Evaluation of Proposed Standard Data Format and Compression Algorithms for 2D/3D Pavement Surface Image

Office of Technical Services
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FOREWORD

This report summarizes the work under FHWA contract DTFH6117P00139 to critically evaluate the standard data format for two-dimensional/three-dimensional (2D/3D) pavement surface images. This report will be of interest to personnel responsible for pavement management data storage and accessibility. The standard data format was clarified as a container-codec format, which is convenient for the following implementation and application to support state highway agencies' operation. The original 2D/3D standard data format was refined by providing additional description to further clarify the standard image representation, sensor system identification, range data registration, and other refinements. The refined 2D/3D standard data format has been reviewed by several state highway agencies, 3D sensing technology vendors, and service providers. To assess the refined 2D/3D standard data format, preliminary testing was performed in cooperation with a state highway agency and a 3D sensing technology vendor. The testing results showed that a data transfer using the refined standard data format can be successfully performed without loss of information. Thus, the 2D/3D data collected by a vendor can be stored in the standard data format and extracted by a state highway agency to perform pavement condition evaluation. Finally, a set of rules was recommended for a state highway agency to verify the data compliance of the standard data format, and recommendations were made for implementation of the standard data format.

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National Resource Center

NOTICE

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16. Abstract
This report summarizes the work under FHWA contract DTFH6117P00139 to critically evaluate the standard data format for two-dimensional/three-dimensional (2D/3D) pavement surface images. First, the standard data format was clarified as a container-codec format, which meets the state of the practice of using 2D/3D images for pavement condition evaluation. Thus, it is convenient for the following implementation and application to support state highway agencies' operation. Meanwhile, other existing data formats, e.g., OpenCRG, can also be included as an image codec, which provides flexibility for future extension to meet data users' different needs. Second, the original 2D/3D standard data format was refined by providing additional description to further clarify the standard image representation, sensor system identification, range data registration, and other refinements. The refined 2D/3D standard data format was reviewed by several state highway agencies, 3D sensing technology vendors, and service providers. Third, to assess the refined 2D/3D standard data format, preliminary testing was performed in cooperation with a state highway agency and a 3D sensing technology vendor. The testing results showed that a data transfer using the refined standard data format can be successfully performed without loss of information. Thus, the 2D/3D data collected by a vendor can be stored in the standard data format and extracted by a state highway agency to perform pavement condition evaluation. Fourth, the compression algorithms evaluated in the original report were verified. The verification results showed some deviation from those in the original contract due to the absence of detailed parameter settings in the original report. Finally, a set of rules was recommended for a state highway agency to verify the data compliance of the standard data format, and recommendations were made for implementation of the standard data format.

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SI* (MODERN METRIC) CONVERSION FACTORS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		APPROXIMATE CONVERSIONS TO SI UNITS		
		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		
in²	square inches	645.2	square millimeters	mm²
ft²	square feet	0.093	square meters	m²
yd²	square yard	0.836	square meters	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km²
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.028	cubic meters	m³
yd³	cubic yards	0.765	cubic meters	m³
		NOTE: volumes greater than 1000 L shall be shown in m³		
		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/m²	cd/m²
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in²	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		
mm²	square millimeters	0.0016	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.195	square yards	yd²
ha	hectares	2.47	acres	ac
km²	square kilometers	0.386	square miles	mi²
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m³	cubic meters	35.314	cubic feet	ft³
m³	cubic meters	1.307	cubic yards	yd³
		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/m²	candela/m²	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/in²

*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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CHAPTER 1. INTRODUCTION

BACKGROUND

With the new national pavement performance measures required by the Fixing America's Surface Transportation (FAST) Act and internal state highway agency needs, state highway agencies have shown fast-growing interest in adopting emerging two-dimensional/three-dimensional (2D/3D) sensing technology for evaluating highway pavements.

Most vendors of this 2D/3D technology use proprietary instrumentation and methods to develop hardware/software platforms to acquire, compress, store, transmit, analyze, and evaluate the images. The communities that purchase these data have determined that a standard data format would enable the communication and interchangeability across different pavement applications and software platforms. As indicated in the RFQ HTSBAL1700000003PR, a standard data format will help the following:

- Reprocessing data when new analysis algorithms are developed.
- Analyzing 2D/3D digital images from different sources.
- Supporting the structure of the American Association of State Highway and Transportation Officials (AASHTO) standards that separate data collection from analysis (similar to the one for longitudinal profilers).
- Effectively exchanging data across users, software tools, and platforms.
- Promoting the development of 2D/3D pavement data collection technology.

To move in this direction, the Federal Highway Administration (FHWA) contracted for the "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" (FHWA contract DTFH6115P00103). The original contractor, Oklahoma State University (OSU), developed three reports and a draft specification for the standard data format. The purpose of this current project (i.e., FHWA contract DTFH6117P00139) is to conduct an independent evaluation to validate the results, and to refine the original 2D/3D standard data format for meeting users' needs.

The objectives of this project are as follows:

- Independently evaluate and, if needed, recommend changes to the three reports and the proposed draft specification for the standard data format and compression algorithm for 2D/3D data, which were delivered under the previous FHWA contract, DTFH6115P00103, to ensure they adequately address and document the subject matter.

- Verify the functionality and performance of the proposed standard data format and compression algorithm in terms of image fidelity processing speed, data storage requirements, and other important parameters.

- Assess the suitability of the standard data format for use by state highway agencies and 2D/3D technology vendors.

- Propose a methodology by which a state highway agency can confirm compliance with the standard data format.

REPORT OUTLINE

Based on the objectives specified above, the following are the major tasks to be conducted:

- Task 1: Review the three reports, the proposed draft specification for the standard data format, and the compression algorithm for 2D/3D data.

- Task 2: Verify the functionality and performance of the proposed standard data format and compression algorithm in terms of compression quality, compression speed, compression ratio, and other important metrics.

- Task 3: Assess the acceptability of the proposed data format for use by state highway agencies and 2D/3D technology vendors.

- Task 4: Propose a methodology by which a state highway agency can confirm compliance with the standard data format.

This final report is organized as follows: Chapters 2 to 5 present the results of the above four tasks, respectively. Chapter 6 summarizes the research findings.

CHAPTER 2. REVIEW OF WORK UNDER CONTRACT DTFH6115P00103

INTRODUCTION

Three reports were delivered under the original FHWA contract DTFH6115P00103. A review has been conducted, including the proposed specification for the standard data format. Figure 1 illustrates the original standard 2D/3D data format process and its possible usage.

As shown in Figure 1, a data vendor that provides 2D/3D data will convert its internal raw data into the standard data format and then transmit it to a state highway agency. In the original standard data format process, a vendor can use either open-source, such as JPEG 2000 (by the Joint Photographic Experts Group) or TIFF (Tagged Image File Format), or its own proprietary compression algorithms to compress the 2D/3D data. The original standard data format process allows different image representations of the decompressed 2D/3D data. The "image representation" defines how pixels are arranged in a decompressed 2D or 3D image. For example, image pixels can be arranged by row or by column in a data stream. The image representation should be further defined to facilitate data use and analysis. The further definition is provided to reduce challenges to state highway agencies due to the potential of different image representations from different vendors. Thus, a standard definition for 2D/3D image representation for the decompressed 2D/3D image is provided.

To visualize and/or analyze the 2D/3D data in the standard data format, analyzer software will first decode the compressed data according to the compression information in the header. If a vendor uses its proprietary algorithms for data compression, it shall provide codec for the analyzer software to decode the data. After 2D/3D data are decoded/decompressed, the analyzer software can read its pixel value for data visualization and/or analysis. As mentioned above, because the original standard format process allows different image representations, the analyzer software needs to know the pixel arrangement of the image from a specific vendor. Other than visualization, the original standard data format supports the extraction of various pavement distresses, such as cracking, rutting, texture/raveling, and faulting. However, the original data format does not support the measurement of cross slopes and smoothness due to the lack of information for range data registration. To support these applications, an additional data item is needed to indicate if range data are registered or not. To calculate pavement cross slopes and smoothness over a region, registered 3D data are required.

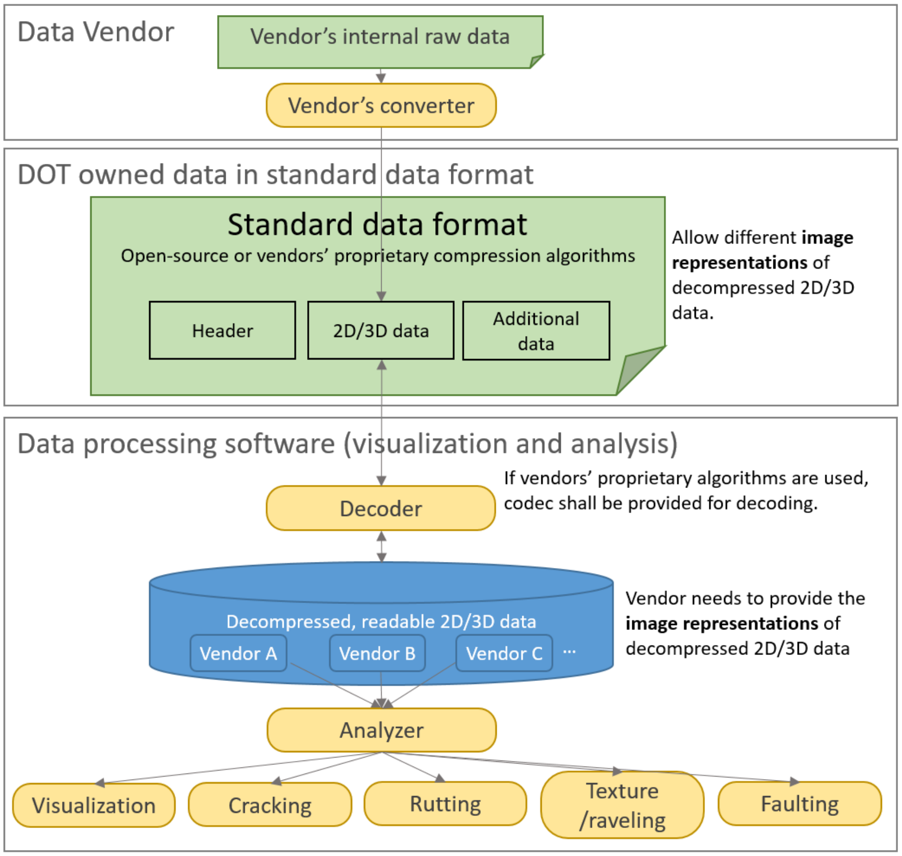

Figure 1. Chart. Original standard 2D/3D data format and possible usage.

REVIEW OF THREE REPORTS

The following subsections summarize the observations and comments from the review of the reports submitted under the original FHWA contract.

Task 2 Report – Research Current Practices

Summary

The Task 2 report is a literature review that summarizes the current technology, including 2D and 3D data collection methods. It summarizes others' synthesis of DOT and other agency practices and identifies the most common data items collected. It also identifies some common 2D (i.e., JPEG) and 3D data (i.e., E57) file formats. This report also compiles results of a survey of agencies related to their use of 2D and 3D data.

Observations and Comments

The Task 2 report identifies several techniques to collect 3D data, including photogrammetric; light detection and ranging (LiDAR); 3D laser triangulation; and laser illumination-based technology, such as laser road imaging systems (LRIS) or laser crack measurement systems

(LCMS). The report appropriately disregards current photogrammetric techniques due to the lighting conditions needed to get accurate results. The report also disregards LiDAR due to its current lack of resolution to measure small cracks; however, the report does not consider potential future improvements in the technology. Laser triangulation is recommended as having the highest potential, and the report notes that several vendors have the capability (i.e., INO/LCMS, WayLink, Pathway, and the Texas Department of Transportation [TxDOT]).

The report identifies some common 2D (e.g., JPEG, BMP, PNG, GIF, TIFF, GeoTIFF, BPG, PGF) and 3D data (e.g., U3D, E57, 3DFC, FEF, OpenCRG®, LandXML) file formats.

- **2D Formats:** JPEG was identified as the most appropriate format for 2D images. Other formats were disregarded for the following reasons:

    - BMP and PNG: File size was the reason in the report to eliminate BMP and PNG.

    - GIF: Was disregarded as it is only 8-bit, and the format has not been updated since 1989.

    - TIFF: Several advantages of the TIFF format were presented in the report, but GeoTIFF was deemed undesirable because GeoTIFF is designed to support geo-referencing and geo-encoding for large-scale raster image, e.g., satellite images. It is not an ideal format for 2D/3D pavement image data. .

    - BPG: Noted as a potential competitor to JPEG, but disregarded since it consists of patented algorithms.

    - PGF: Also considered a potential competitor to JPEG, but due to it is relative newness and limited use, it was not recommended.

  Overall, JPEG is the most used 2D format, and since no other formats stood out as superior it is logical to recommend JPEG for 2D.

- **3D Formats.** It is unclear in the report what format is recommended, beyond the 3D manufacturers' proprietary formats. The report does note in the Conclusion of the Task 2 report that "…the existing data formats have various limitations…it is therefore recommended that a new data format be developed." The report describes several formats but does not recommend any of those:

    - U3D: Noted as a format for computer graphics but disregarded since it is too complex.

    - E57: Has an American Society for Testing and Materials (ASTM) standard and is used by transportation-related imaging vendors like Bentley and AutoCAD. It is based on point cloud/LiDAR systems, and is also eliminated as being too complex a file design.

- 3DFC: Is not clearly described, but appears to need a decoder, so it would also be a proprietary issue.
- FEF: Uses XML, but was also disregarded, as it does not address compression.
- OpenCRG: Was designed to evaluate a vehicle's performance on the road by describing areas of the road in a detailed manner.

  Note: In CRG formats, the road data are stored as rectangular grids, similar to image formats, each having an arbitrary curve along which the rectangular grid is supposed to be curved to give the final representation (Figure 2). The report disregards this format due to concerns of flexibility, based on the limited format of its design. This recommendation is warranted based on the discussion below.
- LandXML: Was noted as widely adopted and nonproprietary but was not recommended due to poor forward compatibility.

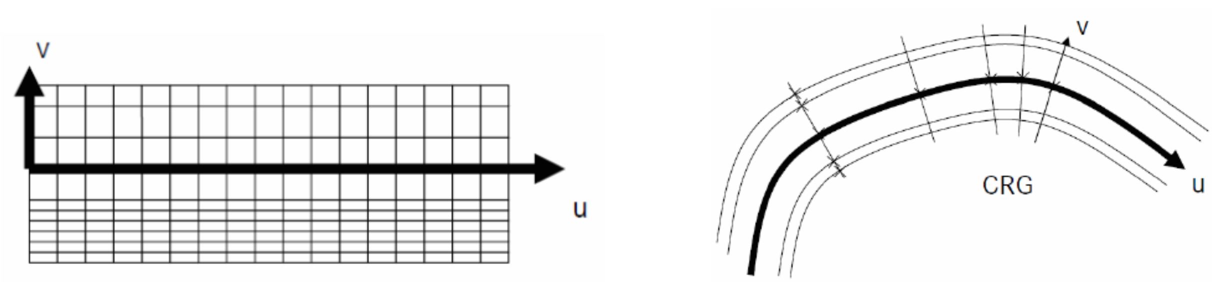

Figure 2. Diagram. CRG data format (OpenCRG, 2015).

The standard file format presented in the Task 4 report is based on the file format of IRI data. Some of the sections in the new standard (3.2, Table 13 in the Appendix) are similar to the existing ASTM standard (E2560-13) for IRI; others are modified versions of the IRI standard. The fields in the file header are directly from the "tentative" items in the original information gathering of the original project (it is assumed that the September 2015 information gathering was conducted very early in the project).

It is noted that, based on the refined data format, OpenCRG can still be used to store a 3D pavement image when it is considered as a codec (see Figure 3). However, the detailed data structure of an OpenCRG file will be hidden to the standard data format. Instead, an encoder will be used to convert an OpenCRG file to a 3D pavement image that complies with the standard image representation, as defined in the next section under "Standard Image Representation," when a 3D image is extracted from a file in the refined standard data format.

Task 3 Report – Evaluate Data Items and Formats

Summary

The Task 3 report covers the originally recommended file structure, which includes a file header, 2D and 3D data, and an optional/additional metadata section.

Observations and Comments

- The originally recommended file header is similar to ASTM E2560-13, which is used for 2D data (IRI).
- The image representation (e.g., the coordinates and storage after decompression) of the 2D intensity and 3D range data is expected to benefit from additional refinement, such as the definition of coordinate system and the pixel storage.
- There is a lack of a field in the original file header to indicate whether the range data are registered or not. Registration is the process of aligning the range value of all pixels in terms of a common or global coordinate system. The detailed explanation of registration is provided in the Range Data Registration section on page 13.

Task 4 Report – Develop Metadata and Proposed Standards

Summary

The Task 4 report summarizes the recommendations for the file structure and the file header from Task 3; it compares different file compression methods (i.e., JPEG and OSU's proprietary methods) using peak signal-to-noise ratio (PSNR). It also recommends "viewer software" be developed to assist in sharing data and viewing 3D images.

Observations and Comments

- Clearly specified the mapping between standard image representation and physical pavement surface using a Cartesian coordinate system.
- Add the sensor system identification information.
- Add a field in the file header to indicate if range data are registered or not.

Standard Specification

Summary

The standard specification is in the same format and contains much of the same information and tables as the ASTM E2560-13 specification (Standard Specification for Data Format for Pavement Profile; the filename extension is PPF) that is used for PPF files used in high-speed inertial profilers (HSIP).

Observations and Comments

Based on the review of the above three reports, the following refinements are recommended

- Clearly specified column-wise pixel storage and row-wise storage for the standard image representation. GPS reference point is also defined in the standard image representation.
- Add a field in the file header to include sensor system identification.
- Add a field in the file header to indicate if range data are registered or not.

RECOMMENDATIONS TO ORIGINAL SPECIFICATION

The following are the recommended items to be added to the original 2D/3D standard data format.

Standard Image Representation

It is highly recommended that a clear mapping between the standard image representation and the physical pavement surface to be formalized and added to the standard. Standard image representation is the in-memory abstraction of a pavement's surface segments and is the key to data interchangeability and data persistency.

Image representation defines how pixels in a matrix are mapped to the pavement surface and stored in a file system. In the original standard data format, it is unclear if an image representation is common or vendor-dependent. Based on this original standard data format, Figure 1 illustrates how data are generated and utilized. The purpose of the standard data format is to separate data collection and data usage (i.e., data visualization and analysis). As shown in Figure 1, when image representation is not unified in the standard data format, it may create barriers for other vendors to read and analyze the pavement data.

To address this issue, a standard image representation is recommended in the refined standard data format. The corresponding flowchart for data generation and data usage is shown in Figure 3. The standard data format can be viewed as a container of the 2D and 3D standard image representation. Thus, different 2D/3D image formats can be included, including OpenCRG. When registered range data are stored in the 3D image (i.e., the range data of each pixel corresponds to a fixed reference), then more pavement data (i.e., cross slope and IRI) can also be measured.

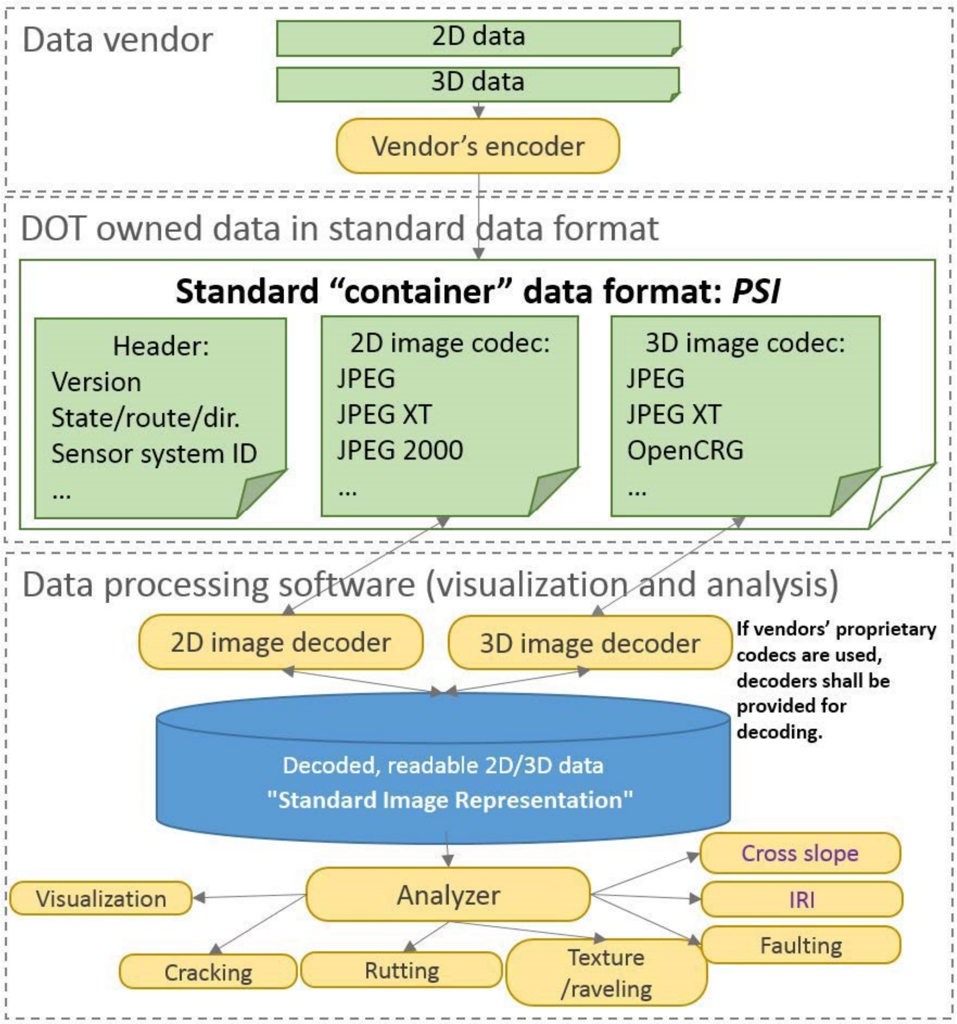

Figure 3. Chart. Recommended standard data format with defined image representation.

Two critical items need to be defined for a standard image representation. The first is a clearly defined coordinate system; the second is a clearly defined pixel storage method. It should be noted that by mapping the standard image representation to the physical pavement surface using a Cartesian coordinate system, we simplified the geometry of the pavement surface to be rectangular. The detailed reasons and consequences are discussed on page 11.

Clearly Defined Image Coordinate System

The definition of a pavement image coordinate system is already present in the original report. The following statements should be added for clarity:

- A row (parallel to the x axis) in the coordinate system corresponds to a transverse profile.
- A column (parallel to the y axis) in the coordinate system corresponds to a longitudinal profile.

The definition of transverse profile and longitudinal profile can be found in the Appendix sections 3.2.21 and 3.3.22, respectively.

Figure 4 illustrates a 2D or 3D image captured on a pavement with a predefined coordinate system. A two-dimensional, Cartesian, right-hand coordinate system is proposed in which the *x* axis is the transverse direction, which is perpendicular to the driving direction and points to the right side, and the *y* axis is the longitudinal/driving direction. A single line of pixels in the *x* direction forms a row; pixels form a column when they are in the *y* direction. The origin is located at the left-most pixel in the first row. Each pixel is located by its column and row numbers, which are counted from 0. An example is shown in Figure 4; the column and row numbers of the red-circled pixel are 14 and 3, respectively. The pixel can be located by the coordinates (14, 3). Please note that the 2D coordinate system shown in Figure 4 applies to both 2D and 3D images. For 2D data, each pixel stores the intensity data; for 3D data, each pixel stores the range data. In addition, the GPS coordinate (longitude and latitude using WGS84) for each image is defined at the origin. If the range data are registered, a reference range value of an image will be stored at the same reference point. The reference point is also the origin of the coordinate system.

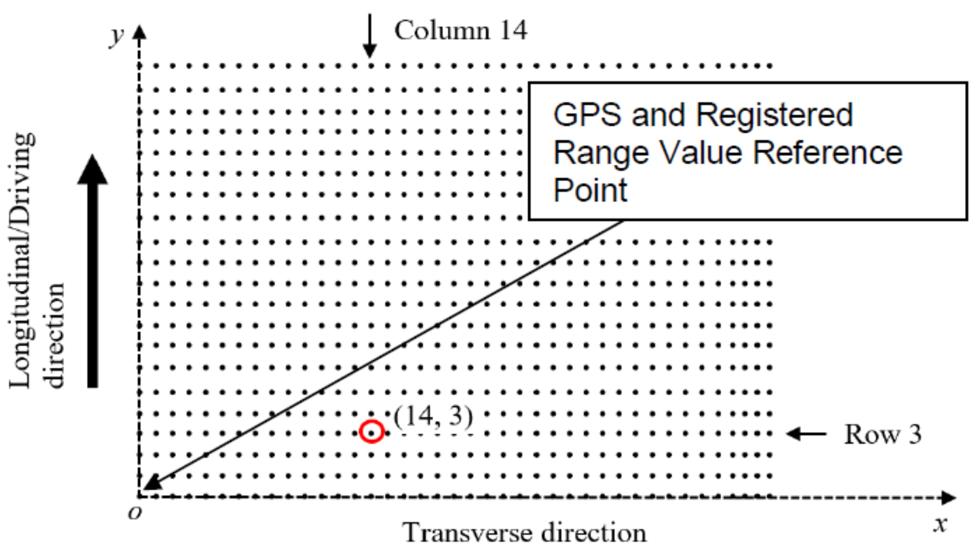

Figure 4. Graph. Recommended coordinate system for a 2D/3D image.

The standard data format accommodates flexible settings of image size and resolutions in transverse and longitudinal directions, which can meet the current practices of 2D/3D pavement image collection by different vendors. Each of the settings, i.e., pixel numbers and resolution in transverse and longitudinal directions, has a corresponding field in the file header. Nevertheless, the length of pavement covered by an image needs to be determined based on the following two factors:

- The length of an image should not be too long to be processed by a computer program for detecting/measuring/classifying pavement distresses. Currently, almost all algorithms are based on 2D-grid images. Processing a long stretch of pavement (e.g., 1 mile) at a time could exceed the computer hardware capability.

- Because one set of GPS coordinates is recorded for each 2D/3D pavement image, and thus, pavement images can be spatially identified on a road network, a long stretch of image (e.g., 1 mile) would make it inconvenient to locate a spot-on road base map.

As a rule of thumb, it is suggested that each image (2D and/or 3D) be considered as an "atom" segment of pavement. Thus, the project- and network-level pavement conditions can be evaluated by aggregating the distresses from the corresponding images. For each "atom" image, it is not necessary to further divide it. In this consideration, storing 5-meter, or so, pavement segment in a 2D/3D image in a longitudinal (driving) direction is adequate and recommended.

Using a rectangular 2D-grid to store 2D and 3D pavement surface images in the standard data format meets the state of the practice of 2D/3D pavement data collection, processing, and analysis. Thus, it is convenient for implementation with the least impact on the current practice.

However, it is recognized that the assumption of a 2D grid for 2D and 3D pavement surface images might not hold true in a curve. When a data collection vehicle travels in a curve, two adjacent transverse profiles might not be parallel. Thus, the actual interval between two profiles could vary along the transverse direction in a curve. In such cases, the measurement accuracy of distresses, e.g., longitudinal cracks, in the inner and outer wheel paths could be affected. To take this situation into consideration, it is necessary to know the orientation of each transverse profile. Then, the actual measurement in the longitudinal direction can be made.

In the current practice, the above impact was not considered for purposes of pavement condition evaluation. The reasons could be as follows. First, other than longitudinal cracks, other distresses are less likely to be affected by the longitudinal measurement accuracy in a curve, e.g., rutting, raveling, and others. Second, the impact on longitudinal distance measurement accuracy could only be significant in some localized cases, e.g., sharp curves. From project- or network-level pavement condition evaluation, this impact could be minimal, and/or canceled out by different curves. Nevertheless, it is suggested that a separate study be performed to study the impact of curves on longitudinal distance measurement accuracy, and the accuracy of project- and network-level pavement condition evaluation, e.g., distress types, distress extents, discount points, ratings, etc.

Please note that the refined 2D/3D standard data format does not exclude the possible consideration of curve impact in the future, though a 2D grid is used to represent a 2D or 3D image. As long as the curve information is known for an image, the longitudinal distance measurement can be adjusted in the data processing and analysis algorithms. The curve information, i.e., curvature, can be acquired from other mapping sources. First, if each image stores an "atom" pavement segment, e.g., 5 meters long, the aggregation of consecutive images based on their GPS coordinates could be used to approximate a curve adequately. If a 5-meter interval is still too coarse for approximating very sharp curves, the standard format allows users to define smaller image length, e.g., 1 meter. Second, if the base map of a road network is available, which is true for most state highway agencies, road curvature can be acquired from the base map. Finally, if profile-by-profile orientation is needed to achieve the highest accuracy of

longitudinal distance measurement, the existing OpenCRG format can be used as a codec to store the 3D pavement images. The corresponding decoder should be able to acquire the profile-based orientations.
In summary, the coordinate system shown in Figure 4 is recommended for the refined 2D/3D standard data format because it complies with the current practice for 2D/3D pavement image collection, processing, and analysis. Thus, it is more convenient for implementation and application to support state highway agencies' operations. The refined standard data format is for the purpose of pavement condition evaluation; thus, it only stores the pavement surface images that are frequently changed. On the other hand, the mapping-related information, e.g., curvature and orientations, is not recommended to be included because it does not need very frequent update, e.g., yearly.

Clearly Defined Method of Pixel Storage

Other than the image coordinate system listed above, a new item needs to be added in the file header to specify how pixels in the coordinate system are mapped into a matrix in the memory. As shown in Table 1, a new item is recommended for storing the information for pixel storage, "R" or "C."

- If "R" is used, then the coordinate system is stored as [Row 0, Row 1 … Row N]
- If "C" is used, then the coordinate system is stored as [Col 0, Col 1 … Col N].

Combined with other existing items in the file header, i.e., "2D Width," "2D Length," "3D Width," and "3D Length," the location of each pixel is determined when pixel storage is defined.

Table 1. Recommended new item for pixel storage.[1]

Variable Name	Data Type	Data Details
Pixel Storage	Uint8	R – Row-first storage; C – Column-first storage

[1]Existing items are omitted.

It is recommended to store the data along the driving path (row-first storage). First, this method enables the sequential, real-time writing of the data. Second, it makes concatenating two consecutive data blocks easier. Also, it should be noted that when visualizing the pavement surface as shown in Figure 4, the rows need to be arranged in reverse order.

2D/3D Sensor System Identification

A field is added to the header (see
Table 2) to identify the hardware system, i.e., 2D/3D sensor system.

Table 2. Recommended item for identifying 2D/3D sensor system.[1]

Variable Name	Data Type	Data Details
Sensor System Number	32-byte String	2D/3D sensor system identification

[1]Existing items are omitted.

Range Data Registration

The roadway/pavement geometry–related features include smoothness, cross slopes, curvature, and grades. To extract the above information from 3D images, the range datum, i.e., *z* coordinate, needs to be registered, which means the depth of each pixel is measured in terms of a common or global reference. On the other hand, for an unregistered image, the depth of each pixel is measured from the sensor to the pavement surface, which cannot capture the geometry of the pavement surface.

To accommodate the storage of either registered or unregistered images, adding a new item in the file header to indicate whether the 3D images are registered or unregistered is recommended (see Table 3).

In addition, to avoid storing a large range value for each pixel, a reference range value will be stored for each image at the reference point. Thus, the resulting range value for each pixel is the sum of the stored pixel range value and the reference range value. For registered images, the reference range values of all images are related to the common or global reference. For unregistered images, the reference range value will be set as 0.

Table 3. Recommended item for identifying image registration.[1]

Variable Name	Data Type	Data Details
3D Registration	Uint8	R – Registered; U – Unregistered
Reference Range Value	Float 32bit	Range value of the reference point. 0 when "3D Registration" is "U."

[1]Existing items are omitted.

SUMMARY

Based on the review of the work under contract DTFH6115P00103, the recommendations to the original standard data format have been incorporated into a refined version, which includes additional definitions for the standard image representation, a field in the file header to identify the sensor system, and a field in the file header to indicate if range data are registered or not. The refined standard data format can be found in the Appendix.

CHAPTER 3. VERIFICATION OF FUNCTIONALITY AND PERFORMANCE OF PROPOSED STANDARD DATA FORMAT AND COMPRESSION ALGORITHM

INTRODUCTION

In this task, the compression tests presented in the original report were verified. Three image formats, TIFF (LZW Algorithm), JPEG XT, and JPEG 2000, were evaluated based on their compression speed in milliseconds (ms), ratio (between uncompressed size and compressed size), and quality in terms of peak signal-to-noise ratio (PSNR).

In addition, several sets of pavement images categorized by pavement types and pavement conditions were collected, and further compression tests and statistical analyses were performed to gain insight into the characteristics of pavement images.

It is assumed that all pavement images have single channel (greyscale). It is recommended to use 8-bit depth for intensity image; and 16-bit for range image. Figure 6 shows the relationship between the maximal vertical windows size (w), minimal vertical resolution (r) and the optimal bit depth (N).

$$\frac{w}{r} = 2^N$$

Figure 6. Equation. Optimal bit depth calculation.

Considering future technology advancements, it is assumed the maximum vertical window size to be 5 m and the minimal vertical resolution to be 0.1 mm, this gives an optimal *N* of 16 bits.

VERIFICATION OF DATA COMPRESSION METHODS

Baseline for Calculating Compression Ratio

Compression ratio is defined as the ratio between uncompressed file size and compressed file size. Four test images in the original project were provided by the original contractor for analysis. The original project chose the size of a 32-bit raw image as the uncompressed file size (shown as “Data Size” in Table 4). It has been demonstrated that 16-bit is sufficient for storing 3D range data, therefore it is recommended to use the size of 16-bit monochrome image as the baseline for calculating compression ratio. However, for a fair comparison, 32-bit was selected as a baseline in the following validation because it was used in the original project for computing the compression ratio.

Table 4. Four Test Images

Image	Data Size (KB)	Width	Height	Pavement Surface	Road Name
1	32770	4096	2048	AC	US-51 EB, Stillwater OK
2	32770	4096	2048	AC	US-51 EB, Stillwater OK
3	32413	4052	2048	PCC	I-44 EB, Oklahoma City
4	32414	4052	2048	PCC	I-44 EB, Oklahoma City

The evaluation of the compression algorithms was conducted on a desktop computer with i7 CPU and 16G RAM. In compliance with the default time measurement implementation in JPEG software, the time (ms) measured includes both compression time and file writing time. In the original project, the execution time and file writing time are reported by the original contractor's compression software.

Verification of TIFF Format

It should be noted that a TIFF is a container image format which supports multiple compression algorithms such as Lempel–Ziv–Welch (LZW), PackBits, JPEG, etc.

Table 5 shows the verification results of TIFF lossless compression as compared to the originals reported in the Task 4 report.

Table 5. Verification results of 16-bit TIFF format.

Image No.	Time (ms)	Size Before Compression (KB)	Size After Compression (KB)	Compression Ratio Observed	Compression Ratio Task 4 Report	PSNR
1	266	32,770	3,204	10.48:1	6.22:1	Inf
2	279	32,770	3,186	10.54:1	6.49:1	Inf
3	283	32,413	3,409	9.86:1	4.74:1	Inf
4	278	32,413	3,560	9.32:1	4.99:1	Inf

The verification results showed that the compression ratio is significantly higher than the original results. One possible reason for the difference is that the parameter settings of the compression algorithm might be different. The Task 4 report did not specify which algorithm was used for the compression testing. In this testing, one of the commonly used compression algorithms that TIFF supports, the LZW algorithm was used. The tool used to perform the test is raw2tiff from the standard TIFF library, libTIFF. The compression time is affected by various factors, such as CPU, memory, and background running processes, and the small difference in compression time is expected and within a normal range.

Verification of OSU Method 1 (lossy)

Table 6 shows verification results of OSU's lossy method as compared to the originals reported in the Task 4 report. OSU's 3D-only image compression software was used in this testing.

Table 6. Verification results of OSU method 1 (lossy).

Image No.	Time (ms)	Size Before Compression (KB)	Size after Compression (KB)	Compression Ratio Observed	Compression Ratio Task 4 Report	PSNR Observed	PSNR Task 4 Report
1	50	32,770	470	71.38:1	54.44:1	94.58	90.67
2	42	32,770	467	71.08:1	54.34:1	94.65	90.72
3	51	32,413	538	61.64:1	43.33:1	92.85	92.85
4	49	32,413	547	60.74:1	43.63:1	92.57	92.57

Results showed that the PSNRs generally agree with the Task 4 Report values, but the compression ratio is higher than the original ones (the PSNR values for Images 1 and 2 are slightly higher than Task 4 Report results).

Verification of OSU's Method 2 (lossless)

The verification of OSU's lossless method was not performed as it would require the OSU lossless compression tool. Table 7 shows the original compression result from the Task 4 report. The compression ratio is greater than that in the TIFF lossless method (see Table 5). However, it requires much more processing time.

Table 7. Compression results: The OSU method 2 (lossless).

Image No.	Time (ms)	File Size after Compression (KB)	Compression Ratio	PSNR after Decoding
1	2,292	2,238	14.64:1	Inf.
2	2,247	2,325	14.09:1	Inf.
3	1,175	2,448	13.24:1	Inf.
4	1,703	2,513	12.90:1	Inf.

Verification of JPEG 2000 and JPEG XT Compressions

Table 8 lists the verification results of JPEG 2000 and JPEG XT. For the compression ratio, the verification results match those from the Task 4 report. For the PSNR, the verification results of JPEG XT exactly match the ones in the Task 4 report. However, the verification results for JPEG 2000 vary for Images 2, 3, and 4.

Table 8. Verification results of JPEG 2000 and JPEG XT compression at Four Quality Factors.

Quality	Format	Image No.	Time (ms)	Size Before Compression (KB)	Size After Compression (KB)	Compression Ratio (All Match)	PSNR Observed	PSNR Task 4 Report
100	JPEG XT	1	318	32770	1340	12.52:1	93.36	93.36
		2	322	32770	1420	11.81:1	93.84	93.84
		3	284	32413	770	21.55:1	86.72	86.72
		4	292	32413	869	19.10:1	87.00	87.00
	JPEG 2000	1	4625	32770	1339	12.53:1	101.81	101.81
		2	4783	32770	1419	11.82:1	102.39	63.94
		3	4704	32413	769	21.58:1	97.45	50.73
		4	4652	32413	868	19.12:1	94.81	53.11
95	JPEG XT	1	290	32770	709	23.66:1	91.19	91.19
		2	293	32770	766	21.90:1	91.64	91.64
		3	267	32413	381	43.56:1	86.03	86.03
		4	268	32413	398	41.70:1	86.21	86.21
	JPEG 2000	1	4552	32770	708	23.70:1	97.62	96.95
		2	4735	32770	760	22.08:1	96.72	63.94
		3	4738	32413	380	43.67:1	96.07	50.73
		4	4680	32413	397	41.80:1	91.34	53.11
90	JPEG XT	1	272	32770	410	40.92:1	89.81	89.81
		2	273	32770	458	36.63:1	90.25	90.25
		3	265	32413	263	63.10:1	85.55	85.55
		4	263	32413	268	61.93:1	85.86	85.86
	JPEG 2000	1	4487	32770	409	41.02:1	88.19	94.01
		2	4681	32770	457	36.71:1	94.88	63.94
		3	4665	32413	262	63.34:1	92.98	50.76
		4	4692	32413	267	62.16:1	88.38	53.11
85	JPEG XT	1	269	32770	312	53.77:1	89.08	89.08
		2	272	32770	351	47.80:1	89.47	89.47
		3	261	32413	234	70.92:1	85.26	85.26
		4	259	32413	235	70.62:1	85.63	85.63
	JPEG 2000	1	4431	32770	311	53.95:1	88.62	91.03
		2	4502	32770	350	47.93:1	92.53	63.94
		3	4654	32413	233	71.23:1	92.76	50.74
		4	4632	32413	234	70.92:1	90.02	53.11

Comparison of JPEG 2000 and OSU Method 1 (lossy)

To facilitate a fair comparison, one more verification was performed to compare JPEG 2000 and OSU's method 1 (lossy). Similar to the test between JPEG XT and JPEG 2000, the target compression ratio of JPEG 2000 was set to match that obtained by OSU's compression method, and then the PSNR results were compared as quality metrics. Table 9 lists the comparison results.

Table 9. Comparison between JPEG 2000 and OSU method 1 (lossy).

Image No.	Compression Ratio	PSNR after Decoding JPEG 2000	PSNR after Decoding OSU Lossy Method
1	35.69:1	90.33	94.58
2	35.92:1	94.97	94.65
3	30.84:1	96.31	92.85
4	30.37:1	93.89	92.57

The results showed that OSU's method 1 outperforms JPEG 2000 on image 1 while slightly underperforming on images 2, 3, and 4, however, it should be noted that OSU's method 1 runs about 10 times faster than the JPEG 2000.

CHAPTER 4. ASSESSMENT OF STANDARD DATA FORMAT FOR USE BY STATE HIGHWAY AGENCIES AND 2D/3D SENSING TECHNOLOGY VENDORS

INTRODUCTION

This section briefly reviews the history of JPEG in the hopes that its success could enable the implementation of the standard data format for 2D/3D pavement surface images. To assess the use of the refined standard data format, preliminary testing was conducted in cooperation with a state highway agency and a 3D sensing technology vendor. The refined standard data format was reviewed by state highway agencies and 3D sensing technology vendors. In this section, all the comments and recommendations are summarized. Currently, psi (pavement surface image) was adopted as the file extension for 2D/3D pavement surface images in standard data format.

A BRIEF REVIEW OF HISTORY OF JPEG

The original JPEG image format (Mitchell, J. 1992) was standardized in 1992 by Joint Photographic Experts Group, a joint committee of two standard-setting organizations: ISO/IEC JTC 1 and ITU-T. After its introduction, the original JPEG with lossy compression quickly became the top-used image format. Even today, the original JPEG is still one of the most ubiquitous image formats despite the abundance of other advanced image formats that are available to end users.

JPEG compression utilizes discrete cosine transform (DCT), quantization, and a statistical encoder to compress images (Wallace, G. 1990). Many attempts have been made to improve compression performance. Amongst the descendants of the JPEG format, JPEG 2000 is the second most commonly accepted image format; however, its presence accounted for less than 0.1% of total images that appear on the internet. In fact, in the 10 years after JPEG's first appearance, very few image formats truly outperformed JPEG in terms of both compression speed and compression rate. Until recently, some image formats, such as WebP, have shown a dominating performance over the JPEG format in terms of both space and speed, even though these image formats usually attach to a very specific domain, and their user base is trivial compared to that of JPEG.

The history of JPEG reveals a few factors that may have contributed to its success as an image format:

- First, JPEG was the universal standard image format that was developed in the early internet age. At that time, disk space was expensive, and a good compression ratio was necessary for the image format to popularize. The original JPEG balanced very well the tradeoff between the space cost and the quality cost; in fact, most implementations of JPEG also provide an adjustable compression ratio.

- Second, JPEG was proposed and backed by ISO/IEC JTC 1, an independent international standard setting committee, and was trusted by the industries, especially the camera makers. Camera industries' early adoption kept away competitor image formats for many years because there was no incentive for them to shift away from a commonly accepted image format.

- Finally, JPEG was license-fee-free and royalty-free.

Despite the prevalence of the JPEG format, ISO/SEC never offered a reference software of the JPEG image format, nor did they officially support any of the third-party implementations. The result is that the majority of the JPEG encoders and decoders only partially implemented the specified features. In July 2017, a JPEG committee called for proposals of a formal guide implementation of ISO/IEC 10918 (JPEG Reference Software Final Call for Proposals). The JPEG committee expects the submitted implementation to be provided in the form of source code and support all required features, and the submitted reference implementations will be verified against a test program provided by the committee. As of July 2019, no formal reference implementation had been selected by the committee. Again, it is reasonable to expect that the majority of the JPEG users have no incentive to shift away from the JPEG encoder they have used for years.

In retrospect, the success of JPEG emphasized that open, free, and early momentum are the three keys for the standard format to gain industry support. The JPEG history also suggests that official libraries and tools should be provided at the earliest possible date in order to avoid duplicate effort and/or conflict implementations.

PRELIMINARY TESTING

To assess the usability of the refined standard data format by state highway agencies and technology vendors, a preliminary testing was performed in cooperation with a state highway agency (DOT A) and a 3D sensing technology vendor (Vendor B). The objective of this testing was to evaluate if the refined standard data format can be used for storing and extracting 2D/3D pavement surface images. Using lossless compression, an evaluation was also performed to validate if there is any information loss. Figure 7 shows the procedures for the preliminary testing.

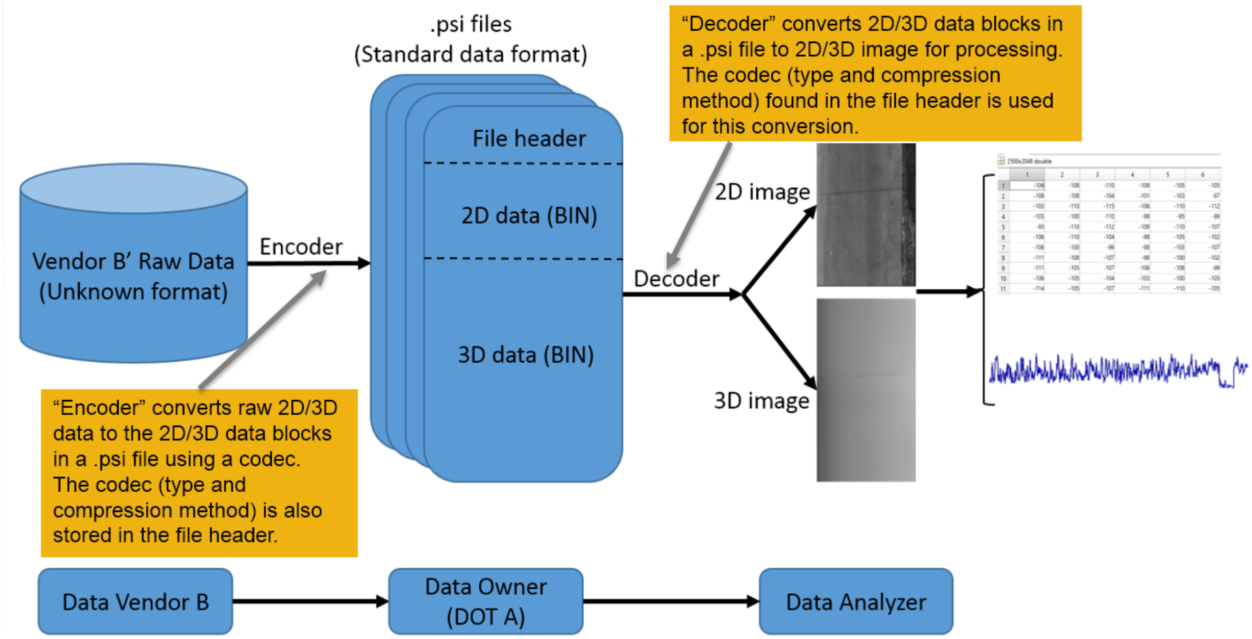

Figure 7. Chart. Preliminary testing of using standard data format.

To perform the test, Vendor B created multiple psi files, each consisting of pavement data of 5 meters in length. The data in these psi files are encoded and the file header is valid and complete. Vendor B submitted these psi files for assessment. First, the integrity of the psi files was verified; then the header and the 2D and 3D images were extracted from the psi files without relying on external information. Finally, the 2D and 3D data were exported as comma-separated values (CSV) files and compared to the original data. The comparison results confirmed that all data had been losslessly transferred. Figure 8. shows the decoded 3D data. These test results prove that there is no loss of information using the psi data format.

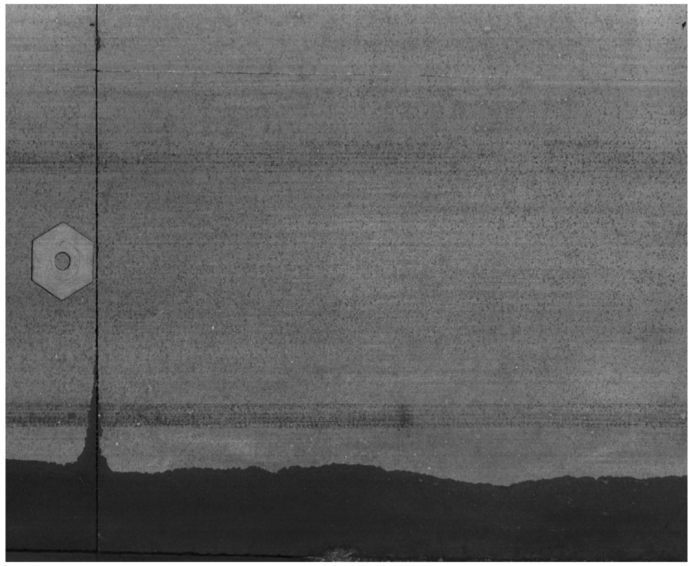

Figure 8. Graph. Decoded 3D data.

SUMMARY OF REVIEW RESULTS FROM STATE HIGHWAY AGENCIES AND SENSING TECHNOLOGY VENDORS

After the preliminary testing, the refined standard data format was distributed to several state highway agencies and sensing technology vendors for their reviews. The following is a summary of the comments and recommendations. After careful review of the comments and recommendations, they were categorized into different groups; while all of the comments are extremely valuable, some have been directly incorporated into the refined specification, and some may need further discussion:

- Accepted and included in the final standard data format:

  - Use better naming convention for the data types, suffix *s* and *u* to the type name to explicitly indicate whether it is a signed variable (e.g., Int32 becomes Int32*s*).
  - Provide a dynamic-linked library (DLL) that implements file loading, file saving, and data extraction functions.
  - Regarding the standard image representation, clearly specify if there are special characters at the end of each row and how it is flattened into a 1D array. (Avoid the misinterpretation that 2D storage exists in hard disk).
  - Choose 16 bit as the required bit depth for 3D range image.
  - Combine and leave more space for the reserved data field; let the user decide how this field should be interpreted.
  - Add an ISO-compliant file signature to the beginning of the psi file.

- For String types, make them “Null” terminated.
- Use type double 64-bit for better GPS latitude and longitude resolution.

- Considered for a future version:

- Remove the metadata section.

  Response: the metadata section is considered useful for providing flexibility to the standard data format.

- Consider supporting collections of images in one file.

  Response: This will make the structure of standard data format much more complicated. This should be considered, if needed, in a future version.

- Add a String field “Tag” to allow fast retrieval of images of interest.

  Response: This should be considered in future versions if collections of images are included in one file.

- For n-byte String, change to UTF-8 encoding for global use.

  Response: This should be considered in future version. ASCII is a subset of UTF-8. Thus, there should be no backward compatibility issue in the future.

- Consider using JPEG XR over JPEG 2000; the memory usage of JPEG 2000 is huge when the image is large.

  Response: The standard data format does not designate specific codec for either 2D or 3D image but keeps it open for flexibility. It can accommodate any type of codec.

- Provide a read/write viewer tool to facilitate the testing of the standard format.

  Response: This is a recommendation for future work to facilitate the implementation of the refined standard data format.

- Original setting recommended:

- In Table 11, the data type of the following variables “File Serial Number”, “Event Marker ID”, “2D Width”, “2D Length”, “2D Data Size”, “3D Width”, “3D Length”, “3D Data Size”, and “Metadata Data Size” should be “Int32u.”

  Response: While “Length” and “Width” are indeed non-negative variables, storing them as a signed variable is more consistent with coding conventions. For the rest, they were updated as unsigned variables.

- Consider using an existing image format to store the pavement data, since JPEG 2000 and JPEG XR all support metadata.

Response: This study assessed the use of an existing image format to store the 2D/3D pavement image. The findings are that a reasonably suitable image format to store 2D/3D pavement data is TIFF, as it solves the metadata, multi-image, and compression all at once; however, the concern is that this existing image format allows features out of the scope of the pavement image, such as colored-image, and lossy compression of the 3D image, etc. To utilize these image formats for the pavement industry, a standard to limit their features is needed, and it should keep track of its updates. As a result, the effort to develop a standard based on an existing format may be more than developing a new one.

- In Table 11 in the Appendix, variables "Time" and "Time stamp" are redundant.

  Response: Time is in HHMMSS format up to second-level precision. Timestamp is the UNIX Epoch since Jan 1, 1970; 00:00:00 offers up to millisecond precision.

CHAPTER 5. PROCEDURE FOR CONFIRMING COMPLIANCE WITH STANDARD DATA FORMAT

INTRODUCTION

When a state highway agency adopts the standard data format, a procedure is needed to confirm compliance with it. Data compliance is the process of ensuring the adherence of data to a predefined set of rules at all stages.

PROPOSED PROCEDURE AND FUNCTIONS

To confirm the data compliance with a standard data format, a set of "minimal rules" has to be determined first. A valid psi file must pass all rules in this set—there is no partial data compliance.

A standalone software program is recommended to check the data compliance of the standard data format. The program must take a psi file as input and then output the verification results according to these rules. The items in Table 10 are an example of minimal rules.

Table 10. Example of minimal rules and validation procedures.

Properties	Sub-rules	Validation Procedure
File Integrity	The file signature is present	Check if the last four bytes of the file is "psi".
	The file trailer is present	Check if the last four bytes of the file is "@@@@".
	The file's checksum equals to the given one	If a checksum is given, calculate the checksum based on the file content and check if it equals to the given checksum.
Header Correctness	The values in the required header fields are valid	For each value in required fields, if the field takes only assigned value, check if the value is in the "assigned values list". For example, version must follow the format "X.YY" where X and YY are numbers.
	The size of the 2D/3D data is correct	If the data are not compressed, check if the following condition holds: "datasize = bitdepth / 8 * width * length"
Data Correctness	The data in the 2D and 3D sections can be extracted using header information	Extract and decode the 2D and 3D data using header provided information. Check if the extracted data can be fit into a width * length matrix of that given data type.

The rules above are for demonstration purposes only and are by no means exhaustive. It should be emphasized that the minimal rules defined here only adhere to issues related to data compliance; they should not be extended to the data quality issues. To maintain backward compatibility, the "minimal rule set" should only expand as the standard evolves. This guarantees that the later version of psi files is valid in earlier versions of the software.

While the scope of this project is limited to evaluation of the current standard, it is recommended that a standard library and software tools be developed for implementing the standard 2D/3D data format. A standard library makes it convenient for a 2D/3D technology vendor to implement the standard data format. It can also minimize potential deviations from its original intention. Keeping one standard library greatly reduces the development and maintenance costs. The software tool will help data users to conveniently verify data compliance and perform different levels of data analysis and pavement distress measurements.

Other future work may include deeper analysis of compression algorithms, development of a data visualization tool, and internationalization. For example, a broader pavement data set categorized by pavement type and distress could be used to evaluate compression algorithms on pavement images, a tool can be implemented to display the header information and render the 2D/3D pavement image for the psi file, and UTF-8 character encoding can be added to the standard to provide basic internationalization support.

CHAPTER 6. CONCLUSIONS

Through this project, an evaluation of the work performed under contract DTFH6115P00103, including the three reports and the original specification for the 2D/3D standard data format was performed. The major contributions include: (1) critical assessment of the original reports and standard data format; (2) development of a refined 2D/3D standard format; and (3) incorporation of input from state highway agencies, 3D sensing technology vendors, and service providers.

Based on the evaluation of the original reports and specification, a refined 2D/3D standard data format was recommended by adding the concepts of standard image representation, sensor system identification, and range data registration. The refined 2D/3D standard data format has been reviewed by several state highway agencies, 3D sensing technology vendors, and service providers resulting in several improvements, such as a better naming convention for data types, the selection of 16 bit as the default bit depth for 3D data, etc. The final version of the refined standard data format can be found in the Appendix.

A verification of various compression algorithms was performed and compared with the ones in the original report. Most of the verification results match the ones in the original evaluation. However, due to the absence of detailed settings of the compression parameters (e.g., the compression algorithms and the parameters used in the TIFF image format), results showed some deviation from the original evaluation.

To assess the refined standard data format, preliminary testing was performed with the cooperation of a state highway agency and a 3D sensing technology vendor. The testing results showed that a data transfer in the standard data format can be successfully performed without the loss of information. The 2D/3D data collected by a sensing technology vendor can be stored in the standard data format and extracted by a state highway agency to perform pavement condition evaluation. Finally, a set of rules was recommended for a state highway agency to verify the data compliance of the standard data format.

The following recommendations for future work are provided to facilitate implementation:

- To facilitate the implementation of the 2D/3D standard data format, a standard library should be developed that can be used by all vendors and data users. The standard library will include the major application programming interface (API) to convert 2D/3D image data to the standard data format and extract 2D/3D image data from files in the standard data format. The library should be developed as early as possible to avoid duplicate effort and/or conflict implementations by different vendors and/or state highway agencies.

- Based on the recommended rules for verifying data compliance, a software tool should be developed for use by all state highway agencies. Meanwhile, the software tool should also include the functions for image visualization, pixel value identification, profile data extraction, and other interactive functions for measuring major types of pavement distresses, e.g., rutting, cracking, macrotexture, faulting, IRI, etc.

- Although 2D/3D standard file format has been developed, there is still a lack of understanding on refined 2D/3D data format, data storage, data management, data processing, and analysis. A clear definition and explanation of these areas are essential for successful implementation. Thus, case studies are recommended to be developed to showcase the use of the standard data format for pavement image data collection, storage, management, processing, analysis, and applications. Both parties, i.e., interested 2D/3D sensing technology vendors and state highway agencies, need to be involved in the case study. A case study would be valuable to 2D/3D sensing technology vendors and state highway agencies for the success of the full-scope implementation of the standard data format.

APPENDIX A: RECOMMENDED DRAFT STANDARD DATA FORMAT

Standard Specification for

File Format of 2-Dimensional and 3-Dimensional (2D/3D) Pavement Image Data (Version 1.0)

AASHTO Designation: MP NN-NN

1. SCOPE

1.1 This specification describes the standard file format of 2-dimensional and 3-dimensional (2D/3D) pavement image data used to determine pavement surface condition and profiles.

1.2 This specification describes the data elements stored in a binary file.

1.3 This specification is designed to be independent of hardware platform, computer language, and operating system (OS).

1.4 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. REFERENCED DOCUMENTS

2.1 ASTM Standards:

- E2560-13 Standard Specification for Data Format for Pavement Profile
- E867-06 Terminology Relating to Vehicle-Pavement Systems
- E2544-11a Standard Terminology for Three-Dimensional (3D) Imaging Systems.

2.2 IEEE Standards:

- IEEE 754–08 (2008) Floating-Point Arithmetic

2.3 ISO Standards:

- ISO/IEC 10918-5 (2013) Digital Compression and Coding of Continuous-tone Still Images: JPEG File Interchange Forma

2.4 Other Publications:

- Office of Highway Policy Information (2016) Highway Performance Monitoring System Field Manual

3. TERMINOLOGY

3.1 *Definitions:*

3.1.1 Terminology used in this specification conforms to the definitions included in ASTM Standard E867 Terminology Relating to Vehicle-Pavement Systems.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 **Signed:** Integer capable of representing negative and positive values.

3.2.2 **Unsigned:** Integer capable of representing only nonnegative values.

3.2.3 **Uint8:** Data type for an 8-bit, unsigned integer.

3.2.4 **Int32:** Data type for a 32-bit, signed integer.

3.2.5 **Uint32:** Data type for a 32-bit, unsigned integer.

3.2.6 **Double:** Data type for a 64-bit, signed real number, such as double precision IEEE floating point.

3.2.7 **n-byte String:** An ASCII string of n characters in length, null terminated. The null character '\0' will occupy one byte, which is not counted toward n.

3.2.8 **Double:** Data type for a 64-bit, signed real number, such as, Double precision IEEE floating point.

3.2.9 **Long Long Int:** Data type for a 64-bit, signed integer.

3.2.10 **Array (Numeric Data Type):** A sequence of data of the specified numeric data type. The size of the array will be stored separately.

3.2.11 **Array (String):** ASCII strings separated by a null character. There is a null character after the last string.

3.2.12 **Backward Compatibility:** Ability of a software system, such as a pavement image viewer, to read an earlier version of the standard file format.

3.2.13 **Forward Compatibility:** Ability of a software system, such as a pavement image viewer, to read a future version of the standard file format.

3.2.14 **Offset:** An index measuring the number of bytes from the beginning of a data file. The offsets in the file header locate the various data sections of the file.

3.2.15 **Pixel**: Pixel is a point in an image. Pavement image is a rectangular grid of pixels, where each pixel contains a single number that represents intensity for 2D image and depth for 3D image.

3.2.16 **Compression:** Reduce file size by encoding information using fewer bits than the original representation. When lossy compression is used, some information could be lost. When lossless compression is used, no information is lost.

3.2.17 **Compression Quality:** A measurement of how much information is lost during the lossy compression. In this specification, compression quality is measured using peak signal-to-noise ratio (PSNR), the ratio between the maximum possible power of a signal and the power of noise that corrupts the signal fidelity. When lossless compression is used, the PSNR will be infinity.

The equation of PSNR is

$$PSNR = 10 \times log_{10}\left(\frac{MAX_I^2}{MSE}\right)$$

where

$$MSE = \frac{1}{mn}\sum_1^m \sum_1^n (I(i,j) - T(i,j))^2$$

I represents the ground truth image. *T* represents the image to be tested. The resolutions of both images are *m* × *n*. The *MSE* is the mean square error between the test image and the reference image. *MAX* is the maximum possible range of a pixel. For an 8-bit intensity image, it is $2^8 - 1 = 255$, and for a 16-bit range image, it is $2^{16} - 1 = 65535$.

3.2.18 **FIPS State Codes:** Federal Information Processing Standard state code. FIPS state codes were numeric and two-letter alphabetic codes defined in U.S. Federal Information Processing Standard Publication.

3.2.19 **Lane Index:** Define the lane index of the leftmost (to the driving direction) driving lane to be 1 and increase by 1 for each lane to the right.

3.2.20 **GPS:** Global Positioning System, the GNSS (Global Navigation Satellite System) owned and operated by the United States government.

3.2.21 **Registration:** The process of determining and applying to two or more profiles the transformations that locate each profile in a common coordinate system so that the profiles are aligned relative to each other.

3.2.22 **Transverse Profile:** the vertical deviations of the pavement surface from a horizontal reference perpendicular to the lane direction.

3.2.23 **Longitudinal Profile:** the perpendicular deviations of the pavement surface from an established reference parallel to the lane direction, usually measured in the wheel tracks.

4. FILE DATA SPECIFICATIONS

4.1 *File Structure*

4.1.1 The file is divided into six sections: (1) File Signature, (2) File Header, (3) 2D Image Data (intensity), (4) 3D Image Data (Range), (5) User Defined Metadata, and (6) File Trailer.

The six sections are laid out sequentially (Figure 1). Storage space for either 2D data or 3D data is variable depending on the compressed data size. The detailed information regarding file signature and file trailer can be found in Section 4.5.

File Signature	File Header	2D Intensity Data	3D Range Data	Metadata (Optional)	File Trailer

Figure 1. Diagram. File structure

4.1.2 **Standard Image Representation:** Figure 2 defines a two-dimensional, Cartesian, right-hand coordinate system in which the x axis is perpendicular to the driving direction and points to the right side, and the y axis is in the driving direction. A single line of pixels in the x direction forms a row; pixels in the y direction form a column. The origin is located at the leftmost pixel in the first row. Each pixel is located by its column and row numbers, which are counted from 0. In Figure 2, the column and row numbers of the red-circled pixel are 14 and 3, respectively. The 2D coordinate system shown in Figure 2 applies to both 2D and 3D images.

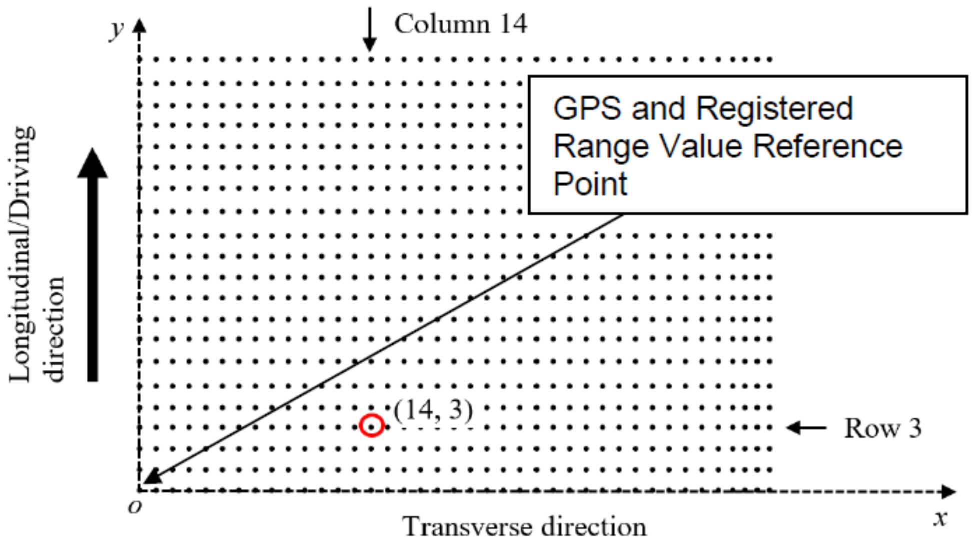

Figure 2. Graph. Standard image representation.

1) A row (parallel to x axis) in the coordinate system corresponds to a transverse profile.

2) A column (parallel to y axis) in the coordinate system corresponds to a longitudinal profile.

3) The constant spacing between two rows in the coordinate system is the longitudinal resolution.

4) The constant spacing between two columns in the coordinate system is the transversal resolution.

4.1.3 **Reference Point:** See Figure 2. The reference point is represented by origin in the standard image representation.

4.1.4 **Pixel Storage:** Defines the order of the pixels stored after an image is uncompressed. If row-first storage is used, then the file is stored as [Row 0, Row 1 … Row N]; if column-first storage is stored, then the file is stored as [Column 0, Column 1 … Column N]. The first element in each column and the first element in each row is on the x axis and y axis.

4.1.5 Because pavement imaging technology will continue to evolve with new capabilities, the pavement image file format must support both backward and forward compatibilities of the related software, such as a pavement image viewer.

4.1.6 To enable backward and forward compatibility, the core section, including File Header, 2D Intensity Data, and 3D Range Data, shall not change as the file format standard evolves. The optional user-defined metadata section can be extended and modified as needed by vendors or highway agencies to accommodate individual data collection practices and equipment.

4.1.7 Each section of the file is described in the following sections. The data types and related descriptors required in the file are included. The data shall be mapped to the file sequentially, with the offsets listed in the file header as guides to find various portions of the file. The "2D data size" and the "3D data size" can only be obtained after 2D/3D data are compressed.

4.1.8 It is recommended that each file in this format stores about 5 meters in length and one lane in width of pavement surface image data.

4.1.9 **Invalid Pixel:** The maximal value of the 2D/3D data type is reserved for representing invalid pixel. (255 for 8-bit depth, 65535 for 16 bit-depth)

4.2. *File Header*

4.2.1 The file header describes the properties of the 2D/3D data stored in the file. Each property shall be denoted by a variable of predefined data type and fixed byte length. An example of the file header is shown in Table 1 .

4.2.1.1 **Required Fields:** Fields that must have a valid value set. Any invalid value in these fields would invalidate the file.

Table 1. File header.

Data Offset (Byte)	Variable Name	Data Type	Data Details
0	Version	4-byte String	Version number of the file format. The format is X.YY where X is the major version numbered from 1-9 and YY is a minor version numbered from 00-99. Required Field.
5	SW version	8-byte String	Identifier of the software that produced the file. The major version of the software shall be included as well, for example: "PaveSys 2"
14	State Name	2-byte String	FIPS State Code as described in 3.2.18.
17	Route Name	12-byte String	Name of the highway HPMS standard.
30	Direction	Uint8	Direction of travel. See Table 2.
31	Lane identification	Uint8	Lane index as described in 3.2.19.

Table 1. File header (continuation)

Data Offset (Byte)	Variable Name	Data Type	Data Details
32	File Serial Number	Uint32	File serial number in continuous data collection
36	GPS Longitude	Double	GPS longitude value (IEEE 754 binary64) of the reference point
44	GPS Latitude	Double	GPS latitude value (IEEE 754 binary64) of the reference point
52	DMI Reading	Int32	Distance Measurement Unit reading at the reference point
56	Date	8-byte String	Date data was collected—(yyyymmdd)
65	Time	6-byte String	Time data was collected—(hhmmss)
72	Event Mark ID	Int32	Event marker(s) by data collection crew
76	Pixel Storage 2D	Uint8	0 – Row-first storage; 1 – Column-first storage Valid only with BIN-uncompressed codecs. See 4.1.4 and Table 2.
77	2D Codec	Uint8	Identifies codec for 2D image, "BIN-uncompressed" should be used if there is no compression. See Table 2. Required Field if 2D data size is greater than 0.
78	2D Longitudinal Resolution	Float 32bit	DMI reported distance between two data rows in longitudinal direction in millimeters. Required Field if 2D data size is greater than 0.
82	2D Transverse Resolution	Float 32bit	Distance between two data columns in transverse direction in millimeters. Required Field if 2D data size is greater than 0.
86	2D Width	Int32	Number of pixels in the transverse direction. Required Field if 2D data size is greater than 0.
90	2D Length	Int32	Number of pixels in the longitudinal direction. Required Field if 2D data size is greater than 0.
94	2D Data Bit Depth	Uint8	The bit depth for each data point in 2D image. See Table 2. Required Field if 2D data size is greater than 0.

Table 1. File header. (continuation)

Data Offset (Byte)	Variable Name	Data Type	Data Details
95	2D Data Size	Uint32	The total size of the 2D data in bytes, if compressed, the size of the compressed data. Zero if no 2D data is stored. Required Field.
99	2D Compression Quality	Float 32bit	Compression quality level (PSNR) for lossy compression. When lossless compression is used, this field should be set to 0.
103	Pixel Storage 3D	Uint8	0 – Row-first storage; 1 – Column-first storage Valid only with BIN codecs. See 4.1.4 and Table 2.
104	3D Codec	Uint8	Identifies codec for 3D image, "BIN-uncompressed" should be used if there is no compression, See Table 2. Required Field if 3D data size is greater than 0. Note: If a codec has no internal compression, e.g., OpenCRG, an external compression method, e.g. ZIP, could be designated. In the future, additional accepted codecs will be added to the Table 2.
105	3D Longitudinal Resolution	Float 32bit	DMI reported distance between two data rows in longitudinal direction in millimeters. Required Field if 3D data size is greater than 0.
109	3D Transverse Resolution	Float 32bit	Distance between two data columns in transverse direction in millimeters. Required Field if 3D data size is greater than 0.
113	3D Vertical Resolution	Float 32bit	Units for range data value in millimeters. Required Field if 3D data size is greater than 0.
117	3D Width	Int32	Pixel counts in transverse direction. Required Field if 3D data size is greater than 0.
121	3D Length	Int32	Pixel counts in longitudinal direction. Required Field if 3D data size is greater than 0.
125	3D Data Bit Depth	Uint8	The bit depth for each data point See Table 2. Required Field if 3D data size is greater than 0.
126	3D Data Size	Uint32	The total size of the 3D data in bytes, if compressed, the size of the compressed data. Zero if no 3D data is stored. Required Field.
130	3D Compression Quality	Float 32bit	Compression quality level (PSNR). When lossless compression is used, this field should be set as 0.

Table 1. File header. (continuation)

Data Offset (Byte)	Variable Name	Data Type	Data Details
134	3D Registration	Uint8	See 3.2.21 and Table 2.
135	Reference Range Value	Float 32bit	Baseline range value of the reference point. Should be 0 when "3D Registration" is "U." See 3.2.21.
139	Metadata data size	Uint32	Size in bytes of the metadata. Required Field.
143	Speed	Float 32bit	Average vehicle speed, in meters per second, associated with the data
147	Time Stamp	Long long int	Milliseconds since UNIX Epoch: Jan 1, 1970 00:00:00
155	Vehicle Number	32-byte String	Vehicle identification
188	Operator Name	32-byte String	Operator identification
221	Contractor Name	32-byte String	Contractor identification
254	Sensor System Number	32-byte String	2D/3D sensor system identification
287	Reserved Item	255-byte String	Reserved for future usage or additional vendor specific information. The unused bytes in this field should be padded with zero.

Table 2. Currently assigned enumerated type and enumerated value.

Variable Name	Enum Name	Enum Value	Value Type
2D Data Bit Depth	Depth8	8	Uint8
3D Data Bit Depth	Depth16	16	Uint8
2D Codec	BIN-Uncompressed	0	Uint8
	BIN-ZIP	1	Uint8
	JPEG	2	Uint8
	PNG	3	Uint8
3D Codec	BIN-Uncompressed	0	Uint8
	BIN-ZIP	1	Uint8
	OpenCRG-Uncompressed	2	Uint8
	OpenCRG-ZIP	3	Uint8
	JPEG2000	4	Uint8
3D Registration	Registered	0	Uint8
	Unregistered	1	Uint8
Pixel Storage 2D	Row	0	Uint8
	Column	1	Uint8
Pixel Storage 3D	Row	0	Uint8
	Column	1	Uint8
Directions	N	0	Uint8
	NW	1	Uint8
	W	2	Uint8
	SW	3	Uint8
	S	4	Uint8
	SE	5	Uint8
	E	6	Uint8
	NE	7	Uint8

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4.3 *Data Sections*

4.3.1 The data sections store blocks of compressed or uncompressed binary data. The 3D data starts from the first byte after the 2D data.

4.3.2 The vendor shall specify the algorithm to decode compressed 2D/3D data into Standard Image Representation. Vendors may use their own algorithms for data compression. In this case, vendors shall provide the compression/decompression algorithm in the form of a software library (DLL or LIB), source code, or other form of programmable tools.

4.3.3 The 2D and 3D images, if both present, must cover the same area of pavement surface.

4.4 *User-defined Metadata Section (Optional)*

4.4.1 In the data format standard, the first value in the metadata portion shall provide the number of metadata entries (MDE) as shown in Table 3. Table 4 shows the partial list of information to construct an MDE. The specific metadata data entries and their tags shall be designed based upon the future needs or specific needs of users.

Table 3. Metadata example.

Variable Name	Data Type	Data
Number of MDEs	Int32	Number of MDEs

Table 4. Metadata entries (partial listing).

Variable Name	Data Type	Data
Tag of MDE	Int32	Metadata tag
Data type of MDE	Int32	Data type index of MDE
Array size	Int32	"−1" if not an array. "0" if array is empty. Numbers greater than 0 specify the number of elements in the array
Count	Int32	For data types "String" and "Array (String)", count = the number of bytes in the string. For other data types, count = 1.
Name length	Int32	For metadata entries listed in Table 14, this is 0. For user-defined entries, this value is the length of the Metadata Name.
Metadata Name	String	Name of the metadata
MDE	varies	Information associated with tag of MDE

4.5 *File Signature, File Trailer and checksum*

4.5.1 The file signature is used to quickly identify a file defined by this specification.

4.5.2 The trailer is used to signal the end of the file.

Table 5. File signature and file trailer.

Variable Name	Data Type	Data	Default Value
File Signature	3-byte String	File Identifier	"psi"
File Trailer	4-byte String	Indicates the end of the file	"@@@@"

4.6 *File Extension*

4.6.1 The file extension is a group of letters occurring after a period in a file name and indicating the format of the file.

4.6.2 The file defined by this specification shall use “psi” as the file extension.

4.6.3 A checksum should be provided separately with the psi file to confirm data integrity.

5. KEYWORDS

5.1 Standard Data Format; Pavement Images; Pavement Surface Condition; 2-Dimensional (2D) Intensity Data; 3-Dimensional (3D) Range Data

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