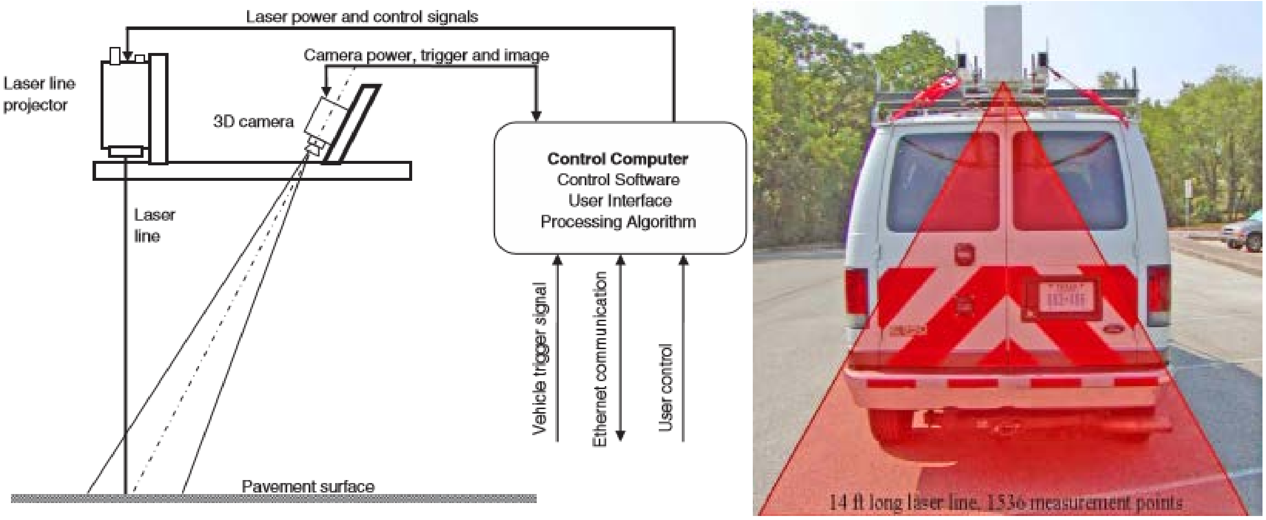
WayLink Systems Corporation has 3D laser based imaging sensors named as PaveVision3D Ultra (3D Ultra for short) to conduct full lane data collection on roadways at highway speed up to 60mph (about 100 km/h) at 1mm resolution (Luo and Wang, 2014). Figure 2.10 demonstrates the data vehicle equipped with 3D Ultra, which is able to acquire both 2D laser imaging intensity and 3D range data from pavement surface. The collected data are saved by image frames with the dimension of 2, 048 mm in length and 4, 096 mm in width (Luo and Wang, 2014).

(a) Data Collection Vehicle (b) Working Principle

Figure 2.10 WayLink Pavevision3D Ultra System

Pathway Services Inc. (http://www.pathwayservices.com/index.shtml) has also developed a laser imaging based 3D data acquisition system to capture the 3D or height deviations of the pavement surface in real-time. The 3D camera has the data speed to capture several profiles every inch at speeds up to 70 MPH. The resulting light intensity and depth images can be used for both rut depth and crack depth measurement. Pathway 3D is a single camera system that compresses the 3D files in real time.

The Texas Department of Transportation (TxDOT) also developed laser triangulation based 3D system for texture (VTexture) and rutting (VRUT) measurement as the subsystems of the TxDOT PMIS data collection vehicle. The TxDOT 3D system uses a high-speed 3D digital camera with built-in laser line image processing capability and a high power infrared laser line projector, as shown in Figure 2.11. The system covers a 14-foot lane width while providing a height resolution of 0.75mm (Huang, Copenhaver, Hempel, Mikhail, 2013).



(a) System Configuration (b) Backview with Laser Line Drawing

Figure 2.11 TxDOT 3D System (Huang, Copenhaver, Hempel, Mikhail, 2013)

Summary of Pavement Data Collection Approaches

Based on a survey conducted by McGhee (2004) and updated by other sources (Pierce et al., 2014; FHWA, 2008), 44 of 65 transportation agencies (50 State highway agencies, the LTPP Program, Eastern Federal Lands, Puerto Rico, District of Columbia, and 11 Canadian provinces) collect pavement condition data using automated pavement condition data collection vehicles, while 21 agencies conduct a windshield-based survey (Table 2.1). It should be noted that the majority of agencies collect profile data for determining the IRI (International Roughness Index), rut depth, and faulting using automated vehicles either as part of or independent of the distress survey.

Many transportation agencies have been collecting network-level pavement condition data for 20 years or more and collectively have used a variety of technologies. While data quality has largely improved in step with technology advances, it has also resulted in data consistency issues. These types of consistency issues are not negligible and must be addressed continually as technology evolves.

Table 2.1 Agency pavement condition data collection (Pierce et al., 2014; McGhee, 2004).

Aspect	Method	# Agency	# Vendor	Total #
Data Collection	Automated	23	21	44
	Windshield	19	2	21
Data Processing	Fully Automated	7	7	14
	Semi-Automated	16	14	30

Pavement Data Items Collected

Pavement Condition Data

Currently, many agencies collect sensor data (i.e., roughness, rut depth, and faulting via transverse and longitudinal profile) on an annual or bi-annual basis and distress data (i.e., fatigue cracking, longitudinal cracking, and patching) on a less frequent basis (Pierce et al., 2014; McGhee, 2004). Table 2.2 further illustrates the details of pavement condition data collection at project- and network-level (Flintsch and McGhee, 2009). The pavement condition data items collected for network-level decisions differ from those used for project-level decisions. Information collected as part of a network-level data collection effort may involve many items, but there is a fairly standard set of condition data typically collected, including roughness, rutting, faulting, and surface distress (Pierce et al., 2014; Flintsch and McGhee, 2009; McGhee, 2004). Other information, such as right-of-way imagery may augment this data and provide information related to other assets. Other than roughness data, there is little to no national level data format standardization of condition and distress attributes, such as cracking, rutting, patching, and other distress features.

Table 2.2 Pavement Condition Data Collection (Pierce et al., 2014)

Aspect	Network-level	Project-level
Uses	• Planning • Programming • Budgeting • PMS treatment triggers, identification of candidate projects, life cycle cost analysis • Network-level condition reporting • MEPDG models calibration	• Project scope • Refine pavement management system treatment recommendations • MEPDG calibration
Data Items Typically Collected	• IRI • Rut depth • Faulting • Cracking • Punchouts • Patching • Joint condition • Raveling • Bleeding • Surface texture	• Detailed crack mapping and other distresses • Structural capacity (e.g., FWD) • Joint load transfer • Base/soils characterization (e.g., GPR, cores, trenches)
Other Items Collected Concurrently	• Video • GPS coordinates • Geometrics (curve, grade, elevation, cross slope) • Other assets (e.g., bridges, signals) • Events (e.g., construction zones, railroad crossings)	• Drainage conditions • Appurtenances (e.g., sign and guardrail location and condition) • Geometrics (curve, grade, elevation, cross slope)
Speed	• Typically highway speeds	• Walking or slower speeds

Cracking and Surface Distress

There is variability among highway and local transportation agencies in the collection of pavement surface distress. While the FHWA, AASHTO, and ASTM have all issued standards for the terminology, definitions, and data collection techniques, there is still variation in the distress types and collection methods used by highway and local transportation agencies (Pierce et al., 2014; Wang, 2011; Wang and Smadi, 2011; McGhee, 2004). Some agencies developed their own distress identification manuals either as stand-alone references or as supplements to AASHTO, ASTM, or FHWA standards or practices, which will be further discussed in the Protocol session. Due to the changes in the HPMS requirements (FHWA, 2010), the new MAP-21 rules on performance measures, and the need for high-quality distress data for the AASHTO ME Design, more and more agencies are recognizing the importance of data quality and consistency. An example of the standardization efforts is the recent awarded NCHRP 01-57 study, *Standard Definitions for Comparable Pavement Cracking Data* (http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3855).

Other Roadway Assets

A number of other data items are frequently collected at the network level concurrently with pavement condition. While not directly related to the pavement condition, many of these are needed by State highway agencies to fulfill Federal reporting requirements, and others are desirable for planning, programming, or inventory purposes (Pierce et al., 2014; McGhee, 2004). These include horizontal and vertical curves, longitudinal grade, elevation, cross slope, and global positioning system data (i.e., latitude and longitude). Some of these data items are collected using the same lasers and accelerometers that are used to collect pavement condition data. Others use equipment that can be easily installed on the data collection vehicles. Increasingly, agencies are using the network-level condition data collection process as an opportunity to collect inventory or condition information on other roadway assets, such as signs, signals, striping, guardrail, and bridge clearances. Many of these are extracted from video captured as part of the distress rating process, but others are collected with additional equipment on the data collection vehicle. Downward-facing cameras collect pavement images that are stitched together to form a continuous record of the pavement surface, while forward-facing camera and sometimes side and/or rear-facing cameras for right-of-way images.

Location Reference Data

Obtain data related to specific roadway segments requires a location referencing system (LRS), which includes identification of a known point (e.g., mile or kilometer post), direction (e.g., increasing or decreasing), and distance (i.e., length and/or offset) (HTC, 2002). Ten core functional requirements of LRS were identified from NCHRP Project 20-27(3), *Guidelines for the Implementation of Multimodal Transportation Location Referencing Systems* (Adams, Koncz, and Vonderohe 2001). There are three widely used LRS methods: location, spatial, and multi-level referencing methods (Pierce et al., 2014).

Location referencing methods (LRM) include route-mile (km) point, route-reference post, link-node, and route-street reference, all of which are appropriate for managing data related to linear features such as a roadway network. The basic methods and key aspects of LRM used for roadway networks are shown in Table 2.3.

Table 2.3 Location referencing method key aspects (Pierce et al., 2014; FHWA, 2001).

Location Referencing Method	Key Aspects
Route-mile (km) point (see figure 1)	• Each route is assigned a unique name or value (e.g., Main Street, State Route 199). • The beginning of the route is defined. • Distance is measured from a given or known point to the referenced location. • Route-mile (km) posts are not physically identified in the field.
Route-reference post (see figure 2)	• Uses signs posted in the field to indicate known locations. • Benefit over the route-mile (km) post is the elimination of problems associated with change in route length (e.g., due to realignment).
Link-node (see figure 3)	• Specific physical features are identified as nodes (e.g., intersections, cross streets). • Each node is assigned a unique identifier or number. • Links are defined as the length between nodes.
Route-street reference (see figure 4)	• Local streets are used to identify roadway features. • Feature is recorded on one street at a specified distance and direction from another street.

A spatial referencing method locates transportation features using GPS to known locations. Coordinate systems use two or more spatial references (e.g., x, y, and z; latitude, longitude, and elevation; or State plane coordinates and elevation). Spatial reference methods are used within a GIS.

Many agencies are moving to multilevel location referencing systems (MLRS) following the business model provided by Adams, Koncz, and Vonderohe (2001). An MLRS provides a base network capable of integrating information from multiple disparate LRS, such as county-route-log mile (km), street name-address, and/or intersection-offset systems. The MLRS provides a transformation mechanism that allows for a common linear description of a network that can relate all of the other supporting systems, which is extremely important for many highway agencies. Pierce et al. (2014) provides an example for the need of MLRS: the planning division may use one LRS for description of traffic data collection locations, while accident statistics are maintained on a completely different LRS by a different agency division. As agencies seek to view and manage assets and information across various divisions within an institution or highway agency, integration of existing systems into an MLRS provides a better means of visualizing and managing features and data more efficiently.

Pavement Condition Indicators

The type of distress surveyed varies significantly from agency to agency and is summarized in Figure 2.12 (Flintsch and McGhee, 2009). For asphalt pavements, rutting is the only universally collected distress, followed closely by transverse cracking and fatigue cracking. Most agencies also collect data on longitudinal cracking, while some also collect bleeding/flushing. For concrete pavements, the majority collect various types of cracking, followed by faulting and spalling.

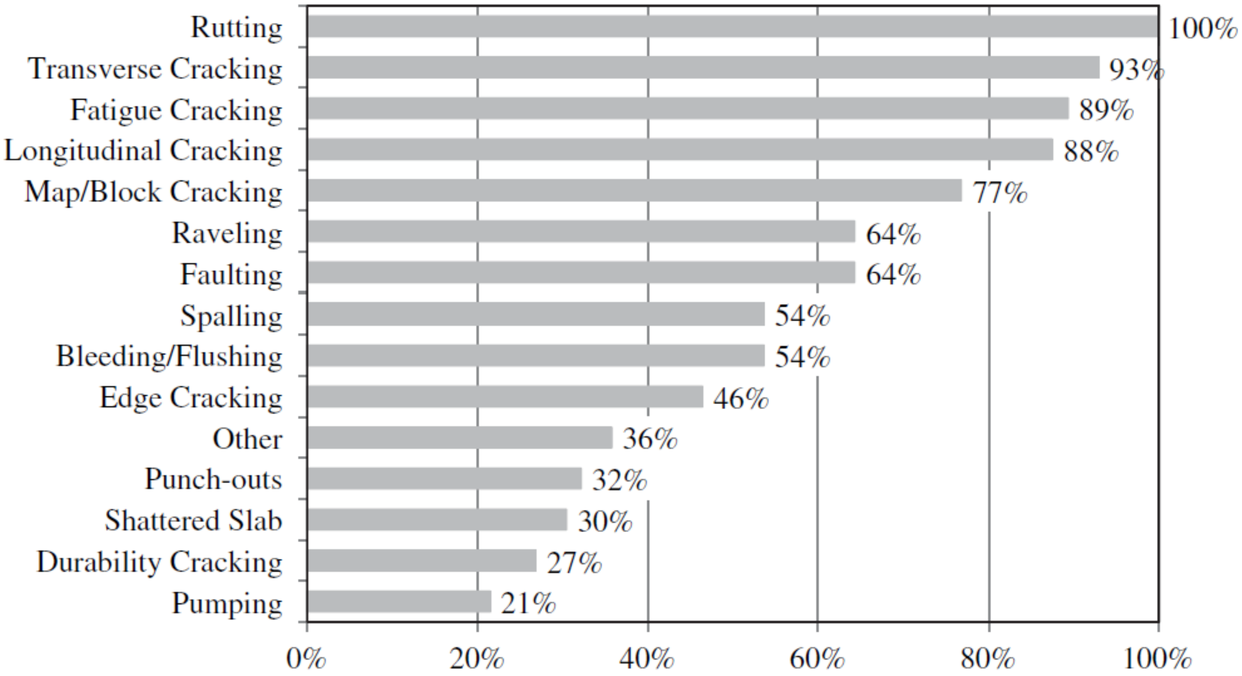


Figure 2.12 Types of Distress Data Collected (Flintsch and McGhee, 2009)

The FHWA Notice of Proposed Rulemaking for 23 CFR Part 490 (FHWA, 2015) commonly referred to as the MAP-21 performance measures for pavements recommends that State DOTs and other local agencies collect data in accordance with the HPMS Field Manual for four condition metrics: IRI, rutting, faulting, and cracking percent, and three HPMS inventory data elements: through lanes, surface type, and structure type. Meanwhile, four measures are proposed to assess pavement condition: (1) percentage of pavements on the interstate system in good condition; (2) percentage of pavements on the Interstate system in poor condition; (3) percentage of pavements on the NHS (excluding the interstate system) in good condition; and (4) percentage of pavements on the NHS (excluding the Interstate system) in poor condition.

Data Collection Frequency and Reporting Interval

State highway agencies differ in the frequency for monitoring pavement surface distresses. According to NCHRP 334 (McGhee, 2004), most agencies (18 out of 30 respondents) collect pavement cracking data every 2 years, 9 agencies reported collecting cracking image data every year, while two every 3 years.

McGhee (2004) found that most State highway agencies using automated data collection sample continuously on the outermost trafficked lane in one direction on a roadway with fewer than four lanes and in both directions for roadways having four or more lanes. NCHRP 334 found that nine State highway agencies reported that they sampled 100 percent of the lane to be evaluated, 12 agencies reported 100 percent sampling of that lane, three agencies reported collecting cracking data on a segment-by-segment basis, and five agencies sample 10 to 30 percent of the roadway, usually on a random sampling basis. The condition reporting intervals are typically some fraction of a mile (km) from 0.01 to 1 mi (0.016 to 1.6 km). Another option is to report the data aggregated to the pavement management analysis section length (McGhee, 2004).

As of 2010, the FHWA requires that the IRI be collected annually on roads comprising the NHS, which includes Interstates, while the non-NHS routes may still be collected on a 2-year cycle (FHWA 2010). HPMS also requires the submittal of several new data items, including rut depth, faulting, and cracking data (FHWA 2010).

Pavement Image Data Protocols

Historically, there has been a lack of uniformity in collecting surface distress imagery data, primarily due to the lack of uniformity in data collection practices since there are currently no nationally or internationally accepted standards (Flintsch and McGhee 2009; Haas et al., 1994; Gramling and Hunt, 1993). However, more recently there have been efforts to standardize distress types and severities definitions, as well as measurement procedures. Some agencies have adopted AASHTO Provisional Standard R 55 (AASHTO, 2001). Other procedures include those developed for the Long-Term Pavement Performance (LTPP) program (Miller and Bellinger, 2003). In addition, 20 agencies are using agency-specific protocols for crack data collection and classification (Ong et al., 2010). Although many pavement surface distress rating procedures for asphalt and concrete pavements used by agencies were written for manual surveys, they are also being used today to support automated distress identification procedures. In the very recent years, some States are implementing the new AASHTO Provisional Standard PP 67-10 (AASHTO, 2010) for image data analysis and PP 68-10 (AASHTO, 2010) for image data collection.

Efforts to standardize data collection have been ongoing during the past decades. Both ASTM and AASHTO have led the development of standards related to pavement management definitions, distress protocols, and image data collection techniques. These standards are not always separate and may reference other standards. The following are some of the more commonly used national standards.

- *Distress Identification Manual for the Long-Term Pavement Performance Program* (Miller and Bellinger, 2003). This was developed as a manual survey methodology to help collect pavement distress data by pavement type and severity level (low, medium, high) in a consistent, repeatable manner.
- ASTM D6433: *Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys*. The distresses defined are a part of a standardized pavement assessment process that results in the calculation of a pavement condition index (PCI), a rating on a scale of 0 to 100 that is used extensively in the U.S.
- AASHTO R55: *Quantifying Cracks in Asphalt Pavement Surfaces*. AASHTO has been working with FHWA on the development and implementation of protocols and standards for pavement data collection.
- AASHTO PP68: *Collecting Images of Pavement Surfaces for Distress Detection*. It describes procedures for collecting images of pavement surfaces using automated methods to detect distress for both network- and project-level analysis.
- AASHTO PP70: *Collecting the Transverse Pavement Profile*. It describes a method for collecting pavement transverse profile, including its relationship to a level horizontal reference, in pavement surfaces using automated measurement devices.
- AASHTO R48: *Determining Rut Depth in Pavements*. This protocol describes a method for estimating rut depth in pavement surfaces from transverse profile measurements using a minimum of five points and the wire method for calculation.
- ASTM E1166: *Standard Guide for Network Level Pavement Management*. This Guide provides an outline of the basic components of a pavement management system, including LRS, data collection and database managements, analysis, implementation, operation, and maintenance.
- ASTM E1656: *Standard Guide for the Classification of Automated Pavement Condition Survey Equipment*. It outlines a method to classify equipment that operates at traffic speeds and collects longitudinal profile, transverse profile, or cracking of the pavement surface.
- AASHTO R36: *Standard Practice for Evaluating Faulting of Concrete Pavements*. This protocol is recommended for joint faulting measurement for HPMS submittal.
- ASTM E2560: *Standard Specification for Data Format for Pavement Profiles*. This specification describes the binary data file format for pavement profile and the variables and sizes of all data that will be stored in the file.

In addition to the descriptions of distresses based on efforts of the FHWA, ASTM, and AASHTO, some agencies have developed their own distress identification manuals either as a stand-alone reference or as a supplement to the FHWA manual, AASHTO and ASTM standards. However, there is no universally accepted approach to cracking data interpretation. Originally intended to improve the consistency in measuring and reporting pavement cracking through a standardized process, the overall impact of these standards and protocols on pavement management practices has been marginal with most agencies using them as research tools rather than for production.

Particularly, for cracking data, 2D and 3D digital imaging systems have gained popularity in recent years, however, there is no standard for storing and sharing such data. As a result, users rely on vendor-specific proprietary software and ad-hoc formats to process, display, and report collected data. Information stored in proprietary data formats can be difficult to access, and ad-hoc data formats increase software development costs and are hindering widespread usage of new software algorithms. With the changes in the new HPMS requirements for State agencies (FHWA, 2010), the new performance measures such as applications of MAP-21 rules, and criticality of high-quality cracking data for the calibration of performance models in the AASHTO Mechanistic-Empirical Pavement Design are the critically needed impetus for the industry to nationally standardize pavement surface condition data analysis, reporting, sharing, and evaluation through establishing a common 2D/3D pavement data format for highway agencies and technology suppliers.

Pavement Image Data Format

This section attempts to enumerate the past and current file formats used for storing 2D intensity and 3D range data. This review serves as a foundation for understanding and designing a proper pavement data format standard in this project.

2D Image Data Formats

As discussed earlier, there are two types of 2D digital cameras used to image a pavement surface: “area scan” and “line scan.” Area scan digital imaging contains 2D visual data similar to consumer 2D photos, which are commonly saved into uncompressed format, such as BMP, or compressed formats such as the Portable Network Graphic (PNG), Graphics Interchange Format (GIF), Tagged Image File Format (TIFF), Joint Photographic Experts Group (JPEG), and many of its successors such as JPEG 2000. Line scan imagers use a single line of sensor pixels to build up a 2-D image. The 2-D images are acquired line by line by successive single-line scans while the object moves (perpendicularly) past the line of pixels in the image sensor. These lines are “stitched” together to form a continuous image or an image frame broken at intervals set by the user.

The BMP format, also known as bitmap image file or device independent bitmap (DIB) file format, is a raster graphics image file format used to store bitmap digital images, independently of the display device (such as a graphics adapter) (Miano, 2000; Wu and Buchmann, 1998). The BMP file format is capable of storing two-dimensional digital images of arbitrary width, height, and resolution, both monochrome and color, in various color depths, and optionally with data compression, alpha channels, and color profiles. Without compression, the image file can be huge in size.

The PNG format is a lossless compression format for transmitting a single bitmap image over computer networks, designed to be a legally patent-free replacement for TIFF (Miano, 2000). The PNG file is suited for flat-color sharp-edged image data, which retain edge and sharpness information if there is no dithering. Since humans are especially sensitive to edge sharpness, The PNG generally appears to be sharper than JPEGs. Unfortunately PNG-8 can only store 256 colors, while PNG-24 allows more depth but is much bigger in size than JPEGs and PNG-8s.

The Graphics Interchange Format (GIF) is limited to the 8 bit palette with only 256 colors, and is most suitable for graphics, diagrams, cartoons and logos with relatively few colors. The GIF format produces ‘Lossless’ quality, implying that it maintains the same level of quality as the original image. Interlacing is another web-specific feature of GIF, a mechanism that makes images appear faster on-screen by first displaying a lower version of the image and gradually showing the full version. However, this format has not been updated since 1989.

The TIFF file is one of the commonly used graphic image formats for exchanging raster graphics images between application programs. Until recently the use of this Lempel-Ziv-Welch (LZW)-based algorithm is limited because this technique is subjected to several patent disputes in various jurisdictions (Taskin and Sarikoz, 2010). The TIFF data format has the following advantages:

- Multiple types of compression. The TIFF file format supports multiple types of compression such as JPEG, LZW, ZIP or no compression at all.
- Flexible tag sets. The TIFF file format allows a flexible set of information fields. The so-called 'private tags' or 'custom tags' can be defined to hold customized application specific information. This scheme allows any relevant information be attached with an image, while little information is absolutely needed so that image headers remain as lean as possible with limited overhead.
- Multi-page. Another important feature of TIFF is that it supports multiple images in a single file.
- Internal tiling. It allows renderers to quickly pick up and decompress portion of an image.

The GeoTIFF file inherits the merits of the TIFF file structure which allows both the metadata and the image data to be encoded into the same file (Ritter et al., 2000). Specifically, GeoTIFF uses six tag keys to encode geographic information associated with a TIFF image that may originate from satellite imaging systems, scanned aerial photography, scanned maps, digital elevation models, or as a result of geographic analyses. Since the GeoTIFF is specially designed to augment an existing raster-data format to support geo-referencing and geo-coding information, it is not the ideal platform to be directly used as the file format for pavement 2D/3D image data.

The JPEG file is an imaging industry standard-setting body, and the most used format for storing and transmitting images (Wang and Smadi, 2011; Miano, 2000; Wallace, 1992). A JPEG is generally “lossy,” meaning some information is lost during the compression process and the original raw image cannot be restored from the compressed image. The JPEG standard also has an option to compress images into lossless format. However, due to low compression ratio, this lossless JPEG compression is not widely used for pavement image data.

Since the release of the JPEG standard, several important JPEG successors has been developed, including **Better Portable Graphics (BPG)**, **JPEG extended range (JPEG-XR)**, **JPEG 2000**, and **Progressive Graphics File (PGF)**.

The BPG format: The JPEG and PNG are the two most popular formats used to display images in web browsers. Even though the internet is getting increasingly faster, it is still important to limit the file size as small as possible. The new BPG format is the alternative to the popular formats, and it promises smaller file size while obtains higher image quality in comparison to the JPEG format. The unique feature of the BPG format is its high compression based on a subset of the High-Efficiency-Video-Coding (HEVC) (Darwiche et al, 2015). Its main advantages are (Darwiche et al, 2015):

- Free access to the source codes of encoders. The encoder is offered as Open Source under the terms of the GPL license.

- Compared with JPEG, BPG is capable of delivering much better visual quality image at the same file size.
- Supports any bit depth from 8 to 14 bits per channel, resulting in a higher dynamic range than that in JPEG with 8-bit-per-channel.
- Supports lossless compression.
- Supports various metadata (such as EXIF, ICC profile, XMP).

Even though the JPEG is the most widely used image format offering both widespread compatibility and small file sizes, its compression artifacts and an 8-bit limitation have posed challenge of its application in disciplines such as 3D pavement imaging. The BPG is the latest new format to challenge the JPEG, however, the BPG is based on the HEVC, which consists of patented algorithms.

The JPEG-XR file is a still-image compression standard and file format for continuous tone photographic images, based on technology originally developed and patented by Microsoft under the *HD Photo* (formerly Windows *Media Photo*) (Dufaux et al, 2009). It supports both lossy and lossless compression, and is the preferred image format for Ecma-388 Open XML Paper Specification documents. As a JPEG alternative, Microsoft released its JPEG-XR format in 2006, which produces smaller files than a JPEG. However, the encode/decode speed is slightly slower, and Microsoft's *Internet Explorer* is the only supporting browser.

The JPEG 2000 uses a different compression algorithm, mathematically based on the wavelet technique (Wang and Smadi, 2011; Marcellin et al., 2000). The advantage of a JPEG 2000 over a traditional JPEG is that JPEG 2000 achieves much higher compression at the similar quality level with a traditional JPEG. In addition, the blocking effect with images compressed with JPEG 2000 is less severe compared to that of images compressed with a traditional JPEG. However, it should be pointed out that encoding and decoding JPEG 2000 images require substantially more computing power than for traditional JPEG images.

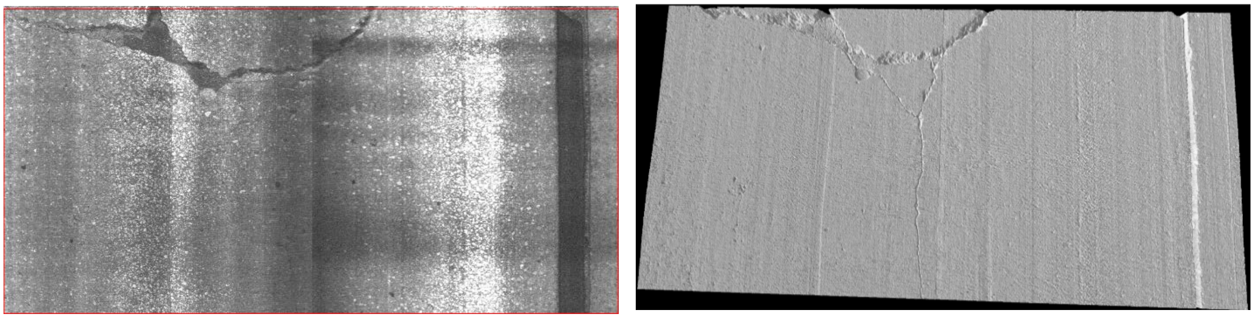
The PGF file is also a wavelet-based bitmapped image format that employs lossless and lossy data compression (Stamm, 2002). PGF was developed at the same time as JPEG 2000 by Xeraina, a Swiss Federal Institute of Technology spin-off company, but with a focus on speed over compression ratio. Comparing to the original DCT-based JPEG standard, PGF can operate at higher compression ratios without taking more encoding/decoding time and without generating the characteristic "blocky and blurry" artifacts. It is also reported that PGF is approximately ten times faster than JPEG 2000. The advantages of PGF format are that (Stamm, 2002):

- It supports grayscale with 1, 8, 16, or 31 bits per pixel, which is able to handle a large range of effective bit rates.
- The PGF codec written in portable C++ code runs on most standard platforms and has been tested on Windows, Macintosh, and Linux.
- The PGF technology has been built without using any patented algorithm and the codes have been published with public access.

Therefore, the PGF format can be a potential candidate to be used in the compression of the 3D pavement data with high-bit count. A concern is that it is not a commonly used compression engine and its potential weaknesses are not known at this time.

3D Image Data Formats

In the recent years, there have been rapid developments on the application of laser imaging technology for capturing 3D pavement surface. Despite the rapid growth of 3D technology, there is currently no open standard for storing such 3D data sets. Producers and consumers of 3D imaging system data rely on proprietary or ad-hoc formats to store and exchange data. Figure 2.13 shows example image frames for 2D intensity data saved in JPEG or JPEG2000 format and 3D range data saved using proprietary format with the dimension of 2,048 mm in length and 4,096 mm in width.



(a) 2D Intensity Images (JPEG/JPEG2000) (b)3D Range Image (Proprietary Format)

Figure 2.13 Example 2D/3D Pavement Images (In Courtesy of WayLink)

The existing 3D data format standards can be roughly grouped into two categories: those established by the computer graphics and computational geometry community, and those used or proposed by the community of highway agencies and equipment suppliers. The computer graphics and computational geometry communities in particular have created more than 140 formats to describe 3D data with numerous related literatures (McHenry and Bajcsy, 2008). However, the majority of them were created before today's sensing technologies and algorithms had been invented. Recently, as 3D point-cloud data from laser scanning (such as LiDAR) is becoming increasingly common, many new versions of 3D data formats have been developed and widely adopted for various applications, such as the Universal 3D (U3D), ASTM E57 file format, and 3DFC.

- **The U3D specification** is published by Ecma International as the ECMA-363 (U3D File Format) standard (ECMA International, 2007). The U3D is a compressed file format standard for 3D computer graphics data. This Standard defines the syntax and semantics of the Universal 3D file format, an extensible format for downstream 3D CAD repurposing and visualization, useful for many mainstream business applications. There are a number of tools and libraries available for the creation of U3D files, such as MeshLab (http://meshlab.sourceforge.net/) and MeVisLab (http://www.mevislab.de/). However, using these tools needs considerable amount of training because the total module base are sophisticated and complex in design so that it can be used for various application from simple to advanced.

- **The E57 format** is defined in the ASTM standard E2761 (Huber, 2011) for 3D imaging system data exchange developed by the E57.04 Sub-committee with representatives from major 3D imaging system manufacturers, 3D imaging software vendors, and 3D imaging service providers, as well as industry consultants and academic researchers. The E57 format is designed to be a general, open standard for storing data produced by 3D imaging systems, such as laser scanners, flash LIDAR systems, structured light 3D scanners, stereo vision systems, and other devices that produce 3D measurements. In addition to storing 3D point measurements, the format can store associated 2D imagery, such as that produced by a digital camera, as well as core meta-data associated with the 2D images and 3D points.

As a general extendable standard, the E57 format has considered the ability (1) to encode extremely large files - up to 9 exabytes in length, (2) to encode organized "gridded" point cloud data as well as unorganized data, and (3) to extend the format to support special-purpose needs such as aerial sensing. The complex design of the data format makes E57 cumbersome for pavement imaging applications. The E57 file format has acknowledged the potential benefits of advanced 3D data compression to manage enormous 3D/2D data sets. However, compression has not been addressed in the current standard.

- **The 3DFC file** is an interoperable 3D format, which can be designed to be compatible with other 3D formats without alteration of files (Berthelot et al., 2012). Since each 3D file format contains specific features for a particular domain, a decoder can be identified in 3DFC and format wrapper implemented according to the given API for each 3D format. The 3DFC format can be applied for pavement image data, however, a format wrapper should be designed for each vendor.

In the recent years, with the rapid developments of laser triangulation principle based 3D pavement data collection systems, proprietary or ad-hoc formats have been developed to store and exchange data. Typically, 2D data (intensity) is stored in JPEG or JPEG 2000 format; however, the 3D data formats are seldom disclosed by technology developers. Below are several exceptions that provide limited discussions of 3D data and the formats.

- **HiSPEQ Project Team at European** (HiSPEQ, 2015) is conducting an on-going research project to establish standard formats for several different types of survey data, including those for location, profile, travel speed deflectometer (TSD), ground penetration radar (GPR), and imagery data. Specifically for image files, HiSPEQ suggests that there is no need to develop new standard considering numerous well-established image file formats. They agree that there is a need to specify whether full resolution or compressed images should be delivered. It is concluded that a compressed image (e.g. 70 percent quality jpeg) is good enough for general manual analysis. However, uncompressed images are needed if automatic analysis is to be performed.

  The HiSPEQ study primarily focuses on 2D intensity image. How to store and compress 16-bits 3D range data is not mentioned in their interim report. Instead only an outline with the core requirements for the file formats are provided. For instances, HiSPEQ suggests a "broadly transferrable" data format, meaning that the core components of the format remain the same (e.g. the file layout, metadata, level of detail etc.) whilst specific customization for each application is needed.

- **File Exchange Format (FEF)**: Tsai and Wang (2014) suggested the FEF format for line laser imaging data through a study of Remote Sensing and GIS-based Asset Management System (RS-GAMS). In the proposed FEF standard, each survey consists of two types of files: a single index file and data frame files. The index file is an XML file that describes the survey data consisting of three major components: general information of the survey, physical attributes of the cameras, and the location details of each data frame. A data frame file is a single image frame captured by the line laser camera including both range and intensity data. For one survey, it is recommended that all the files, including the index file and data frame files should be kept within a single folder. Several key issues, such as 3D range data compression, are not addressed in the FEF data format.

- **Open Curved Regular Grid (OpenCRG®) format** is the successor of a format called "Curved Regular Grid" (CRG), which has been used internally for several years by Daimler AG with an entire suite of MATLAB® and FORTRAN tools for the handling, evaluation and generation of CRG data. The objective of OpenCRG® is the provision of a series of open file formats and tools for the detailed ("microscopic") description of road surfaces (Rauh, 2009). As stated on the OpenCRG® website, OpenCRG® data sets are designed to describe patches of road surfaces in a very detailed manner, so that they may be used for applications such as tire simulation, vibration simulation, driving simulation, and durability load analyses. The OpenCRG® provides the following features (Rauh, 2009):
    - Various ASCII/binary file formats with clear-text headers.
    - Handling of arbitrary scalar data vs. a reference grid, such as elevation, friction coefficients, pavement surface temperatures etc.
    - Open source C-API for data handling and evaluation, open source MATLAB® API for data manipulation and generation, and growing library of sample data.

  In order to represent road elevation data close to an arbitrary road center line, openCRG**®** adopts a new coordinate plane system noted by u and v axles. This coordinate plane system is built by lateral cuts along a curved road reference line so that a curved regular grid can be generated. To transfer pavement image data into openCRG**®** format, the following post-processing are needed (Rauh and Gimmler):
    - Smoothening curvature to eliminate high frequency contents of measured vehicle's movements.
    - Deriving smooth road reference line with minimal lateral displacement from vehicle trajectory.
    - Discretizing reference line into a smoothed equidistant point sequence.
    - Determining virtual cross cuts orthogonal to the smoothed reference line in all equidistant points.
    - Generating evaluation points on the cross cuts to achieve the target CRG-Grid-resolution.
    - Interpolating the 3D road surface based on the measurement points at the CRG-Grid-Point locations (e.g. by Matlab grid data function).

  In summary, OpenCRG® provides a more or less generalized approach to linking local properties of a road surface to the respective evaluation routines and providing tools necessary for data generation and handling and vehicle/tire simulations. Therefore, OpenCRG® can be considered as one of the many applications of using raw pavement image data for the purpose of evaluating vehicles' dynamic performance on a specific pavement by auto makers. Its applications may only need a pre-determined resolution of 3D pavement surface for vehicle performance analysis now and in the future. Therefore it may not be a good fit as a candidate for pavement 3D data format as flexibility and accommodation of future technologies are important to the pavement industry.

- **The LandXML format** is a non-proprietary universal data standard to communicate highway geometric data, which was agreed upon by a consortium of major civil/survey product manufacturers (including Bentley and Autodesk) and government agencies. The focus of LandXML data format is the exchange of civil design information between software applications based on various data types, including points, survey measurements, alignments, profiles, cross sections, surfaces. LandXML's geometric roadway design schema elements has been adopted by the TransXML format (Ziering et al., 2007). The pros of LandXML include:
    - A widely adopted non-proprietary data standard.
    - Availability of LandXML Development Kit, validator software, and a free LandXML viewer, which can generates 3D image thumbnails automatically in Windows File Explorer.

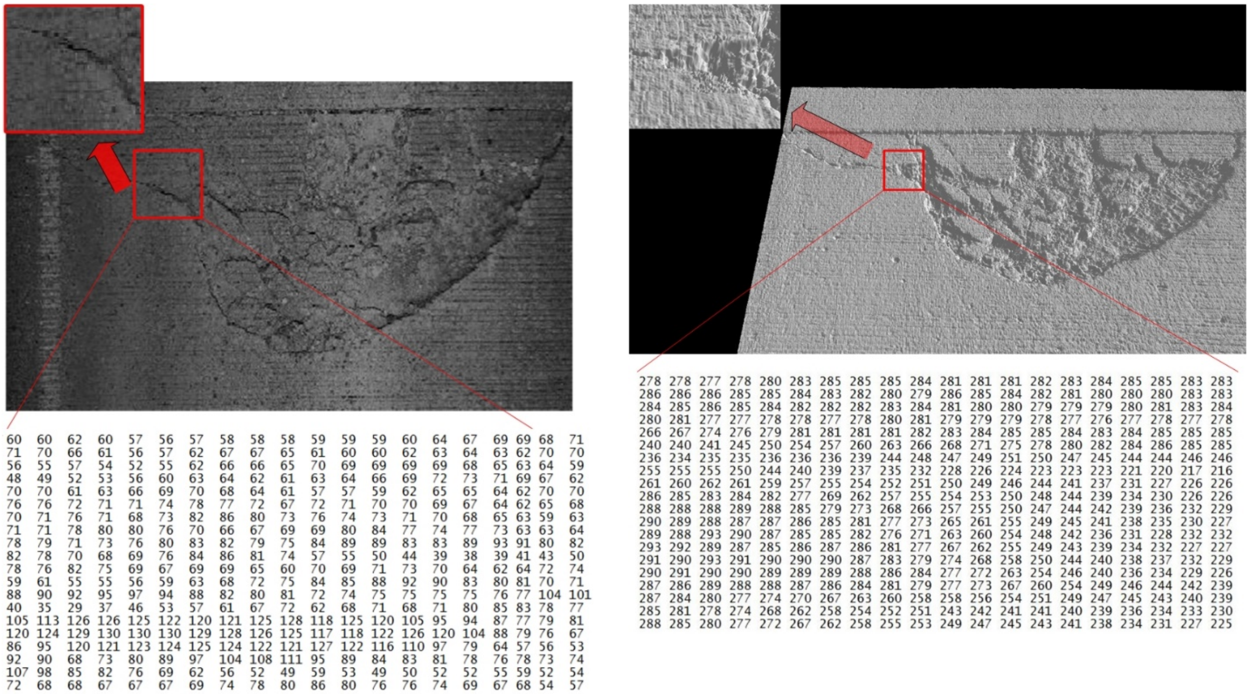
  However, LanXML has poor forward compatibility. The data in the format of LandXML-2.0 cannot be well supported by an older software package that was built upon the version 1.0. Moreover, the lack of an effective compression scheme for raster image data is a concern, as the LandXML file size can be enormous with high-resolution pavement image data, such as gigabytes per file.

- **The Elementary Data format** (Gajewski, 2012) was first introduced to the Federal Road Authorities in Germany in 2005. It uses the XML format to define the structure and content of the pavement condition data. The XML file does not content the original data, but a header to include the information of the folder where all photographic documentation is saved. Since it was originally developed about one decade ago, this data format is mainly designed for the storage of 2D photographic information, transverse and longitudinal elevation profiles. It does not address the related issues of dense collected 3D range data.

Assessment of Existing Data Format

In order to investigate the suitability of existing formats for the development of standard data format for 2D/3D images, an example pavement image with 2D (intensity) and 3D (range) data is illustrated in Figure 2.14. Both 2D and 3D data are stored in organized grids in the form of data matrices. As can be seen from Figure 2.14(a), all the pixel values of a 2D image fall within the range of 0 to 255, while the range data in Figure 2.15(b) can go beyond 255 depending on the height differences of features on the pavement surface. It should be noted that the 3D height data range as shown is not representative of an entire pavement surface, as 3D height reference points can be 0 or in single digit for a pavement surface. Generally pavement with large surface variations, such as severe rutting and other major defects, would have high dynamic range in 3D height data as well. But such variations mostly would be within 10-bit to 12-bit range.

The 2D intensity images with dynamic range of 0~255 can be efficiently stored into one of these commonly used raster graphics formats, such as TIFF, PNG, JPEG and JPEG 2000. Currently, most if not all of the venders and technology developers implemented JPEG or JPEG2000 as the data formats for 2D image storage, and therefore there is no need to investigate a new format. One aspect to consider is the proper compression rate that is desired for pavement data collection and analysis, which can be adjusted by users in theory.



60	60	62	60	57	56	57	58	58	58	59	59	59	60	64	67	69	69	68	71
71	70	66	61	56	57	62	67	67	65	61	60	60	62	63	64	63	62	70	70
56	55	57	54	52	55	62	66	66	65	70	69	69	69	69	68	65	63	64	59
48	49	52	53	56	60	63	64	62	61	63	64	66	69	72	73	71	69	67	62
70	70	61	63	66	69	70	68	64	61	57	57	59	62	65	65	64	62	70	70
76	76	72	71	71	74	78	77	72	67	72	71	70	70	69	67	64	62	65	68
70	71	76	71	68	73	82	86	80	73	76	74	73	71	70	68	65	63	59	63
71	71	78	80	80	76	70	66	67	69	69	80	84	77	74	77	73	63	63	64
78	79	71	73	76	80	83	82	79	75	84	89	89	83	83	89	93	91	80	82
82	78	70	68	69	76	84	86	81	74	57	55	50	44	39	38	39	41	43	50
78	76	82	75	69	67	69	69	65	60	70	69	71	73	70	64	62	64	72	74
59	61	55	55	56	59	63	68	72	75	84	85	88	92	90	83	80	81	70	71
88	90	92	95	97	94	88	82	80	81	72	74	75	75	75	75	76	77	104	101
40	35	29	37	46	53	57	61	67	72	62	68	71	68	71	80	85	83	78	77
105	113	126	126	125	122	120	121	125	128	118	125	120	105	95	94	87	77	79	81
120	124	129	130	130	130	129	128	126	125	117	118	122	126	120	104	88	79	76	67
86	95	120	121	123	124	125	124	122	121	127	122	116	110	97	79	64	57	56	53
92	90	68	73	80	89	97	104	108	111	95	89	84	83	81	78	76	78	73	74
107	98	85	82	76	69	62	56	52	49	59	53	49	50	52	52	55	59	52	54
72	68	68	67	67	67	69	74	78	80	86	80	76	76	74	69	67	68	54	57

278	278	277	278	280	283	285	285	285	284	281	281	281	282	283	284	285	285	283	283
286	286	286	285	285	284	283	282	280	279	286	285	284	282	281	280	280	280	283	283
284	285	286	285	284	282	282	282	283	284	281	280	280	279	279	279	280	281	283	284
280	281	277	277	278	278	277	278	280	281	279	279	279	278	277	276	277	278	277	278
266	267	274	276	279	281	281	281	281	282	283	284	285	285	284	283	284	285	285	285
240	240	241	245	250	254	257	260	263	266	268	271	275	278	280	282	284	286	285	285
236	234	235	235	236	236	236	239	244	248	247	249	251	250	247	245	244	244	246	246
255	255	255	250	244	240	239	237	235	232	228	226	224	223	223	223	221	220	217	216
261	260	262	261	259	257	255	254	252	251	250	249	246	244	241	237	231	227	226	226
286	285	283	284	282	277	269	262	257	255	254	253	250	248	244	239	234	230	226	226
288	288	288	289	288	285	279	273	268	266	257	255	250	247	244	242	239	236	232	229
290	289	288	287	287	286	285	281	277	273	265	261	255	249	245	241	238	235	230	227
289	288	293	290	287	285	285	282	276	271	263	260	254	248	242	236	231	228	232	232
293	292	289	287	285	286	287	286	281	277	267	262	255	249	243	239	234	232	227	227
291	290	293	291	290	290	290	287	283	279	274	268	258	250	244	240	238	237	232	229
290	291	290	290	289	289	289	288	286	284	277	272	263	254	246	240	236	234	229	226
287	286	289	288	288	287	286	284	281	279	277	273	267	260	254	249	246	244	242	239
287	284	280	277	274	270	267	263	260	258	258	256	254	251	249	247	245	243	240	239
285	281	278	274	268	262	258	254	252	251	243	242	241	241	240	239	236	234	233	230
288	285	280	277	272	267	262	258	255	253	249	247	245	243	241	238	234	231	227	225

(a) 2D image with pixel data matrix (b) 3D image with range data matrix

Figure 2.14 Example pavement image with 2D and 3D data matrices

For 3D data, however, only a few raster graphics formats can handle data with dynamic range beyond 255, such as BPG and PGF. Most existing 3D file formats were developed based on complex mechanisms for the storage of un-organized data, while pavement images data contains well organized "gridded" data in the form of a matrix of pixels or range values. Each point on a pavement surface can be defined by a unique *X*, *Y* coordinate pair plus the height information. Optimal data representation and compression methods could be significantly different between organized and un-organized data. XML-based data formats could handle data with any data ranges, but at the cost of possible large storage requirements. Considering the data storage efficiency, none of them are comparable to these optimized raster graphics formats for 2D/3D pavement images which are in the well-organized grids form.

Pavement Image Data Management Practices

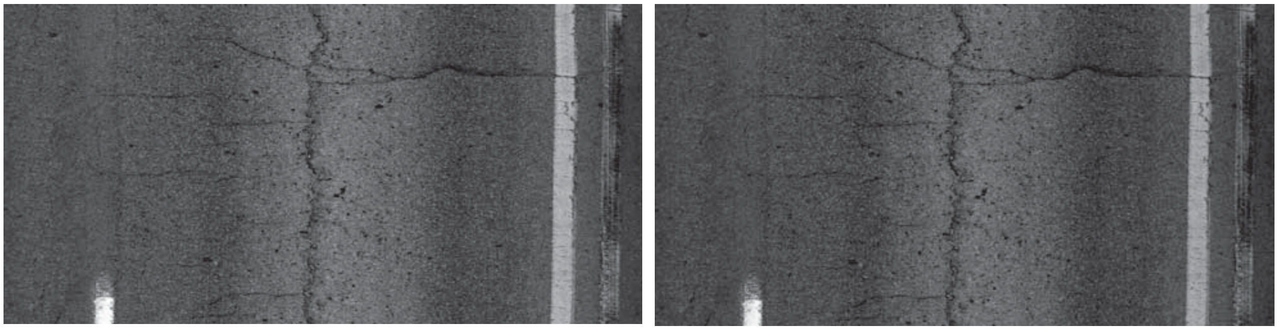
Efficient data management has become an ever-increasing concern as large amount of data are collected with a single pass of pavement data collection. Because almost all of the data management software and handling procedures are proprietary, it is challenging to characterize the industry as a whole. Essentially every technology supplier uses different formats and procedures and users can be at a loss as to how a given data management system works. According to NCHRP 334 Report (McGhee, 2004), the great variety of responses makes it very difficult to identify any consensus procedures, highlighting the need for standardization of data management systems.

One critical component of data management is “metadata,” which are the background information that describes the content, quality, condition, and other appropriate characteristics of pavement surfaces. Metadata serves many important purposes including data browsing, data transfer, and data documentation (McGhee, 2004). Metadata can be organized into several levels ranging from a simple listing of basic information of available data to detailed documentation of an individual data set. At a fundamental level, metadata may support the creation of an inventory 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 applications. At a more detailed level, metadata insures that potential data users can make an informed decision about whether data are appropriate for the intended use. Due to the lack of standards, 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.

Image data management depends greatly on the means of image capture. 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 for later archiving and removal to the user's media.

The storage and management of pavement condition data and images are common problems for both vendors and users. Although the great volumes of data produced have overtaxed storage capabilities in the past, the data storage industry has solved 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.

Compression is widely used for image archiving and data management. For 2D intensity image data, JPEG or JPEG 2000 standard is widely used for data compression. Two examples are given in the TRB draft circular (Wang and Smadi, 2011). The example in Figure 2.15 (a) is a restored JPEG image compressed 6:1 with the size of approximately 1.4 MB using Discrete Cosign Transfer (DCT) coding algorithm, while the same pavement surface compressed with JPEG 2000 in Figure 2.15 (b) has the size of approximately 400 KB, with a compression ratio of approximately 20:1 using wavelet-based method. The JPEG format is a "lossy" compression protocol that decreases file size by permanently removing image information, such as spatial resolution, tonal range, and color. Depending on the settings, JPEG2000 can be either lossless (LL) or lossy (lo) compression. The JPEG2000 format offers improved image quality over JPEG, with the file size being slightly to significantly smaller. However, more CPU resources are required to encode and decode a JPEG2000 image, which may cause challenges for real time data acquisition and data analysis for pavements in some occasions. It should also be noted that both JPEG and JPEG2000 only support 8-bit images.



(a) JPEG Compressed (b) JPEG2000

Figure 2.15 Compression of a 4,096-pixel resolution image (Wang and Smadi, 2011).

For 3D range data, 16 bits depth data is commonly used because 8 bit depth dynamic range may not be adequate for pavements in fair to poor conditions, or with special features such as curbs or edge drop-offs. However, the commonly used compression algorithms, such as GIF, JPEG, and PNG, cannot be directly used for the compression of 16-bit single channel data. To our best knowledge, this challenge has not been addressed by any public accessible literatures. Several venders have developed their own proprietary software for the compression purpose. Uncompressed raw data format is also used by some agencies, such as TxDOT.

Data management with compressed images can be conducted through database management software, such as Microsoft Access or SQL database. Many vendors or technology suppliers develop special software (Wang and Smadi, 2011) to manage collected data sets, including images and location information obtained during field operation, and to build, save, use real-time viewing applications and generate reports.

3. INTERVIEW TPF-5(299) PARTICIPATING HIGHWAY AGENCIES AND TECHNOLOGY SUPPLIERS

Introduction

Another important work in Task 2 is to survey various individuals representing the SHAs and the pavement industry associations that are heavily involved in pavement surface condition data collection and analysis. The purpose of these interviews is to obtain information and insight regarding surface condition data (including transverse profile) collection practices, data items collected and their formats, crack data processing and reporting, desired crack data usage in pavement management program, data quality and variations, desired improvement of surface condition data collection practices. The design of the survey is discussed and agency responses are documented. The team will solicit all available pertinent documentation for follow-up evaluation of these practices in Task 3.

Design of Survey Questionnaire

In particular, agencies participating in the Transportation Pooled-Fund Study TPF-5(299): *Improving the Quality of Pavement Surface Distress and Transverse Profile Data Collection and Analysis* (https://collaboration.fhwa.dot.gov/dot/fhwa/tpf5299/default.aspx) were selected as the primary source of information. The participating highway agencies at the time of the survey include FHWA, Alabama, Arkansas, California, Florida, Georgia, Kansas, Kentucky, Maryland, Mississippi, Montana, North Carolina, North Dakota, Ohio, Oregon, Pennsylvania, South Dakota, Texas, Virginia, and Washington. The survey questions are designed as below into four broad areas, answers from which would be used as basis to develop standard data formats for 2D/3D pavement image data for the project.

- Pavement Image Data Collection
  - What pavement image data are desired in your agency?
  - Does your agency collect pavement image data at network level for pavement management, and/or at project level to support planning and programming of pavement preservation, rehabilitation, and reconstruction activities?
  - What type of data collection technology is used in your agency: manual, semi- or fully-automated? 2D based or 3D based technology?
  - Which data collection protocol(s) does your agency use?
  - What data items are collected in the existing practice?
  - What data formats are used for pavement surface condition and transverse profile?
  - Are the data compressed during data collection? What data compression algorithm(s) does your agency use?
  - How image data are managed in your agency?
  - What is your agency's QC/QA procedure during data collection?
  - How is the image data processed, analyzed and reported?

- Desired Image Data Usage
  - How does your agency use pavement image data?
  - What is your agency's plan to establish pavement performance measurements using image data to meet the MAP-21 data requirements?

- How does your agency collect imaging data for the new HPMS reporting?
- How does your agency collect imaging data for pavement management system decision making?
- Does your agency have plans to implement MEPDG? What is your data source for local calibration?

- Pavement Image Data Evaluation

  - Are existing pavement imaging data adequate for your agency? What are the missing data item(s)? What data item(s) can be excluded from existing practices?
  - What are the desirable precision, accuracy, and tolerance of the data items collected in your agency?
  - What are the costs of the data items collected in your agency? Are they feasible to meet various needs in your agency?
  - Is your agency satisfied with the image data collected, their data formats, and data management practices?

- Desired Improvement to Current Image Data Collection Practices

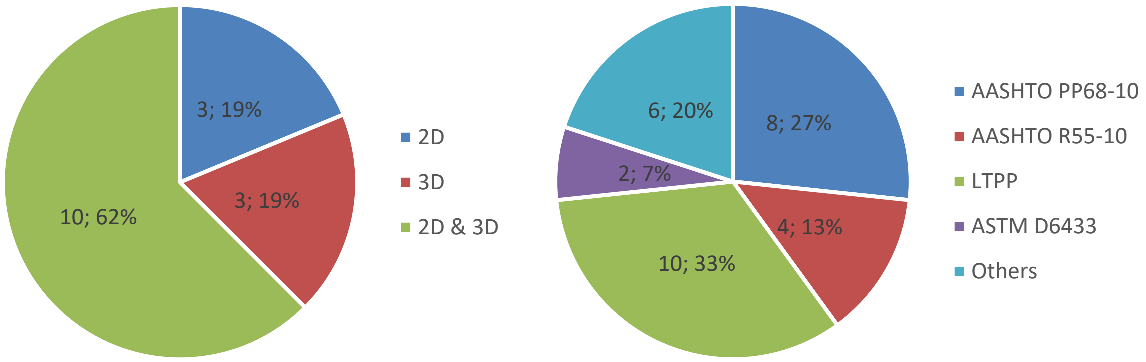
  - What does your agency like to do to improve the image data collection process, including technology, data items collected, data format, and data collection protocols?
  - What does your agency like to do to improve the image data analysis process?
  - Have you initiated any process to upgrade and/or current image data collection and processing procedures?

The survey questionnaire is provided in Appendix A, which was sent to FHWA, the TPF-5(299) participating States, seven technology providers (Fugro Roadware, Pathway, International Cybernetics Corporation, Dynatest, Pavemetrics, Mandli, and Surface System & Instruments), and one academia (Georgia Tech) in September 2015. Sixteen responses, including twelve State DOTs (Florida, Kansas, Louisiana, Maryland, Mississippi, North Carolina, North Dakota, New Jersey, Pennsylvania, South Dakota, Texas, Washington), three technology providers (Fugro Roadware, Pathway, and Mandli), and Georgia Tech, were obtained. The list of survey participants are provided in Appendix B to appreciate their time and efforts for completing the survey and providing feedback.

Survey Results

The detailed summary of the survey responses is in Appendix C. This Chapter only summarizes the key points from the survey. It should be noted that some of the surveys were incomplete, leading to inconsistent total number of survey respondents in the figures. The following is a summary of the key points from the survey.

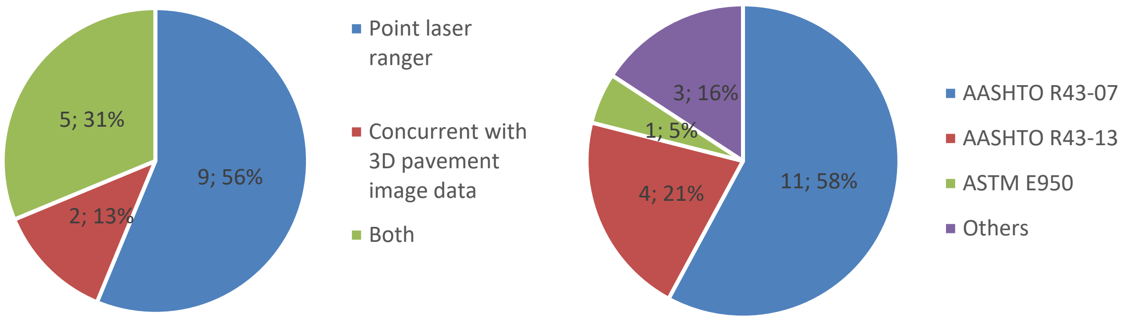
- **Pavement surface image data collection technology** (Figure 3.1a): Ten participants report that they collect both 2D and 3D image data, while three collect only 2D and three only 3D image data.
- **Pavement surface image data collection protocols**: More than fifty percent of the agencies (10 responses) are using the *LTPP Distress Identification Manual* for image data collection, while eight agencies have implemented the new provisional approved AASHTO PP68-10 protocol, four are following the AASHTO R55-10 protocol. There are eight agencies that also report that they have developed their State-specific protocols (Figure 3.1b).



(a) Data Collection Technology (b) Data Collection Protocols

Figure 3.1 Pavement Image Data

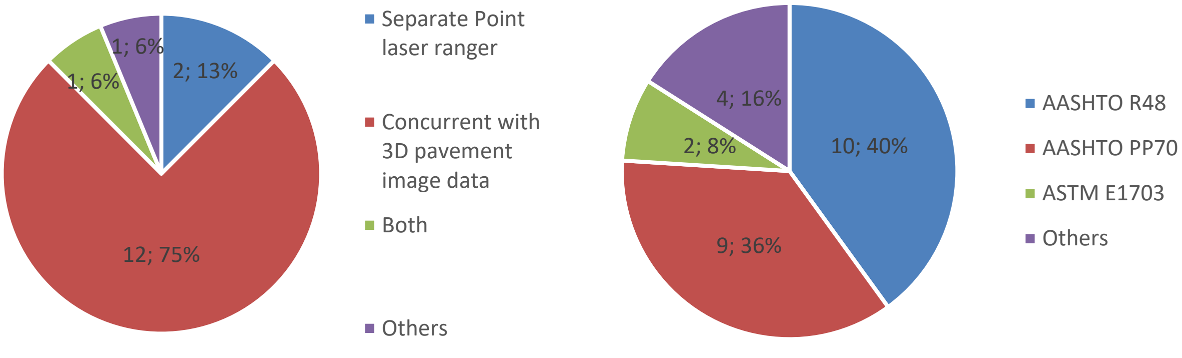
- **Longitudinal profile data collection technology**: Two of the 16 participants are obtaining longitudinal profiles from 3D pavement image data, while nine are using point laser ranger as a traditional equipment, and five using both methods for longitudinal profile data collection (Figure 3.2a).
- **Longitudinal profile data collection protocols**: Longitudinal profiling is collected primarily following the AASHTO R43-07 protocol (11 responses). Four report that they are using the AASHTO R43-13 protocol, while four also depend on other protocols such as those developed by their States (Figure 3.2b).



(a) Data Collection Technology (b) Data Collection Protocols

Figure 3.2 Longitudinal Profile Data

- **Transverse profile data collection technology**: Most participants (12 of the 16) are collecting transverse profile concurrent with 3D pavement image data in a single pass, while two are using point laser ranger as traditional equipment, one using both, and one using other methods for transverse profile data collection (Figure 3.3a).
- **Transverse profile data collection protocols**: Transverse profiling is collected primarily following the AASHTO R48 protocol (10 responses) and the newly Provisional AASHTO PP70 protocol (nine responses). Four report that they are using the AASHTO R43-13 protocol, while two follow the ASTM E 1703 protocol, and four also depend on other protocols such as those developed by their States (Figure 3.3b).



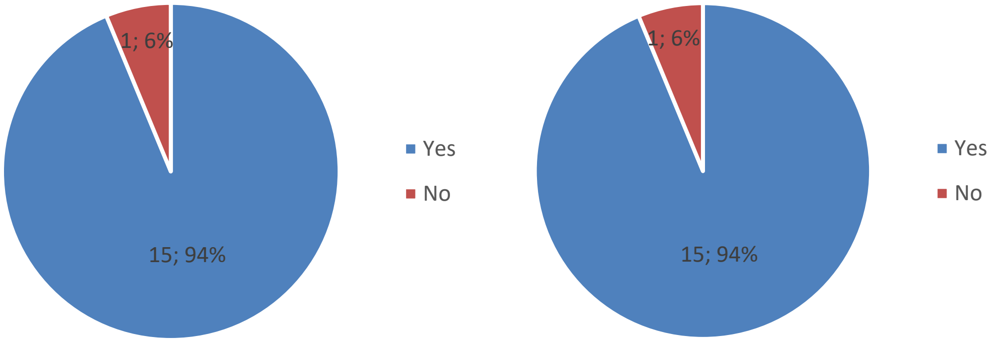
(a) Data Collection Technology (b) Data Collection Protocols

Figure 3.3 Transverse Profile Data

- **Peripheral Data**: All participants except one collect peripheral data, among which 14 collect right-of-way (ROW) data, 6 collect sign inventory data, several others also collect shoulder, guard rail, geometry, and/or rumble strips data. Twelve participants report they use additional cameras for peripheral data collection, while the rest rely on other technologies (Figure 3.4a).
- **Inertial Measurement Unit (IMU) Data**: All participants except one collect IMU data (Figure 3.4b). The data items collected by IMU vary among the participants, as shown in Table 3.1.

Table 3.1 IMU Data Collection

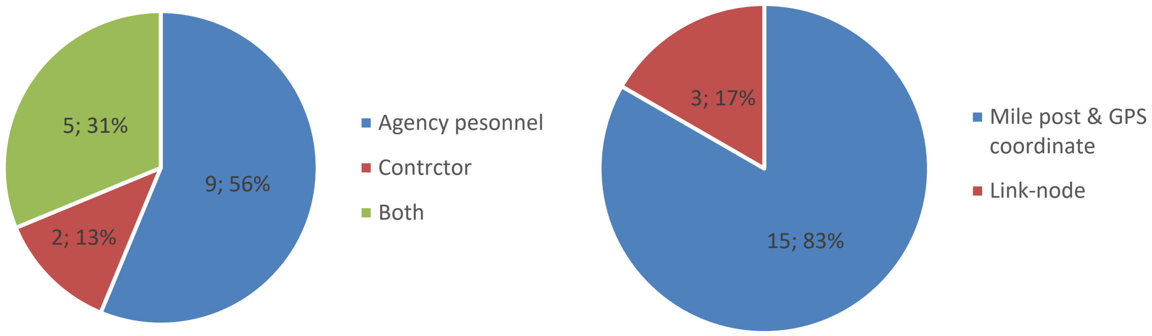
Data Items	# Responders
Position, such as GPS coordinates, elevation	15
Dynamics, such as angular rate and acceleration in the longitudinal, transverse, and vertical directions	10
Attitude, such as roll, pitch, heading	14
Speed	13
Velocity in north, east, and down direction	4



(a) Peripheral Data collection (Y/N) (b) IMU Data collection (Y/N)

Figure 3.4 Other Data

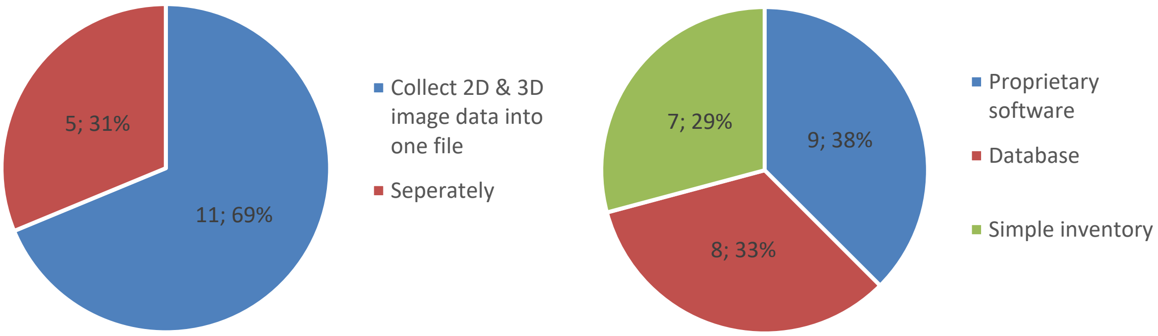
- **Image Data Collection Crew**: Nine agencies rely on agency personnel for image data collection, while two totally contract out the image data collection. Five agencies use a combination of both methods (Figure 3.5a).
- **Location Reference Data**: All participants except one collect location reference data using “Mile post” and “GPS coordinate,” while three agencies are deploying the “Link-node” method (Figure 3.5b).



(a) Data Collection Crew (b) Location Reference

Figure 3.5 Data Collection Crew & Location Reference

- **Image Data Management**: Most participants (11 of 16) prefer to store 2D and 3D image into one file rather than save them separately. For image data storage, 8 use database management, 7 utilize simple inventory method, and 9 of them rely on proprietary software. For data sharing, all except one share data through network-based file server, 11 also use electronic media, and 8 use other web-based interfaces (Figure 3.6).

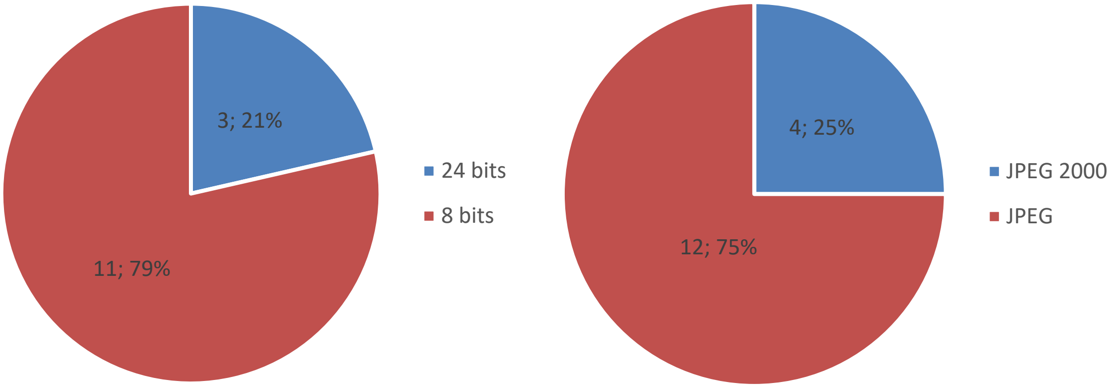


(a) Image Storage (b) Data Storage Type

Figure 3.6 Data Management

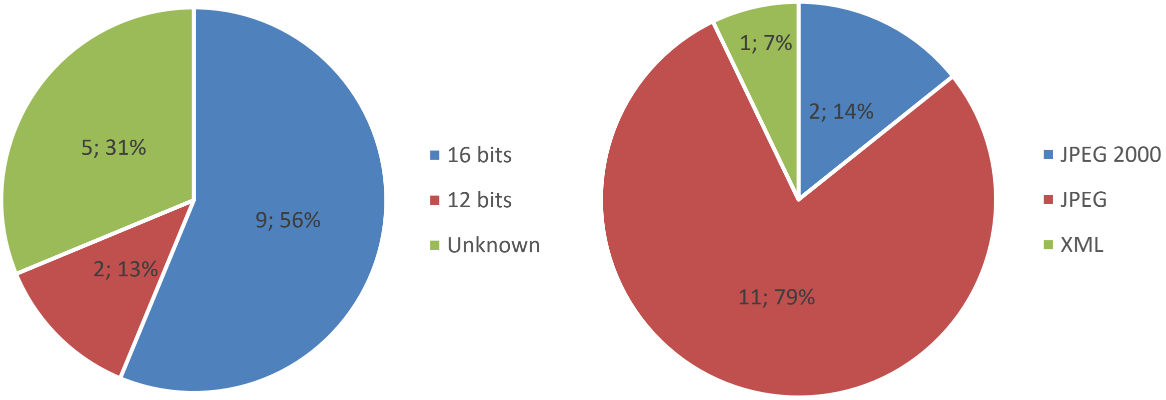
- **2D Image Data Format**: For 2D image data type (Figure 3.7), eleven use “Gray 8 bits” and three use “Color 24 bits.” The 2D image data compression is based primarily on JPEG (12 responders), and JPEG2000 (four responders).
- **3D Image Data Format**: Most of the responders (nine responses) use “16 bits” for the 3D image dynamic range, while two use “12 bits,” and five unknowns. The JPEG (11 participants) and JPEG2000 (two responses) are the primary data compression methods, and one report using XML data format for 3D data (Figure 3.8).

- **Others**: Right-of-way data are primarily saved in JPEG format. Four participants report that they collect LiDAR data, and four responses recommend including the LiDAR into the to-be-developed standard data format.



(a) Data Type (b) Data Compression

Figure 3.7 2D Image Data Format



(a) Data Type (b) Data Compression

Figure 3.8 3D Image Data Format

4. CONCLUSIONS

There is a critical need to develop a standard interchangeable data format for pavement surface condition and transverse profile for highway agencies and technology suppliers. Commonly agreed-upon data standards would yield substantial benefits. When implemented, the pavement image data from various sources can be shared across different analysis software platforms. Other expected benefits include facilitating workable protocols for condition surveys, improving implementation of new technologies, and accelerating the development potential of analysis tools for pavement condition. This report summarizes the Task 2 work performed by the research team. In this Task, a comprehensive literature review is conducted regarding the current practices of various methodologies within highway agencies for automated pavement image data collection. Existing industry image data formats and management of such data sets are assessed and documented.

- While the FHWA, AASHTO, and ASTM have all issued standards for the terminology, definitions, and data collection techniques, there is still variation in the distress data and collection methods used by highway and local transportation agencies.
- There are handful of vendors and technology suppliers that have been practicing the collection of pavement imaging data over the past several decades either as integrators of Pavemetrics® LCMS sensors or technological developers such as WayLink PaveVision3D, Pathway, and TxDOT VTexture systems.
- 2D images have been widely used to collect pavement cracking data and estimate pavement distress. In the recent years, there have been rapid developments on the application of laser imaging technology for pavement surfaces, however, producers and consumers of 3D imaging system data rely on proprietary or ad-hoc formats to store and exchange data without open standards.
- More than 140 types of 3D data format standards have been established primarily by the computer graphics and computational geometry community, the majority of which were created before today's modern sensing technologies and algorithms. Recently, as 3D point-cloud data from laser scanning is becoming increasingly common, many new versions of 3D data formats have been developed for various applications, such as the U3D, ASTM E57 file format, and 3DFC. Particularly, several efforts have been made to establish standard formats for transportation related applications, such as the HiSPEQ Project in Europe, the FEF, the OpenCRG® format, LandXML, and the "Elementary Data" format. However, most existing 3D file formats were developed based on complex mechanisms for the storage of un-organized data, while pavement images data contains well organized "gridded" data in the form of a matrix of pixels and range values. Optimal data representation and compression methods could be achieved for organized data comparing to un-organized data.
- The 2D intensity images with dynamic range of 0 to 255 can be efficiently stored into one of these commonly used raster graphics formats, such as TIFF, PNG, JPEG and JPEG 2000. For 3D data, however, only a few of raster graphics formats can handle data with dynamic range beyond 255, such as BPG and PGF. Currently, majority if not all of the venders and technological developers are implementing JPEG or JPEG2000 as the data formats for 2D image storage. The 3D pavement data formats are seldom disclosed by technology developers.
- Due to the changes in the HPMS requirements, the MAP-21 rulemaking on performance measures, and the need for high-quality distress data for the AASHTO Mechanistic-Empirical Pavement Design, more agencies are recognizing the importance of data

quality and consistency. Some agencies have developed their own distress identification manuals either as stand-alone references or as supplements to AASHTO, ASTM, or FHWA standards or practices. In the very recent years, States are implementing the new AASHTO Provisional Standard PP 67-10 for image data analysis and PP 68-10 for automated image data collection.

In addition, a questionnaire survey is performed to determine the current state-of-the-practice in their automated distress collection techniques and data management. Results obtained from TPF-5(299) participating State highway agencies, data collection vendors, and technology suppliers that are heavily involved in pavement surface condition data collection and analysis. The information and insight regarding surface condition data collection practices, data items collected and their formats, crack data processing and reporting, desired crack data usage in pavement management program, data quality and variations, desired improvement of surface condition data collection practices are obtained and summarized.

- The 3D laser scanning and imaging technology has rapidly gained its popularity for pavement surface image data collection. Three respondents are totally depending on 3D technology, 10 participants report that they collect both 2D and 3D image data, while three agencies collect only 2D image data.
- The 3D data sets are increasingly used for longitudinal and transverse profile measurements. 10 of the 16 participants collect longitudinal profiling data concurrent with 3D pavement image data in a single pass, while eight are using point laser ranger as traditional equipment. For transverse profile, 12 of the 16 participants acquire it directly from 3D pavement image data.
- There has been a lack of uniformity of distress protocols for pavement surface image data collection. Ten agencies are using the LTPP Distress Identification Manual (which was written for manual surveys), while eight agencies have implemented the new AASHTO PP68-10 protocol (which was designed to support automated data process), four are following the AASHTO R55-10 protocol. Eight States also report that they have developed their State-specific protocols.
- For 2D image data, 11 participants use “Gray 8 bits” and three respondents use “Color 24 bits”. The 2D image data compression is based primarily on JPEG (12 respondents), and JPEG2000 (four respondents).
- For 3D image data, most of the responders (nine responses) recommend or use “16 bits” for the 3D image dynamic range, while two use “12 bits,” and five unknowns. JPEG (11 participants) and JPEG2000 (two responses) are the primary data compression methods, and one report using XML data format for 3D data.

The literature review and questionnaire survey will serve as the foundation of the assessment of existing data items collected and data formats of pavement image data (Task 3) and the development of a standard data format to determine pavement surface condition and profiles (Task 4). The team will solicit all available pertinent documentation for follow-up evaluation of these practices in Task 3. In summary, data format to be used to store pavement 3D surface information needs to be powerful to accommodate large size data, flexible for higher resolution data and new features in the future, and adaptable to implement future automated analysis algorithms. Based on the literature review, the existing data formats have various limitations. However, several compression algorithms can be adopted for pavement 3D data storage. It is therefore recommended that a new data format be developed. Task 3 report contains recommended data structure for 3D pavement data and Task 4 report provides recommendations of compression requirements and suitable compression algorithms.

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APPENDIX A. SURVEY QUESTIONAIRE

Survey Questionnaire

September 2015

Development of Standard Data Format for 2-Dimensional and 3-Dimensional (2D/3D) Pavement Image Data that is used to determine Pavement Surface Condition and Profiles

For TPF-5(299) Participating Highway Agencies and Technology Suppliers

You are asked to help develop a standard data format for 2-Dimensional and 3-Dimensional (2D/3D) pavement image data by participating in this survey. The standard data format for pavement image data on cracking and transverse profile will become a valuable resource for the industry to advance and apply new technologies in a cost-effective manner. When implemented, the new data format will allow pavement image data from various sources to be shared and processed with a standard platform, such as a software written to the standard can read data files from different suppliers. This questionnaire has been simplified to the extent possible given the nature of the material. Please do not hesitate to directly contact Kelvin Wang (kelvin.wang@okstate.edu, mobile: 479-799-6513), or the project Technical Point of Contact Andy Mergenmeier (Andy.Mergenmeier@dot.gov, phone: 667-239-0879) if you have issue with the questionnaire. **After receiving the survey data from you, members of the research team may contact you for additional information or clarifications. Your efforts and assistance are appreciated!**

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).

Name: ____________________

Agency: ____________________

Title: ____________________

Telephone: ____________________

E-mail: ____________________

Please return the completed questionnaire by e-mail by October 5, 2015 to the five email addresses of the core research team and TPOC:

kelvin.wang@okstate.edu, Andy.Mergenmeier@dot.gov, qiang.li@okstate.edu, ghm.chen@gmail.com, gkchang@thetranstecgroup.com

Part I - Pavement Image Data Collection Practices

1. Pavement surface image data collection

    a. Data collection technology

        ☐ Manual

        ☐ 2D Digital Image only

            ☐ Line Scan

            ☐ Area Scan

        ☐ 3D Range Data only

            ☐ 3D Laser Triangulation

            ☐ LiDAR

            ☐ Others, please describe: ______________________________

        ☐ Hybrid 2D and 3D data (Collect both 2D and 3D data)

            Please describe: ______________________________

    b. Data collection protocol

        ☐ AASHTO PP68-10 *Collecting Images of Pavement Surfaces for Distress Detection* LTPP

        ☐ *Distress Identification Manual*

        ☐ ASTM D6433 *Standard Practice for Roads & Parking Lots PCI Surveys*

        ☐ AASHTO R55-10 *Quantifying Cracks in Asphalt Pavement Surfaces*

        ☐ Others, please describe: ______________________________

2. Longitudinal profile data collection

    a. Data collection technology

        ☐ Concurrent with 3D pavement image data in a single pass

        ☐ Point laser ranger as a traditional equipment

    b. Data collection protocol

        ☐ AASHTO R 43-07 *Standard Practice for Quantifying Roughness of Pavements*

        ☐ Others, please describe: ______________________________

3. Transverse profile data collection

a. Data collection technology

☐ Concurrent with 3D pavement image data in a single pass

☐ Separate point laser ranger

b. Data collection protocol

☐ AASHTO PP70 *Collecting the Transverse Pavement Profile*

☐ AASHTO R48 *Determining Rut Depth in Pavements*.

☐ Others, please describe: ______________________________

4. Peripheral data (Right-Of-Way images, sign inventory, other items)

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

☐ Yes ☐ No

b. Types of data collected

☐ Right-of-way images

☐ Sign inventory

☐ Drainage inventory

☐ Other inventory data, please describe: ______________________________

c. Data collection technology

☐ 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.)

5. Location referencing used for pavement image data collection

☐ Mile post

☐ Link-node

☐ GPS coordinates

☐ Other protocol: ______________________________

(If agency specific protocol are used, please attach or e-mail copies.)

6. Initial Measurement Unit (IMU) data

a. Does your agency collect IMU data?

☐ Yes ☐ No

b. If yes, list the data items that are saved/used in your data sets

☐ Position, such as GPS coordinates, elevation

☐ Dynamics, such as angular rate and acceleration for the longitudinal, transverse, and vertical direction

☐ Attitude, such as roll, pitch, heading

☐ Speed

☐ Velocity in north, east, and down directions

7. Are pavement image data collected by

☐ Agency personnel

☐ Contractor

☐ Both

☐ Other, please describe: ____

Part II Pavement Image Data Management

1. Considering the convenience for data analyzing, reporting, sharing and management, what is your preferred pavement length stored in one single data file? (Such as 6 feet, 100 feet, et.al.) Please note that the file size will grow proportionally with this length value: _______________

2. Do you prefer to store simultaneously collected 2D and 3D image data into one file?

☐ Yes ☐ No, I prefer to store 2D data and 3D data into separated files

3. How do you manage pavement image data?

☐ Simple inventory without database management

☐ Database archive: Access, SQL Express, SQL Server, Oracle

☐ Propitiatory software: ____

4. How do you share pavement image data?

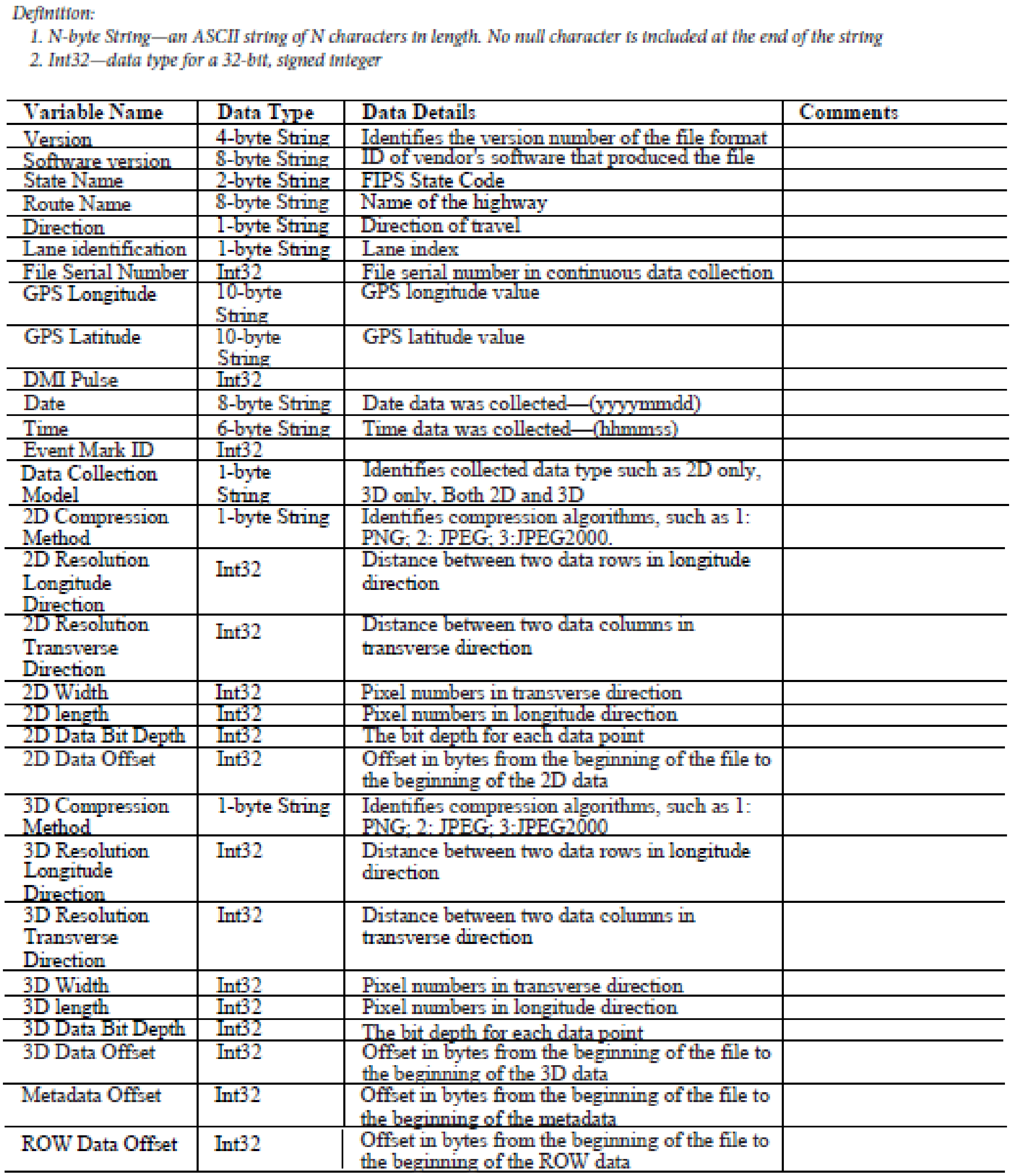
☐ Electronic media such as CD, Thumb Drive, or Hard Disk

☐ Network-based file server

☐ Other methods, please describe: ______________________________________

Part III Pavement Image Data Format

1. File Header: tentative data items are shown in the table for the pavement 2D and 3D data. The research team would like to have your input and comments regarding the data items and their descriptions/specifications. The final draft for the data items will be different from the items shown. Please provide your additional comments below the table if the space is not enough.



Definition:

1. *N-byte String—an ASCII string of N characters in length. No null character is included at the end of the string*
2. *Int32—data type for a 32-bit, signed integer*

Variable Name	Data Type	Data Details	Comments
Version	4-byte String	Identifies the version number of the file format	
Software version	8-byte String	ID of vendor's software that produced the file	
State Name	2-byte String	FIPS State Code	
Route Name	8-byte String	Name of the highway	
Direction	1-byte String	Direction of travel	
Lane identification	1-byte String	Lane index	
File Serial Number	Int32	File serial number in continuous data collection	
GPS Longitude	10-byte String	GPS longitude value	
GPS Latitude	10-byte String	GPS latitude value	
DMI Pulse	Int32		
Date	8-byte String	Date data was collected—(yyyymmdd)	
Time	6-byte String	Time data was collected—(hhmmss)	
Event Mark ID	Int32		
Data Collection Model	1-byte String	Identifies collected data type such as 2D only, 3D only, Both 2D and 3D	
2D Compression Method	1-byte String	Identifies compression algorithms, such as 1: PNG; 2: JPEG; 3:JPEG2000.	
2D Resolution Longitude Direction	Int32	Distance between two data rows in longitude direction	
2D Resolution Transverse Direction	Int32	Distance between two data columns in transverse direction	
2D Width	Int32	Pixel numbers in transverse direction	
2D length	Int32	Pixel numbers in longitude direction	
2D Data Bit Depth	Int32	The bit depth for each data point	
2D Data Offset	Int32	Offset in bytes from the beginning of the file to the beginning of the 2D data	
3D Compression Method	1-byte String	Identifies compression algorithms, such as 1: PNG; 2: JPEG; 3:JPEG2000	
3D Resolution Longitude Direction	Int32	Distance between two data rows in longitude direction	
3D Resolution Transverse Direction	Int32	Distance between two data columns in transverse direction	
3D Width	Int32	Pixel numbers in transverse direction	
3D length	Int32	Pixel numbers in longitude direction	
3D Data Bit Depth	Int32	The bit depth for each data point	
3D Data Offset	Int32	Offset in bytes from the beginning of the file to the beginning of the 3D data	
Metadata Offset	Int32	Offset in bytes from the beginning of the file to the beginning of the metadata	
ROW Data Offset	Int32	Offset in bytes from the beginning of the file to the beginning of the ROW data	

Distance Uni	Int32	Units for distances	
Elevation Unit	Int32	Units for elevation	
Speed Unit	Int32	Units for speed	
Speed	Int32	Average vehicle speed associated with data	

Additional comments

2. In addition to the items defined in the file header, please specify other items to be included.

Variable Name	**Data Type**	**Data Details**

3. Image data types and compressions that you think would be appropriate for future deployment. Please mark your selection and provide comments.

a. 2D image type

Format	**Comments**
☐ Color: 24 bits	
☐ Gray: 8bits	
☐ Others	

b. 2D data compression, please mark your selection, and provide comment

Compression Standard	Comments
☐ JPG	
☐ JPG 2000	
☐ PNG	
☐ BMP	
☐ Other 1	
☐ Other 2	

c. 3D image dynamic range, please mark your selection, and provide comment

Dynamic Range	Comment
☐ 8-bit	
☐ 10-bit	
☐ 12-bit	
☐ 16-bit	
☐ Others	

d. 3D data compression, please mark your selection, and provide comment

Compression Standard	Comments
☐ JPG	
☐ JPG 2000	

☐ PNG	
☐ Others	

e. What is your current 3D data compression rate (such as 2:1, 5:1, 10:1, 20:1, et.al. You may give a range)?

____

4. Peripheral Data (right of way, signage data etc)

a. Right-of-Way Data format

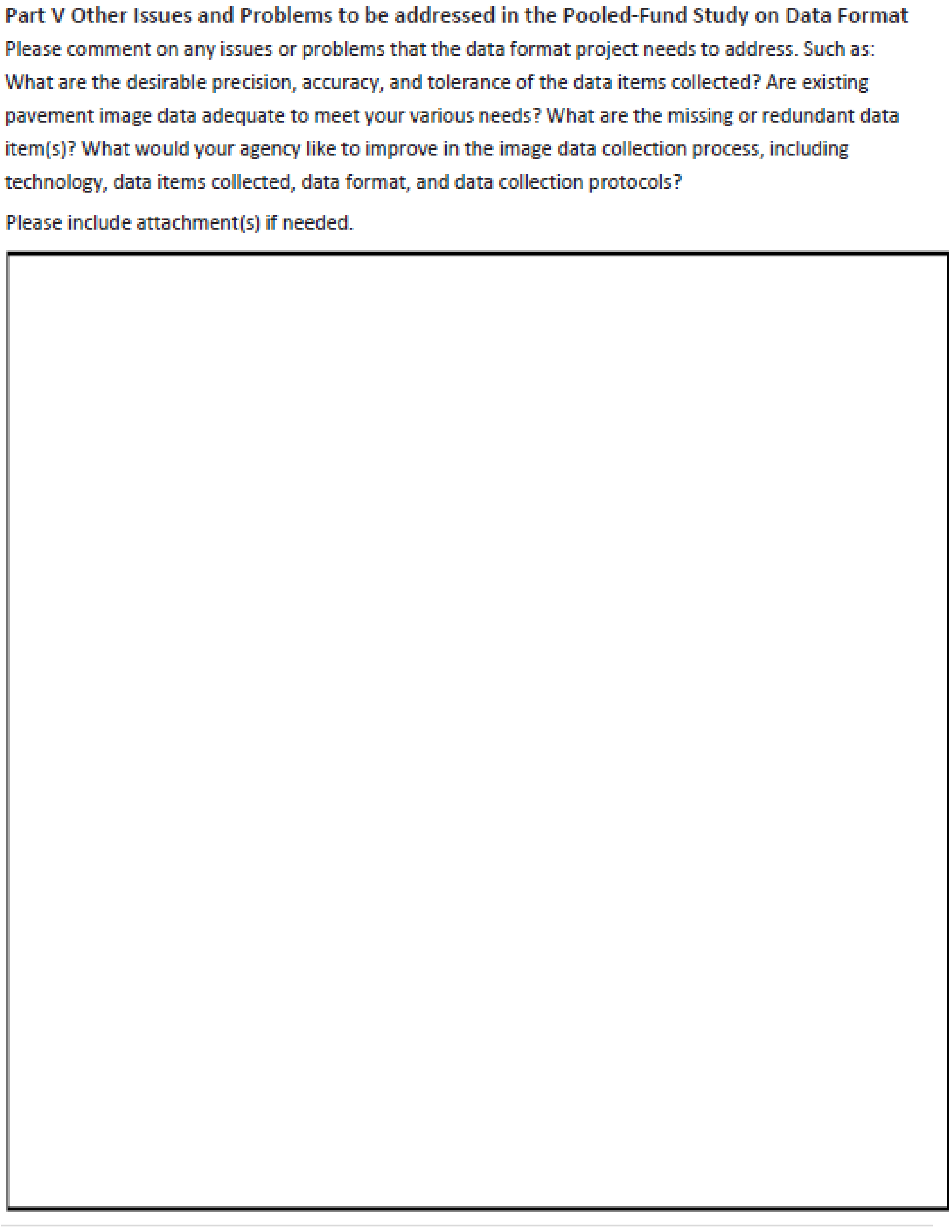
Compression Standard	Comments
☐ JPG	
☐ JPG 2000	
☐ PNG	
☐ BMP	
☐ Others	

b. LiDAR data

Do you collect LiDAR data?	☐ Yes	☐ No
Should we include LIDAR data into the data format?	☐ Yes	☐ No

Part IV Pavement Data Processing

Briefly describe your practice of data reduction and processing for distress analysis, including if manual or automated processing	
Briefly describe the cracking and rutting protocols you are using in production environment	



Part V Other Issues and Problems to be addressed in the Pooled-Fund Study on Data Format

Please comment on any issues or problems that the data format project needs to address. Such as: What are the desirable precision, accuracy, and tolerance of the data items collected? Are existing pavement image data adequate to meet your various needs? What are the missing or redundant data item(s)? What would your agency like to improve in the image data collection process, including technology, data items collected, data format, and data collection protocols?

Please include attachment(s) if needed.

APPENDIX B. SURVEY PARTICIPANTS

A total of 16 responses were received from the questionnaire survey. Their time and efforts to complete the survey and also provide their feedback and comments are appreciated.

Name	Agency	Title	Telephone	E-mail
Abdenour Nazef	Florida Department of Transportation (DOT)	Pavement Systems Engineer	352-955-6322	abdenour.nazef@dot.state.fl.us
Rick Miller	Kansas DOT	Pavement Management Engineer	785-291-3842	rick@ksdot.org
Christophe Fillastre	Louisiana DOT	Management Systems and Data Collection Pavement Management Engineer	225-242-4577	Christophe.Fillastre@LA.GOV
John Andrews	Maryland State Highway Administration	Assistant Division Chief	443-572-5177	Jandrews@SHA.state.MD.US
Cynthia J. Smith	Mississippi DOT	Assistant State Research Engineer	601-359-7648	cjsmith@mdot.ms.gov
Randy Finger	North Carolina DOT	State Pavement Management Engineer	919-835-8209	afinger@ncdot.gov
Stephanie Weigel	North Dakota DOT	Pavement Management Engineer	701-328-2528	sjweigel@nd.gov
Philip Bertucci	New Jersey DOT	Pavement Management Supervisor	609-530-4489	Philip.Bertucci@dot.nj.gov
John Van Sickle	Pennsylvania DOT	Program Management and Quality Control Engineer	717-705-8920	jvansickle@pa.gov
David Huft	South Dakota DOT	Office of Research Program Manager	605-773-3358	Dave.Huft@state.sd.us
Robin (Yaxiong) Huang	Texas DOT	Pavement Equipment Coordinator	512-832-7309	robin.huang@txdot.gov
David Luhr	Washington State DOT	Pavement Management Engineer	360-709-5405	LuhrD@wsdot.wa.gov
Damion Orsi	Fugro Roadware	Product Manager	905-567-2899	dorsi@fugro.com
Michael J Richardson	Mandli Communications	Project Manager	608-216-4438	mrichardson@mandli.com
Scott Mathison	Pathway Service Inc.	VP Operations	918-259-9883	smathison@pathwayservices.com
Yichang (James) Tsai	Georgia Institute of Technology	Professor	404-894-6950	james.tsai@ce.gatech.edu

APPENDIX C. SUMMARY OF SURVEY RESPONSES

The survey includes four parts: Pavement Image Data Collection Practices, Pavement Image Data Management, Pavement Image Data Format, and Pavement Data Processing. The survey responses are summarized in the following tables.

Part I Pavement Image Collection Practices

Agency	**Pavement image data collection** technology	**Pavement image data collection** protocol	**Longitudinal profile data collection** technology	**Longitudinal profile data collection** protocol	**Transverse profile data collection** technology	**Transverse profile data collection** protocol	**Peripheral data collection**	**Peripheral data** types	**Peripheral data** collection technology	Location referencing used for pavement image data collection	Collect IMU data?	Saved IMU data items	IMU data collected by
FDOT	2D, Line scan	Distress Identification Manual,	Point laser ranger	Florida Method (FM) 5-549	Separate point laser ranger	FM 5-549 for Rut Measurement and FM Develop	No		Additional cameras, Automated Faulting, AASHTO R 36 (Method B)	GPS coordinates	Yes	Position, Attitude, Speed, Dynamic	Agency personne, in-house consultant
KDOT	2D & 3D, Pavemetrics	AASHTO PP68-10	Point laser ranger	AASHTO R 43-07	Concurrent with 3D pavement image data in a single pass	AASHTO PP70, AASHTO R48	Yes	Right-of-way images, Sign inventory	Additional cameras- Forward cameras facing straight and left	Mile post, GPS coordinates	Yes	Position, Attitude, Speed	Agency personnel
LA-DOTD	2D, Area scan	Distress Identification Manual, LADOTD Protocals	Point laser ranger	AASHTO R 43-07, LADOTD Protocals	Separate point laser ranger	AASHTO PP70, AASHTO R48, LADOTD Protocals	Yes	Right-of-way images, Sign inventory, Geometry	Other technology	Mile post, GPS coordinates LADOTD Protocals	Yes	Position, Attitude, Speed, Dynamic, Velocity	Contractor
MDOT	2D & 3D, Contractor 3D, MDOT 2D	Distress Identification Manual,	Both	others	Concurrent with 3D pavement image data in a single pass	others	Yes	Required HPMS attributs	HPMS Field Manual	Mile post, GPS coordinates	Yes	Position, Attitude, Speed,	Both

Agency	**Pavement image data collection** technology	**Pavement image data collection** protocol	**Longitudinal profile data collection** technology	**Longitudinal profile data collection** protocol	**Transverse profile data collection** technology	**Transverse profile data collection** protocol	**Peripheral data collection**	**Peripheral data** types	**Peripheral data** collection technology	Location referencing used for pavement image data collection	Collect IMU data?	Saved IMU data items	IMU data collected by
NCDOT	2D & 3D, 3D but w/intensity data converted to 2D JPEG imaging	AASHTO PP68-10, Distress Identification Manual,	Both	AASHTO R 43-07, AASHTO R 43-13	Concurrent with 3D pavement image data	AASHTO PP70, AASHTO R48	Yes	Right-of-way images, Shoulder and guard rail	Additional cameras, IMU &GPS	Mile post, GPS coordinates	Yes	Position, Attitude, Speed, Dynamic, Velocity	Contractor
ND DOT	2D & 3D, 3D but w/intensity data converted to 2D JPEG imaging	AASHTO PP68-10, Distress Identification Manual,	Both	AASHTO R 43-13	Concurrent with 3D pavement image data in a single pass	AASHTO PP70, AASHTO R48	Yes	Right-of-way images, Inventory is post-process	Additional cameras, IMU & GPS	Mile post, GPS coordinates	Yes	Position, Attitude, Speed, Dynamic	Agency personnel
NJ DOT	2D & 3D, 3D but w/intensity data converted to 2D JPEG imaging	AASHTO PP68-10, Distress Identification Manual,	Both	AASHTO R 43-13	Concurrent with 3D pavement image data in a single pass	AASHTO PP70, AASHTO R48	Yes	Right-of-way images, Inventory is post-process	Additional cameras, IMU & GPS	Mile post, GPS coordinates	Yes	Position, Attitude, Speed, Dynamic	Agency personnel
PENN DOT	3D	PennDOT Pavement Condition Survey Manual	Point laser ranger	AASHTO R 43-07, ASTM E950	Concurrent with 3D pavement image data in a single pass	AASHTO R48, PennDOT Pavement Condition Survey Manual	Yes	Right-of-way images, Geometry, Rumble strips	Ground Penetrating Radar	Pennsylvania Location Reference Sys.	Yes	Position, Speed, Dynamic	Both
SD DOT	2D & 3D, LCMS Sensor	AASHTO PP68-10, Distress Identification Manual, AASHTO R55-10 , ASTM D6433	Point laser ranger	AASHTO R 43-07	Concurrent with 3D pavement image data in a single pass	AASHTO PP70, AASHTO R48	Yes	Right-of-way images, Sign inventory, Drainage inventory	Additional cameras, Other technology	Mile post, GPS coordinates Link-node	Yes	Position, Attitude, Speed, Dynamic, Velocity	Agency personnel

Agency	**Pavement image data collection** technology	**Pavement image data collection** protocol	**Longitudinal profile data collection** technology	**Longitudinal profile data collection** protocol	**Transverse profile data collection** technology	**Transverse profile data collection** protocol	**Peripheral data collection**	**Peripheral data** types	**Peripheral data** collection technology	Location referencing used for pavement image data collection	Collect IMU data?	Saved IMU data items	IMU data collected by
TxDOT	2D & 3D, Also with intensity image data	TxDOT PMIS	Point laser ranger	others	Concurrent with 3D pavement image data in a single pass	others	Yes	Right-of-way images	Additional cameras- Single Ethernet camera	Mile post, GPS coordinates	No		Agency personnel
WSDOT	3D, 3D Laser Triangulation	AASHTO PP68-10	Concurrent with 3D pavement image data in a single pass	AASHTO R 43-07	Concurrent with 3D pavement image data in a single pass	ASTM E1703	Yes	Right-of-way images	Additional cameras- 3-camera forward view	Mile post, GPS coordinates ARM	Yes	Attitude	Agency personnel
Fugro Roadware	2D & 3D, Line Scan, Area Scan, 3D Laser Triangulation	AASHTO PP68-10, Distress Identification Manual, AASHTO R55-10 , ASTM D6433	Point laser ranger	AASHTO R 43-07	Both	AASHTO PP70, AASHTO R48	Yes	Right-of-way images, Sign inventory, Drainage inventory, Bridge Clearances, etc.	Additional cameras, GPR	Mile post, GPS coordinates Link-node	Yes	Position, Attitude, Speed, Dynamic	Both
Mandli Communications	2D & 3D, LCMS	AASHTO PP68-10, Distress Identification Manual, AASHTO R55-10 , ASTM D6433	Point laser ranger	AASHTO R 43-07	Concurrent with 3D pavement image data in a single pass	AASHTO PP70, AASHTO R48	Yes	Right-of-way images, Sign inventory, Drainage inventory	Additional cameras, Other technology	Mile post, GPS coordinates Link-node	Yes	Position, Attitude, Speed, Dynamic, Velocity	Both
Maryland SHA	2D, Line Scan Area Scan	AASHTO R55-10 , It's in the "spirit of R55"	Point laser ranger	AASHTO R 43-07, ITSO R43	others	Transverse line & Ultrasonic	Yes	Right-of-way images, Inventory derived from ROW images	Other technology	Mile post, GPS coordinates	Yes	Position, Attitude, Speed, Dynamic,	Agency personnel

Agency	**Pavement image data collection** technology	**Pavement image data collection** protocol	**Longitudinal profile data collection** technology	**Longitudinal profile data collection** protocol	**Transverse profile data collection** technology	**Transverse profile data collection** protocol	**Peripheral data collection**	**Peripheral data** types	**Peripheral data** collection technology	Location referencing used for pavement image data collection	Collect IMU data?	Saved IMU data items	IMU data collected by
Pathway Service Inc.	2D & 3D, 3D but w/intensity data converted to 2D JPEG imaging	AASHTO PP68-10, Distress Identification Manual, AASHTO R55-10 , 32 State DOT Distress Manuals	Both	AASHTO R 43-07, AASHTO R 43-13	Concurrent with 3D pavement image data in a single pass	AASHTO PP70, AASHTO R48	Yes	Right-of-way images, Sign inventory, MUTCD, MIRE, Map 21	Additional cameras, IMU, GPS GPR, LiDAR	Mile post, GPS coordinates Link-node	Yes	Position, Attitude, Speed, Dynamic, Velocity	Both
Georgia Institute of Technology	3D, 3D Laser Triangulation, LiDAR	Distress Identification Manual, GDOT distress identification manual	Concurrent with 3D pavement image data in a single pass,	AASHTO R 43-07	Concurrent with 3D pavement image data in a single pass	ASTM E1703	Yes	Right-of-way images, Sign inventory,	Additional cameras,	Mile post, GPS coordinates	Yes	Position, Attitude	Agency personnel

Part II Pavement Image Data Management

Agency	Preferred pavement length	Do you prefer to store simultaneously collected 2D and 3D image data into one file?	How do you manage pavement image data?	How do you share pavement image data?
FDOT	Full section length varies	No, I prefer to store 2D and 3D data into separated file	Simple inventory without database management	Electronic media such as CD, Thumb drive, or Hard Disk Network-based file server Other methods-File Transfer Protocol (FTP)
KDOT	26.4 feet	Yes	Database archive: Access, SQL Express, SQL Serve, Oracle	Network-based file server
LADOTD	W13ft X L21.12ft	No, I prefer to store 2D and 3D data into separated file	Database archive: Access, SQL Express, SQL Server, Oracle Propitiatory software-Fugro Roadware iVision and Vision software	Electronic media such as CD, Thumb drive, or Hard Disk Network-based file server Other methods-Fugro Roadware iVision and Vision Software
MDOT	Possibly 1/10 mile	Yes	Propitiatory software- Have used both Pathweb and Visiweb	Network-based file server
NCDOT	26.4 feet	Yes	Simple inventory without database management, Propitiatory software-contractor desktop and web viewing applications	Electronic media such as CD, Thumb drive, or Hard Disk Other methods-PathWeb
NDDOT	26.4 feet	Yes	Simple inventory without database management, Propitiatory software-contractor desktop and web viewing applications	Electronic media such as CD, Thumb drive, or Hard Disk Network-based file server Other methods-PathWeb
NJDOT	26.4 feet	Yes	Simple inventory without database management, Propitiatory software-contractor desktop and web viewing applications	Electronic media such as CD, Thumb drive, or Hard Disk Network-based file server
PENNDOT	20 feet	Yes	Database archive: Access, SQL Express, SQL Server, Oracle	Network-based file server
SDDOT	Doesn't matter	No, I prefer to store 2D and 3D data into separated file	Database archive: Access, SQL Express, SQL Server, Oracle	Network-based file server Other methods-Web-based interface
TxDOT	28	Yes	Simple inventory without database management, Propitiatory software-Both in house and contractor software	Electronic media such as CD, Thumb drive, or Hard Disk Network-based file server
WSDOT	N/A	No, I prefer to store 2D and 3D data into separated file	Propitiatory software-PathView II	Electronic media such as CD, Thumb drive, or Hard Disk Network-based file server; Other methods-Website
Fugro Roadware	10m	Yes	Database archive: Access, SQL Express, SQL Server, Oracle Propitiatory software-Vision	Electronic media such as CD, Thumb drive, or Hard Disk Network-based file server Other methods-Internet (web server)

Agency	Preferred pavement length	Do you prefer to store simultaneously collected 2D and 3D image data into one file?	How do you manage pavement image data?	How do you share pavement image data?
Mandli Communications	N/A	No, I prefer to store 2D and 3D data into separated file	Simple inventory without database management, Database archive: Access, SQL Express, SQL Server, Oracle	Electronic media such as CD, Thumb drive, or Hard Disk Network-based file server
Maryland SHA	N/A	Yes	Database archive: Access, SQL Express, SQL Server, Oracle Propitiatory software	Electronic media such as CD, Thumb drive, or Hard Disk Network-based file server
Pathway Service Inc.	26.4 feet	Yes	Simple inventory without database management, Propitiatory software-contractor desktop and web viewing applications	Electronic media such as CD, Thumb drive, or Hard Disk Network-based file server Other methods-PathWeb
Georgia Institute of Technology	15feet	Yes	Database archive: Access, SQL Express, SQL Server, Oracle	Network-based file server

Part III Pavement Image Data Format & Part IV Pavement Data Processing

Agency	2D image type	2D data compression	3D image dynamic range	3D data compression	Current 3D data compression rate	Right-of-Way Data Format	LiDAR data collection?	Should include LiDAR data?	Data analysis	Cracking and Rutting Protocol
FDOT	Gray: 8bits	JPG JPG 2000	12 bit	JPG 2000		JPG	No	Yes	2D LRIS imaging is used to evaluate cracking and other surface distresses (ex spalling) for PCC pavements that are difficult to survey by windshield survey. A point and trace method is used to measure the distresses from images. We have an ongoing a study to implement automated/semi-automated imaging pavement distress survey method(s)	windshield survey(cracking); 3 single point lasers(rutting); 2D images for certain PCC areas.
KDOT	Gray: 8 bits	JPG	Others	JPG		JPG	No	Yes	Automated	AASHTO
LADOTD		JPG		JPG		JPG	No	No	Automated and Manual processing using Fugro Roadware Vision Processing software	
MDOT							No		Contractor processes and reduces data; we do QA on it. The QA is partly automated and partly manual.	Slightly modified LTPP Distress Identification Manual.
NCDOT	Gray: 8 bits	JPG	16 bit	JPG		JPG	No	No	Fully automated and performed by contractor per NCDOT type, severity and extent specifications. Third party contractor QCs 5% of mileage collected.	Performed by contractor per industry standards
NDDOT	Gray: 8 bits	JPG	16 bit	JPG	vendor allows anywhere from 1:1 to 200:1	JPG	No	No	Semi-automated. We QC a small percentage of the fully automated data and add our patching data manually since it's hard to detect effectively.	North Dakota-specific cracking definitions. Load associated cracking is most important
NJDOT	Gray: 8 bits	JPG	16 bit	JPG	vendor allows anywhere from 1:1 to 200:1	JPG	No	No	Semi-automated. We QC a small percentage of the fully automated data and add our patching data manually since it's hard to detect effectively.	New Jersey-specific cracking definitions. Load associated cracking is most important
PENN DOT	Gray: 8 bits	JPG	Others	JPG	Unknown	JPG	No	Yes	It is a semi-automated process. Our vendor uses their proprietary software for automatic crack detection. However there are distresses we collect that the software cannot detect and the images are reviewed manually for those conditions.	Protocols are described in our Publication 336 which will be provided with this survey.

Agency	2D image type	2D data compression	3D image dynamic range	3D data compression	Current 3D data compression rate	Right-of-Way Data Format	LiDAR data collection?	Should include LiDAR data?	Data analysis	Cracking and Rutting Protocol
SD DOT	Color: 24 bits Gray: 8 bits	JPG JPG 2000	16 bit	JPG JPG 2000 PNG	10:1	JPG JPG 2000	No	No	We are currently working on converting from manual to automated processing.	
TxDOT	Gray: 8 bits		16 bit		1:1	JPG	No	No	Processing at real time. Not raw data are saved for network level data collection	PMIS, AASHTO
WSDOT									Distresses are manually marked based on the pavement images. The integration of automated capabilities is still under review, with a goal of incrementally including automated data as appropriate.	Cracking is categorized according to the attached manual. Rutting follows AASHTO E1703
Fugro Roadware	Gray: 8bits	JPG JPG 2000	8bit 12bit 16bit	JPG Lossless/ 95%		JPG	Yes	No	We use JPEG and .FIS file formats in our automated detection algorithms in a batch processor. We can also manually rate the images or .FIS files in our software and all distresses are stored in the SQL database.	Our flexible software algorithms are able to process the data using any AASHTO, ASTM and EN protocol
Mandli Communications	Color: 24 bits	JPG	16 bit	JPG Others-XML		JPG	Yes	No	Automated, With Manual rating	AASHTO, HPMS
Maryland SHA	Gray: 8 bits	JPG JPG 2000	64 bit to cover range and resolution	Others-specialized			No	No	Automated and Manual using vendor proprietary software and in-house developed analytics	"Wisecrax" and manual systems combined into a unique reporting system
Pathway Service Inc.	Gray: 8 bits	JPG	16 bit	JPG	anywhere from 1:1 to 200:1	JPG	Yes	No	Fully automated. Analyze raw 3D files, then convert the detected data into "cracks" per client-specific definitions. Type, severity and extent are programmable.	All industry standards are supported for processing and reporting.
Georgia Institute of Technology	Color: 24 bits	others, Lossless compression would be better for pavement images	16 bit Consider the accuracy improvement in the future	others .		JPG	Yes	Yes	Semi-automatic method is used for image processing to extract pavement distress data.	GDOT pavement distress identification manual is currently used.