South Africa
COTO
Committee of Transport Officials

TMH13

AUTOMATED ROAD CONDITION ASSESSMENTS
PART G: IMAGING

Committee Draft Final
May 2016

Committee of Transport Officials

TECHNICAL METHODS
FOR HIGHWAYS

TMH 13

AUTOMATED ROAD CONDITION ASSESSMENTS

Part G: Imaging

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Synopsis

TMH13 provides the guidelines and procedures to assist road authorities to plan, execute and control automated road conditions assessments for: roughness, skid resistance, texture, rutting, deflections and distress imaging. Automated measurement concepts as well as background to different devices are provided. TMH 13 is a companion document to TMH 22 on Road Asset Management Systems and as such includes aspects of data capturing, analysis and documentation.

Withdrawal of previous publication:

This publication is new publication.

Technical Methods for Highways:

The Technical Methods for Highways consists of a series of publications in which methods are prescribed for use on various aspects related to highway engineering. The documents are primarily aimed at ensuring the use of uniform methods throughout South Africa, and use thereof is compulsory.

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Any comments on the document will be welcomed and should be forwarded to coto@nra.co.za for consideration in future revisions.

Document Versions

Working Draft (WD). When a COTO subcommittee identifies the need for the revision of existing, or the drafting of new Technical Recommendations for Highways (TRH) or Technical Methods for Highways (TMH) documents, a workgroup of experts is appointed by the COTO subcommittee to develop the document. This document is referred to as a Working Draft (WD). Successive working drafts may be generated, with the last being referred to as Working Draft Final (WDF). Working Drafts (WD) have no legal standing.

Committee Draft (CD). The Working Draft Final (WDF) document is converted to a Committee Draft (CD) and is submitted to the COTO subcommittee for consensus building and comments. Successive committee drafts may be generated during the process. When approved by the subcommittee, the document is submitted to the Roads Coordinating Body (RCB) members for further consensus building and comments. Additional committee drafts may be generated, with the last being referred to as Committee Draft Final (CDF). Committee Drafts (CD) have no legal standing.

Draft Standard (DS). The Committee Draft Final (CDF) document is converted to a Draft Standard (DS) and submitted by the Roads Coordinating Body (RCB) to COTO for approval as a draft standard. This Draft Standard is implemented in Industry for a period of two (2) years, during which written comments may be submitted to the COTO subcommittee. Draft Standards (DS) have full legal standing.

Final Standard (FS). After the two-year period, comments received are reviewed and where appropriate, incorporated by the COTO subcommittee. The document is converted to a Final Standard (FS) and submitted by the Roads Coordinating Body (RCB) to COTO for approval as a final standard. This Final Standard is implemented in industry for a period of five (5) years, after which it may again be reviewed. Final Standards (FS) have full legal standing.

Table of Contents

ITEM **PAGE**

List of Figures

List of Tables

G.1 Introduction

G.1.1 Context and Scope

TMH 13 *Part G* is the last of seven parts on Automated Road Condition Assessments. Part G provides guidance and methodologies on the planning, execution and control of automated road condition surveys using imaging technologies. *Because of the wide range of applications associated with imaging technologies, Part G not only focuses on the pavement itself but incorporates other related Right of Way (ROW) assets.* This part should be read in conjunction with TMH 13 Part A which includes basic concepts and key definitions related to imaging. Part A also covers general aspects related to the planning of automated road condition surveys.

TMH 13 Part G is a companion document to TMH 22 which is the official requirement for Road Asset Management of the South African Road Network. Part G complements TMH 22 on providing guidelines and methods to capture ROW data and pavement distress through imaging. Imaging includes photographic measurements through various camera technologies as well as laser scanning technologies. These technologies potentially encompass the collection of a wide range of data related to different road assets and their respective characteristics. Whilst the document addresses aspects of data management and reporting, reference is made to TMH 22 and TMH 18, respectively, for supplemental information and data type requirements. In general, reference is made to other documents in the series along with appropriate standards.

The scope of these guidelines are primarily concerned with the needs of roads agencies or managers of road networks. Although some details of measurement procedures are discussed, the emphasis remains on the needs of the network manager, and not on the needs of the contractor in charge of the actual measurements.

G.1.2 Objective

The primary objective of Part G is to assist road network management personnel to plan, execute and control imaging surveys. Secondary and associated objectives are to provide background, definitions and clarification of key concepts. Whilst concepts are explained throughout TMH 13, it was attempted to consolidate the content related to the secondary objectives in Part A: General.

G.1.3 Layout and Structure of Part G

The document is written in concise format as far as possible to enable network managers to use it firstly as a practical guide, and only secondly as a source of general information on the use of imaging technologies.

Concept summaries and checklists are included. A comprehensive reference list is provided and related but non-essential aspects are discussed in sidebars. Sidebar boxes are also used to highlight references to other related TMH documents and specifications. The guidelines are structured as follows:

Section G.2 introduces the main types of imaging systems and peripheral devices to enhance or supplement network level surveys.

Section G.3 covers the validation of imaging systems and control testing to ensure continued delivery of quality results. The selection of validation sections is discussed, and schemes and criteria for system validation are outlined.

Section G.4 addresses operational and quality control procedures for imaging systems.

Section G.5 provides references and a glossary is included in **Section G.6**.

G.2 Imaging Systems

TMH 13 Part A introduces concepts of imaging and provides an overview of its use within the context of road management. Whilst manual or traditional 'walk over' or 'drive over' visual data collection methods exist as described in TMH 9, TMH 13 Part G focuses on technologies applied in automated high speed imaging surveys. The following systems currently available and used in transportation applications are presented in this section:

- Frame imaging;
- Scaled frame imaging;
- Line scan imaging systems;
- Range imaging systems, and
- 3D laser scanning.

Data types can range from basic photo and video imagery to highly accurate geo-referenced laser-based point clouds. Applications may range from validation and update of asset registers to mapping and condition evaluation of asset components. Collection of this data creates a permanent visual record for future reference and auditing. In addition, the use of imaging technologies includes benefits such as potentially greater accuracy, consistency, and repeatability compared to more traditional visual surveys.

Reference should be made to documents in the series such as TMH 22 and TMH 9 for classification, nomenclature and methods used for describing the condition of road assets and road asset components, respectively. Such standards apply regardless of the technology adopted for recording or measurement.

Road and roadside asset data collection may be divided into:

- Inventory - fixed positions and dimensions
- Condition - changes to be monitored

Although a single technology may be able to detect aspects of both asset inventory and condition, technologies are normally used in a complementary fashion due to different inherent capabilities and limitations. For example, 3D laser scanners (e.g. LIDAR) are primarily used to acquire asset inventory and geospatial data, whilst some condition data such as reflectivity of road signs can be collected as part of the same process. Specialised systems directed to the road surface are used to collect pavement condition data, whilst inventory items such as road paint markings can also be extracted from this data. Imaging surveys can be divided into:

- Observing/ recording the asset, and
- Processing/ interpreting data

Processing of the data may be performed after collection (post-processing) or in real-time. Imaging processing depends on the system software design which may specifically cater for manual extraction of asset features (post-processing only) or automated extraction of features (post-processing or in real-time).

G.2.1 Frame Imaging

The most basic imaging technology is frame imaging using area view cameras. The images are used as visual reference of assets and windshield condition ratings. The only additional data needed is a location reference. The location reference is usually a road name and linear location (i.e. km position) or GPS co-ordinate. Cameras capable of GPS tagging is commonly available nowadays.

Capturing of images is usually triggered by the distance measuring instrument (DMI) at user-defined intervals to achieve the desired location accuracy. Distance based image capturing also eliminates the capturing of repetitive information when the vehicle is stopped at intersections or in heavy traffic conditions.

The images are usually stored in JPG format (image size compression format) with the location reference as part of the image name. Images from different cameras (on the same system) include an identifier in the file name. This makes it possible to identify the camera (or view) from the file name. A standard naming convention makes it easy for third party software to view the images.

Surveying vehicles such as the Dynatest Mark III Road Surface Profiler (RSP) (Dynatest, 2010) accommodates a number of independent cameras as part of the system. Communication between various subsystems is facilitated by a Local Area Network (LAN) and operations software makes location reference public over its network. Third party software can use the public location reference as trigger for events. However, the disadvantage of using this method is latency. It is not guaranteed that images will be taken at the correct location at the same time. But as the images are used for visual reference this is not a cause for concern.

Camera mountings are portable and the viewing angles can be adjusted or even relocated to satisfy the needs of an application. It is customary to have one camera facing to the front (Right of Way) and if the survey is not done in both directions, one camera facing to the back. The second camera, or a third camera if provided for, can also be used to image road side furniture not clearly visible by the camera facing to the front.

Fugro Roadware's ARAN (Automatic Road Analyzer) ROW video imaging subsystem comprises up to six high definition 3CCD (three CCD sensors) broadcasting quality cameras that enable complete capturing of the Right of Way panoramic view. Cameras are typically mounted in a turret type enclosure above the vehicle cabin, but angled to emulate a windshield view. This affords maximum visibility without restricting driver movements, and also allows for more camera angles than in-cab mounting alternatives. Where the turret is not available or camera type/ configurations preclude this option, in-cab windshield mounting is available (Fugro, 2013).

Aspects such as minimum resolution, field of view, frame rate, shutter speed and collection interval influence the quality and ability of images to capture relevant details (see Part A). Some systems, such as the ARAN ROW video imaging subsystem provide for real-time image quality monitoring and common manual adjustments including contrast, brightness, and white balance facilitated through a digital video storage graphical user interface. In addition, automatic adjustments are made to minimise the impact of transitions from light to dark areas normally impose (such as travelling through tunnels, underpasses, and tree-canopied areas). Data compression ratios are also adjustable during collection through the digital video storage graphical user interface (Fugro, 2013).

The collected imagery may serve as a standalone video inventory of surveyed areas, or may be used in conjunction with additional software applications. Image viewing software typically display all collected views concurrently and 'visit' sections on demand through a section inventory list, map interface, or graphs of pertinent associated data.

G.2.2 Scaled Frame Imaging Systems

Scaled frame imaging can be used to extract and measure inventory items and condition, including quantification of visual pavement distress. Scaled images mean that the images are calibrated using photogrammetric principles. A pixel on a scaled image can be expressed as a 3-dimensional co-ordinate and basic measurements can be made. More advanced stereo-photogrammetric systems can potentially deliver point cloud data, and therefore classify under 3D imaging systems.

Whilst the same area view camera setups are often used as described above, some important aspects need consideration. Scaled frame imaging is more complex since more information from other sub-systems is required, e.g. grade and cross-fall. The distance between captured images must be exact, as these are all parameters used for scaling. The mountings of cameras must be fixed and calibration of the imaging system is required. Scaled frame imaging is therefore usually an integrated part of the survey system and not an "add-on".

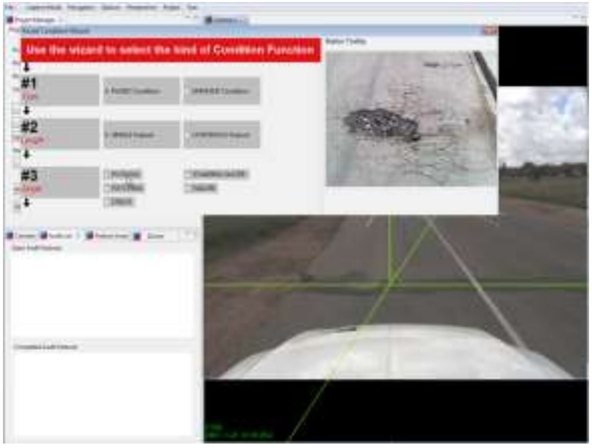
Naturally, image resolution is a primary consideration when items such as cracks are to be measured. Generally, image resolution and crack width is directly related (Wang and Smadi, 2011). Although resolution of cameras has increased with time, measurements are also impacted by other influences such as parallax issues and lens distortion (Wang and Smadi, 2011; Wix and Leschinski, 2012). Many systems rely on natural lighting which affects image quality in a number of ways despite the use of manual or automated optical adjustment techniques. With these systems, cracks down to 3 mm wide are normally detected.

Manual post-processing software is used with calibrated digital images to perform asset and geometric feature inventories, distress logging and measurements. Figures G.1 and G.2 show example software interfaces of asset logging and distress logging (rating and measurement), respectively, developed by Inivit (Pty) Ltd.

Crack imaging systems using area scan cameras mounted on rigid extension arms and facing downwards have been used with artificial lighting.

Step 1: Choose type of asset or use the shortcuts in the popular and favorites lists

Figure G.1 Asset logging and condition rating interface (Inivit, 2010)



Use the wizard to select the kind of Condition Function

Figure G.2 Pavement distress logging and measurement interface (Inivit, 2010)

Fugro's Pave2D system uses two high resolution monochrome digital cameras triggered by a DMI to capture a continuous stream of pavement imagery over the full lane width. High camera resolution (1392 x 1040 pixels), a synchronized high speed shutter setting in combination with optimally angled camera-synchronised strobe lights enable recognition of cracks down to 2 mm wide. Strobe lights eliminate shadows from trees, bridges and other objects providing consistent illumination of pavement images.

WiseCrax post-processing software automatically detects, analyses and reports crack type, severity, extent and location. Manual interaction is allowed for during this process to apply engineering judgement and experience to the automated outputs (Fugro, 2013).

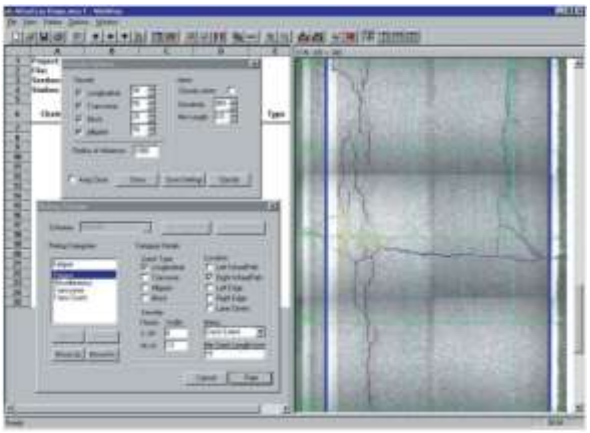


Figure G.3 WiseCrax automated crack detection software interface (Fugro, 2013)

G.2.3 Line Scan Imaging Systems

These types of systems comprises two or more line scan cameras facing downward and sampling at mm intervals to produce a continuous 2D image of the pavement surface. Line scan imaging offers benefits such as higher resolution, no 'fisheye' lens distortion, and blur-free images at highway speed without the need for shuttering. As with area view cameras, the images are also adversely affected by lighting and surface condition (Wix and Leschinski, 2012). For these pavement dedicated imaging systems, various lighting enhancement and crack illumination designs have been implemented. Integrated trailer mounted survey platforms as well as vehicle mounted platforms exist as illustrated in the figures to follow.

The RoadCrack device was originally developed by the Commonwealth Scientific and Industrial Organization (CSIRO) for the Roads and Maritime Services (RMS) of New South Wales and was upgraded by ARRB in 2010. Figure G.4 shows the 5th wheel trailer and illumination system. The system requires a large power supply along with significant electrical infrastructure. The imaging system consists of four transversally fitted line scan cameras each with its own lighting module, covering a total survey width of 2.2 m. High intensity line illumination is achieved using eight iodide lamps with reflectors. Angled lighting accentuates cracks, producing high contrast images (Wix, 2012).

Automated crack detection and analysis is performed in real time without the need for post processing or data handling.

Processing of results include crack classification and crack width measurement down to 1 mm. All images, or optionally only those containing cracks, can be saved in compressed or uncompressed format (Wix and Leschinski, 2012).

Figure G.4 RoadCrack trailer and pavement lighting (Wix and Leschinski, 2012)

INO Systems in collaboration with Pavemetrics™ Systems Inc. developed the Laser Road Imaging System (LRIS). The LRIS represents a data acquisition system that uses two line scan cameras in conjunction with laser line projectors that are aligned in the same plane in a symmetrically crossed optical configuration.

As shown in Figure G.5, this optical configuration increases the visibility of cracks by using the incident illumination angle of the line laser to cause the cracks to project shadows. The LRIS system can operate in full daylight as well as in darkness because it is immune to variations in outside lighting conditions and unwanted shadows. The system only consumes a few hundred watts of power compared to more traditional lighting systems. The system images near 4 meter transverse road sections at more than 100km/h with 1 mm resolution.

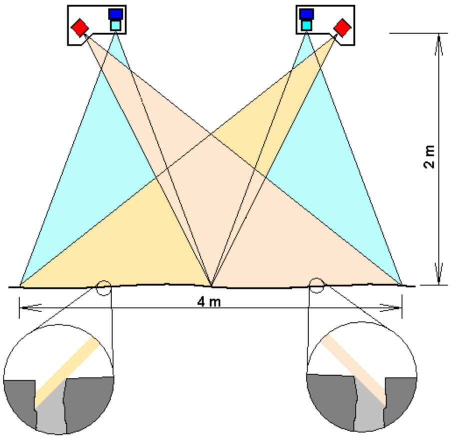


Figure G.5 Laser Road Imaging System (Pavemetrics, 2010)

The LRIS has been implemented by service providers such as Dynatest (Figure G.6).

Dynatest's post-processing software is used for manual distress identification, measurement, and classification.

Figure G.6 Dynatest Multi-Functional Vehicle

G.2.4 Range Imaging Systems

As described in Part A, range imaging produces a 3D structure of a scene employing active range sensors consisting of a light source and receiver. The most commonly used systems use laser line projectors and high speed cameras, respectively. High speed CCD or CMOS cameras detect the changes in the laser line or light strip. By using optical triangulation, a depth map of surface points under the strip is obtained. High speed cameras typically generate a couple of thousand profiles per second while scanning an object which is used to construct the 3D image. With these sensors, the application range is normally from millimetres to a few meters, whilst sub-millimetre resolutions can be achieved.

Commercial systems developed for road survey applications primarily focus on characterization of the road surface with specific interest in automated crack detection and measurement. Figure G.7 illustrates implementation of this technology by INO Systems and Pavementrics™ in the Laser Crack Measurement System (LCMS).

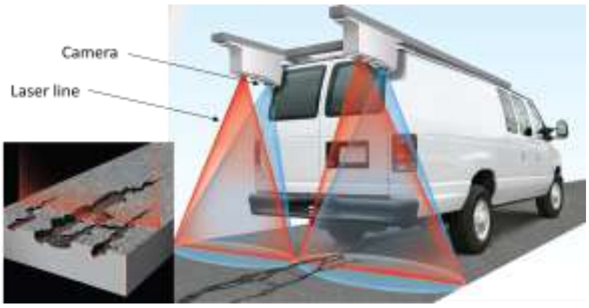


Figure G.7 Laser Crack Measurement System (Pavemetrics, 2014)

Figure G.8 shows WayLink System's PaveVision3D Ultra crack detection system incorporated into SANRAL's latests road survey vehicle. The design of SANRAL road survey vehicle makes provision for storage of the equipment inside the vehicle for safekeeping when not in use (SANRAL, 2014).

This system comprises two modules each equipped with four cameras and a laser line projector emitting green light for improved visibility. The use of four 3D cameras helps prevent occlusion effects and produce high accuracy surface range maps. The 3D system with camera array achieves profile line rates of 30,000/second with full lane coverage and capturing true 1 mm pavement surface features at any speed up to 100 km/h (Wang, 2013).

In addition to high definition cracking, 3D surface characterization enables a number of additional pavement parameters to be determined such as pothole measurements, volumetric texture, rutting, roughness and road geometry. Inclusion of some of these features, such as roughness is optional and may require additional software and hardware modules.

These systems generally come fully automated, including data acquisition and interpretation. Compressed raw data, 2D and 3D, and/or processed data are normally saved depending on the software for crack detection and analysis either done in real time or by post-processing.

Software typically produce crack coordinates enabling compilation of crack maps, classification of cracks, and crack width measurements. The WayLink PaveVision3D crack detection and interpretation software interface is shown in Figure G.9.

Figure G.8 SANRAL Survey Vehicle equipped with PaveVision3D Vision Ultra (SANRAL, 2014)

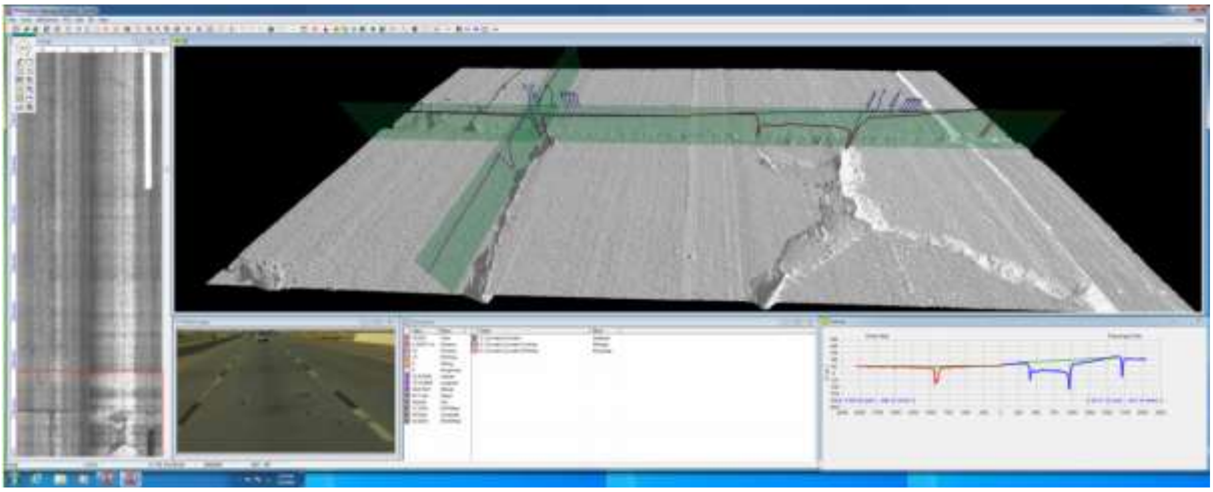


Figure G.9 PaveVision3D Ultra crack detection and analysis interface (Wang, 2013)

G.2.5 Three-dimensional (3D) Laser Scanning

3D laser scanning or LIDAR (Light Detection and Ranging) can rapidly acquire a substantial amount of highly detailed geospatial information. The value of this technology is in the features of the road and road side inventory that can be extracted from the data such as bridge clearance, gantry locations, sight distance, curvature, barriers etc. Whilst this technology has successfully been used to measure pavement rutting and roughness, its application to automated distress detection largely remains in the research and development arena (Olsen et al, 2013).

Laser scanners work by emitting light and detecting the reflected light from an object to accurately determine the distance to that object. 3D laser scanners facilitate millions of measurements in a few seconds through firing laser pulses either by an internal rotating mirror (fixed scanning head) or rotating scanning head operation (Olsen et al, 2013). Immediately after one pulse is received and measured, the scanner transmits another pulse at a fixed angular increment. The distance and orientation of each pulse allows determination of the associated xyz coordinates. In addition, the intensity (signal strength) of the reflected pulse is determined. In general, higher reflections are associated with lighter coloured objects and closer objects. The coordinates and intensity values output of millions of measurements make up the ‘point cloud’ (Kemendy and Turner, 2008).

The accuracy of the positioning system of the mobile LIDAR largely determines the accuracy of the final point cloud. Measurements from all system components are synchronized to a common time reference frame using a precise time stamp. Figure G.10 shows typical components of a mobile LIDAR system. Refer to TMH13 Parts A and B for further information on positioning systems.

A rigid platform is needed to firmly attach the laser scanners, positioning components, digital cameras and ancillary devices. Careful calibration of each component is required so that the offsets between them are known and remain stable. In addition, the platform may be designed in such a way to make provision for transfer of the mobile LIDAR system from vehicle-to-vehicle with more ease than moving individual components (Olsen et al, 2013).

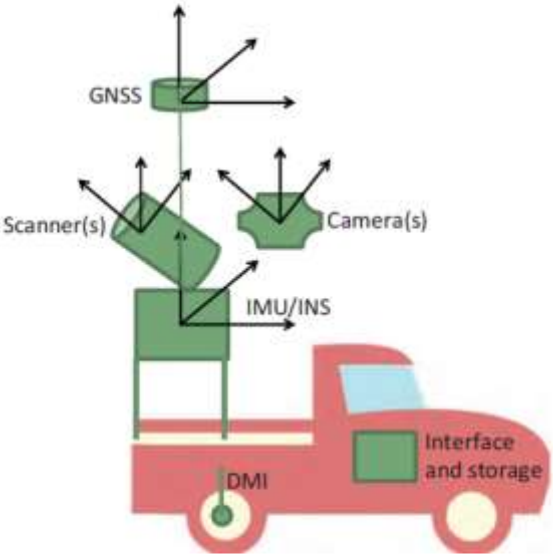


Figure G.10 Typical mobile LIDAR components (Olsen et al, 2013)

Digital cameras are commonly incorporated as part of the mobile LIDAR system to aid in visualisation. Cameras can be arranged to cover different views or a 360 degree panoramic view. Due to availability of different intensity values, point clouds intrinsically exhibit photographic qualities, that is, lighter and closer objects appear brighter than darker and distant objects. Colour information provides an added level of detail when a coloured point cloud is produced by assigning red, green or blue (RGB) with the location of each point (Kemendy and Turner, 2008; Olsen et al, 2013). The need for co-acquired imagery geo-referenced to the point cloud should be communicated to service providers. In addition, service providers should ensure that they provide imagery taken from appropriate viewpoints and under proper lighting conditions (Olsen et al, 2013).

SANRAL road survey vehicle uses a Trimble MX8 Mobile Spatial Imaging system (Figure G.11). As shown in Figure G.8, the system can be safely stored inside the truck when not in use.

Figure G.11 SANRAL Survey Vehicle equipped with Trimble MX8 LIDAR (SANRAL, 2014)

The Trimble MX8 system is equipped with a pair of high performance, 360-degree mobile laser scanners each capturing 360 000 points/s. Four high frequency digital cameras facing backwards are imbedded in a rigid enclosure, whilst provision is made for three cameras facing forward to capture a 360 degree view. The system integrates an Applinax POS LV (positioning and orientation for land vehicles) inertial navigation subsystem that is capable of sub-metre accuracy at 80km/h.

The Trimble MX8 is supplied with laser and imagery capture, synchronization and extraction software. Software includes automated as well as manual feature extraction capabilities. Manual feature extraction typically includes 3D measurements from point clouds or images with options to add or delete photogrammetric and point cloud features. Automated extraction includes features such as detection of poles and signs; sign recognition, compiler and library; pavement marking detection; edge and centreline detection; road modelling (DTM, cross sections, and profiles); horizontal/ vertical line of sight and clearance (Trimble. 2014).

Big Data Considerations

Imaging surveys require Big Data resources. Managing the process of acquiring and using Big Data can be a challenge which requires knowledge of Big Data workflows. Expansion of IT policy and procedures to handle high-volume data may be necessary (NCHRP Project 15-44: Olsen et al, 2013)

G.2.6 Equipment Selection and Specifications

Table G.1 broadly classifies different imaging systems introduced in this section. It is reiterated that Part G focuses on data collection at or near highway speed.

It should also be noted that Table G.1 covers current road surveillance implementations and it is not implied that specific technologies are limited to the applications indicated. In addition, many applications emerge due to ongoing refinement and development of these systems. Usually, different systems are combined to incorporate their advantages into a better product, e.g. LIDAR point cloud data combined with digital imagery.

As suggested in Table G.1, selection of equipment requires consideration of data use which will dictate resolution and accuracy needs, and processing or software needs. Decisions should be an outflow of the survey objectives based on specific network requirements, agency practices and resources (see Part A). Road owners should note that imaging surveys in general requires resources to work with large datasets, or Big Data (See information block).

Table G.1 Classification of Imaging Systems

Imaging System	Application[1]				Data Processing & Analysis[1,2]		System Example
	Basic/ Qualitative[3]		Detail/ Quantitative[4]				
	ROW	Pavement Distress	ROW	Pavement Distress	Manual	Semi- to Fully Automated	
Frame/ Area	✓	✓	×	×	✓	×	Commonly used
Scaled Frame	✓*	✓	✓*	✓	✓*	✓#	Inivit HSDA*, Fugro Pave 2D#
Line Scan	×	✓	×	✓	✓	✓	INO LRIS, CSIRO RoadCrack
Range Imaging	×	✓	×	✓	✓	✓	INO LCMS, Waylink Ultra, Fugro Pave 3D
3D Laser Scanner	✓	×	✓	×	✓	✓	Trimble MX8

Legend: RoW denotes Right of Way and includes all roadway and roadside assets; * and # refer to specific system examples

Notes:

1) Application and processing fields represent typical features of available systems and do not imply that a single system includes all
2) Data processing and analysis software modules are often optional to cater for different operational needs and budgets.
3) Basic/ Qualitative resembles surveys of inventory items and distress rating (type, severity and extent). Detection of distresses are often limited to higher severity levels, e.g. wide cracks
4) Detail/ Quantitative implies measurement of position and size as a minimum. Measurement capability differs from system to system, e.g. some systems are limited to measurement of crack length whilst others also produce crack width.

G.2.6.1 Right of Way Imaging

Right of Way (ROW) imaging is a useful network review tool and in its basic form can be used to record inventory and road furniture information. It can also be used to help resolve anomalies or characteristics observed in other data types.

It is common practice to video the forward or driver view of the pavement along with location referencing information using high-speed high resolution cameras mounted to the survey vehicle. The system should be specified with one to three cameras. Only a single camera is needed if only the ROW in front of the vehicle is needed, whilst additional cameras may be included to record the side views. File size may be reduced by sampling images at regular intervals, provided that sufficient data is collected for management purposes. Table G.2 provides minimum equipment requirements (Brown and Thomsen, 2007).

Table G.2 Minimum ROW Imaging Equipment Requirements

Parameter	Requirement
Camera	
Image Position Error	< 1m
Camera Type	1EEE - 1394 Firewire or equivalent
Picture Size	800 x 600 pixels min.
Colour	24-bit Colour
Min. Sampling Interval	5m at 80 km/hr
Frame Capture Rate	Distance based
File Format	JPG or other industry standard
Survey Speed	20 - 80 km/hr
Exposure Range	1/10000 F1.4
Camera enclosure	IP 65
Overlay Software	
• Software will facilitate overlay of positional data including Distance, GPS, Road and Location Reference Point ID. • Imaging data must be integrated with other condition data.	

Notes:

1) Minimum resolution that meets the needs for many applications. Higher resolutions may be specified but increases cost of hardware and storage requirements.
2) If mounted on the roof of the vehicle a waterproof enclosure is required.

A key benefit of ROW imaging is that a single acquired data set provides a record of the facility for future data mining and broader deployment of the data across the organization, i.e. not only for asset management, but also risk management, design, construction, maintenance monitoring etc. The possible applications and therefore benefits increase substantially with the development and use of high-end 3D imaging technologies such as digital photogrammetry and LIDAR.

Much emphasis has been placed on the use of mobile LIDAR in the transportation sector in recent years (Faber, 2014). However, modern photogrammetry offers a competitive alternative in meeting specifications for infrastructure mapping. Traditionally the equipment cost for photogrammetric systems are significantly less if compared to LIDAR although considerable cost reductions are expected with advances in LIDAR technology (Nulty and Noble, 2013). In many cases, these technologies are often (and ideally) integrated and used in a complementary fashion.

In the context of TMH 13 it is assumed that most agencies will hire the services of contractors for data collection and processing. As accuracy requirements for 3D imaging are increased, the survey cost can increase exponentially. These costs are associated for example with the establishment of a very accurate survey control framework, increased number of ground control targets, number of phases in each direction, the use of high grade IMU and scanner(s) and additional office processing (Faber, 2014). Apart from data collection costs and information technology (IT) costs (storage, servers, backups etc.) consideration should be given to data extraction costs. These costs rely heavily on the number of features to be extracted and the level of automation of this process. Manual identification and extraction of features can be labour intensive. Depending on the feature, even systems with highly automated feature extraction capabilities generally exhibit accuracies of about 80 percent. Cost-effective extraction of data is therefore critical to realising the benefit of 3D imaging (Faber et al, 2014).

Although using a technology such as mobile LIDAR has many benefits, it may not always be the optimal solution for the network under consideration. The significant volumes of data generated by 3D imaging systems provide a valuable, yet challenging resource (See information block on ‘Big Data Considerations’). It should be noted that the agency may be more concerned with the end product than the technique used to collect the data. A cost/benefit analysis should be conducted to determine if the candidate technique is optimal for the survey under consideration especially when considering high-end solutions such as mobile LIDAR. Such an analysis should consider (Olsen et al, 2013):

- All potential data uses during data life span;
- Capacity needed to perform quality control;
- Integration of data into current workflows and possible improvements to current systems;
- The ability to share data and cost within and outside the agency;
- Survey resolution and accuracy needs, and
- Collection of additional data from the same platform.

Specifications for 3D imaging surveys generally address the required information and data quality that should be provided and are broad enough not to limit service provider equipment and technology. Although detailed equipment component specifications are not required, the agency may specify the equipment type depending on aspects such as past experience, survey objectives, network characteristics and agency resources that should reflect in the cost/benefit analysis. Because accuracies of equipment components and system parameters impact the overall expected data accuracies, an equipment calibration report should be requested from the service provider as part of the validation process (See Section G.3).

Different data applications require different levels of accuracy and density (resolution) of data. Data quality requirements will dictate the use of equipment or service providers with appropriate capabilities. For this reason the level of detail or general data application category needs to be established for data collection procurement purposes.

More Information: Selecting and Implementing Mobile LIDAR Technology

NCHRP Project 15-44 “Guidelines for the Use of Mobile LIDAR in Transportation Applications” (Olsen et al, 2013) provides information on aspects such as workflow and data management, organizational data mining, procurement considerations, and implementation plans for transportation agencies

A mobile LIDAR application matrix developed under NCHRP Project 15-44 (Olsen et al, 2013) offers suggested accuracy and resolution requirements for different applications (**Appendix G-1**). This matrix may be used as an indication of the desired output for any equipment capable of producing a point cloud dataset. The matrix in Appendix G-1 presents nine categories (1A through 3C) where the numbers represent varying orders of accuracy (1 = High, 2 = Medium, 3 = Low) and letters representing levels of point density on the targets of interest (A = Coarse, B = Intermediate, C = Fine).

Accuracy has the greatest influence on project cost whilst point density can be achieved by driving slower or making multiple passes. As an example, for asset management and inventory mapping applications the matrix recommends Category 3C: Intermediate Density (30 to 100 points/m^2) and Low Accuracy (>0.2 m). However, when determining appropriate requirements for procurement purposes, specific project requirements and agency practices also need to be considered.

Ideally, an agency would coordinate needs between departments to determine optimum data utilisation. Naturally, datasets collected at higher accuracies and point densities (e.g. Category 1A) will be usable for applications that require lower quality data (e.g. Category 2B), although this may not be cost-effective. In contrast, data collected at a lower accuracy and point density (e.g. Category 2B) may still be useful for an application requiring higher quality data (e.g. Category 1A) compared to what is available. However, the analysis may be more difficult to perform and less reliable than if the recommended higher category data were collected (Olsen et al, 2013). Once the network manager has decided on the general data collection category, detailed contract requirements can be developed. More detailed aspects are included in Section G.3.

G.2.6.2 Pavement Distress Imaging

Typical distress imaging systems introduced, highlight a general focus on crack detection and analysis. The systems typically capture pavement images using a high-speed-high-resolution camera mounted securely to the survey vehicle such that the pavement surface detail is recorded along with location reference information.

The recording method may be area scanning, line scanning, or 3D scanning. Systems with illumination or without (passive) can be used. Images may be recorded as a dimensional map or any combination of technologies that achieves the specified distress rating or crack detection reliability.

Table G.3 provides minimum equipment requirements. Whilst basic equipment specifications are presented, acceptance is primarily based on adequate validation to meet specified system output criteria (see Section G.3). Specifications should aim to standardize thereby contributing to consistent pavement condition estimates while not unduly limiting equipment innovation (AASHTO, 2014a).

Table G.4 classifies pavement distress imaging systems into two classes based on typical system capabilities. Detailed crack analysis can be done with Class 1 systems, whilst Class 2 systems are essentially used for distress ratings. The classification also considers processing. For semi-automated processing, software facilitates recording and detailed measurement of distresses by the reviewer, whilst automated systems detect, record, and analyse distresses, often refined with human intervention. With manual processing, the reviewer uses software to view the images, while assigning and recording types of distresses and condition ratings.

Compared to manual (or traditional) reference methods as described in TMH 9, higher level of automation in the methodology offers benefits in improved personnel safety, more rapid and cost effective data collection, better reporting and planning capabilities, production of higher quality data in terms of repeatability, and potentially better statistical representation of the network (Austroads, 2006). As indicated above and similar to high-end ROW imaging technologies, the selection/ specification of distress imaging equipment involves big data considerations, i.e.

Table G.3 Minimum Equipment Specifications for Distress Imaging

Parameter	Requirement
Camera	
Image Position Error	< 1m
Camera Type	Area or line scan
Colour	8-bit grey scale
Minimum resolution	2mm/pixel
File Format	JPG or other industry standard
Minimum coverage	100% of lane width + 300 mm
Maximum image length in travel direction	100 m
Survey Speed	20 - 80 km/hr
Camera enclosure	IP 65
Review Software	
Software will facilitate on demand viewing and full logging and condition rating to produce an inventory of pavement defects that can be integrated with other condition data.	

the ability of the agency to utilise and effectively manage the data. The type of network, agency objectives and resources need to be taken into account. The following general considerations affect the selection and specification of equipment (adapted from Austroads, 2006):

- Data collected and processed using fully automated systems may be more expensive due to higher equipment cost. However, time and reliability of processing should be considered for systems that rely on manual distress detection, analysis and rating.
- Detailed reporting is possible with automated distress detection and processing, including crack type, crack width, severity, and extent.
- Systems that can detect more detail, potentially offer higher savings through correctly targeted early application of low cost maintenance treatments.
- More dedicated systems normally has less restrictions such as the ability to conduct surveys during daylight (irrespective of position of sun) or at night.

Table G.4 Pavement Distress Imaging System Classes

Class	Typical System	Imagery	Processing	Typical Outputs
1	Scaled Frame/ Scaled Line Scan/ 3D Imaging	2D measureable pavement/ 3D measurable pavement	Semi-Automated/ Automated	• Distress type & rating • Crack map • 2D crack dimensions (including crack width)/ 3D crack dimensions (including crack width)
2	Frame/ Scaled Frame	RoW/ pavement/ measurable RoW	Manual	• Distress type & rating

G.3 Validation and Control Testing

A validation program should be conducted prior to acceptance of the equipment and/or before data collection starts. TMH 13 Part A introduces general aspects of calibration, validation, and measurement control that require consideration during the survey planning process.

TMH 13 generally covers automated surveys, including both measurement and processing aspects which are relatively easy to validate. Although Part G also involves high speed surveys, it includes non-data deliverables where quality is often described in more subjective terms. Moreover, depending on the type of system, imaging processing may still involve the use of human assessors, essentially the methodology contained in TMH 9. In the context of TMH 13, however, assessors may be office-based and using software to view, detect, record and analyse imagery.

This section provides guidelines and methods for validation of imaging surveys including:

- Right of Way (ROW) Imaging
- Pavement Distress Imaging

G.3.1 General Approach

Calibration and validation concepts are introduced in Part A. Part A describes validation as a referencing exercise conducted on predetermined validation (or reference) sections. The survey system must be validated at each of the selected validation sites against reference data. Reference surveys are conducted by the agency (or third party) using appropriate reference survey techniques.

Calibration and validation are required before production data collection starts and include aspects such as personnel training/ calibration/ certification, equipment calibration/ certification, selection of validation sites or points, performing reference and validation surveys, and application of validation criteria. Once the system has been accepted and production surveys start, control testing should be done on a regular basis to ensure that the system remains valid throughout the survey contract.

G.3.2 Calibration

Components of equipment are configured according to the purchaser's requirements and calibrated as specified by the manufacturer. Some of these components can only be calibrated by the manufacturer while other aspects of the system can be calibrated by the owner. Where imaging outputs are used for measurement, such as in photogrammetric, LIDAR, and pavement distress measurement systems, a rigid framework is normally used to firmly attach the scanners, cameras, positioning components, and ancillary devices. However, depending on the system and the methodology used to install the components, the system calibration parameters may not be of a high temporal stability. Providers are therefore required to submit a calibration report that contains the following minimum information (Olsen et al, 2013):

- The equipment used for data collection;
- Equipment installation schematics;
- The calibration procedure used;
- The calibration parameters and estimated accuracies, and
- Verification of temporal or long term stability of calibrated parameters

For visual assessments or distress ratings required as part of manual or semi-automated image processing, validation sites are used to train and calibrate assessors in the proper application of the THM 9 or specified protocols. For fully automated processes, validation sites are used to calibrate and adjust software algorithms that are used for data reduction. Compatibility of outputs with TMH 9, TMH 20, and TMH 22 is required. **Appendix G-2** provides definitions of distresses, in particular cracks, to complement TMH 9 for interpretation from an image analysis software perspective. More detailed methodologies are provided subsequently in sections that deal with validation.

G.3.3 Validation Test Requirements

Part A includes general guidance for the selection of validation sections. This part outlines additional requirements and considerations for the selection of sections or sites for imaging validation. Concepts of geometric correction and validation required for 3D imaging (such as LIDAR that produces point cloud data) are different from general imaging and these aspects are therefore presented separately.

G.3.3.1 General Validation Test Requirements for ROW Imaging

Validation sections for ROW frame imaging and scaled-frame imaging need to include the following:

- A tight curve to verify that the field of view (FOV) is wide enough to cover all relevant features.

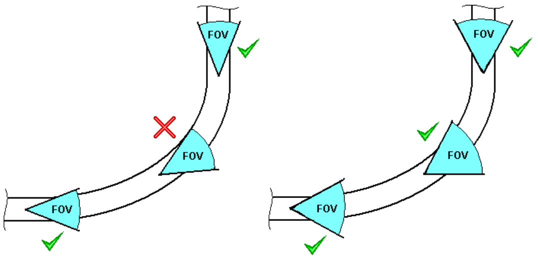


Figure G.12 Validation of Field of View (FOV)

- Steep gradient and cross-fall to verify that the inertial system compensates for these aspects in image measurement
- Measureable items, e.g. road signs
- Longitudinal measureable items, e.g. guard rails, shoulder changes etc.

- Areas with ambient light changes i.e. trees next to the road to verify that the camera(s) compensates for changes in ambient light

It should be noted that the requirements outlined above are different from normal straight or tangent sections recommended for validation of other pavement surveillance measurements. These sites may therefore not be appropriate to use for validation of other equipment.

A minimum of five (5) validation sections shall be selected each with a length of one (1) kilometre. Each site shall have a lead-in and lead-out of at least 0.1 km to visually assist validation of start and end locations.

No validation data shall be collected if the surveillance vehicle is forced to collect the majority of the data while travelling towards the sun. Validation sections should not have excess water on the roadway nor should any validation imaging occur during inclement weather. ROW imaging shall only be performed during daytime hours under sufficient ambient lighting conditions.

The reference or benchmark data for general ROW imaging is an inventory of visible items for each section, with unique item identifier, and location reference. Where item dimension measurement is required, the items with relevant dimensions, geo-references and other location referencing that apply should be included.

G.3.3.2 Control and Validation Points for 3D ROW Imaging

Three dimensional (3D) ROW Imaging generally refers to any system capable of producing a point cloud dataset, whether obtained from laser scanning (e.g. LIDAR) or 3D reconstruction (high-end photogrammetric systems). In addition to general requirements for validating ROW imaging, aspects addressed in the following paragraphs shall apply.

Point cloud data, especially at high accuracy levels, will generally not meet engineering survey standards without geometric correction to benchmark *control points (or local transformation points)*. These control points are identified in the imagery and the point cloud is adjusted by a local transformation to the well defined control point locations. *Validation points* are independent from control points and used as a reference to verify the final geospatial values (Olsen et al, 2013; Faber, 2014).

Important!

Where high accuracy levels warrant geometric correction of the point cloud, the control points observed in the dataset shall serve as direct input observations into the raw navigation trajectory estimation during post-processing, i.e. Geometric correction shall be applied though re-processing of system navigation trajectory. Full documentation including methodology, type, and magnitudes of any applied geometric correction should be provided (NCHRP Project 15-44: Olsen et al, 2013)

Depending on the point cloud accuracy level specified (Section G.3.4) required accuracies may be achieved without geometric adjustment by combining data from multiple runs, collected by systems equipped with high accuracy inertial measurement units (IMUs). Although setting up control points may be redundant in such cases, validation points are still needed to verify system accuracy (Faber, 2014).

Datasets shall be tested with a minimum of 20 validation points. Based on NCHRP Project 14-55 (Olsen et al, 2013) control and validation points:

- Can either be established as part of a permanent control network or can be project specific and temporary.
- Shall be located at the beginning, end, and widely distributed throughout the project corridor to reflect variance across the project extents.
- Can be artificial or existing natural targets that have been appropriately surveyed with an independent source.

In selecting the characteristics and placement of targets, consideration shall be given to:

- Appropriate size relative to point cloud resolution.
- Shapes suitable to allow both vertical and horizontal accuracy validation.
- Use of non-reflective and reflective targets.
- Potential issues with reflective targets surveyed using laser scanners.
- Safe placement as close as possible to the survey vehicle path.

- Placement on both sides of the road, across or alternately.
- Placement on other features of interest, where the road is not the only or primary data of interest.

Table G.5 provides control point spacing and intervals for selection of validation point spacing, depending on the required accuracy. Point density validation shall also be conducted throughout the dataset using similar intervals, particularly for objects of interest. The frequency of validation needs to be established and depends on the variability observed in the dataset as well as spatial frequency of the objects of interest (Olsen et al, 2013).

Control and validation point datasets shall be of a higher accuracy than the point cloud accuracy specifications. Reference datasets shall be obtained independently through DGPS or total station surveying. As an example (refer to Section G.2.6.1 and **Appendix G-1**), for accuracy level 1 certification, static GPS surveying would be required. For accuracy levels 2 and 3 certification, faster methods such as RTK GPS can generally be used (Olsen et al, 2013).

Table G.5 Control and Validation point Intervals for different Accuracy Levels

Accuracy Level[1]	Control Point Interval[2]	Validation Point Interval
1	≤ 450 m	150 - 300 m
2	≤ 450 m*	300 - 750 m
3	≤ 450 m*	750 - 1500 m

Notes:

1) Refer to Section G.2.6.1 and Appendix G-1
2) Control points may not be required for lower accuracy levels*

G.3.3.3 Validation Test Requirements for Pavement Distress Imaging

In order to validate the performance of pavement distress imaging systems, especially in avoiding the reporting of false positive cracks, a variety of sections should include features such as (PIARC, 2012):

- Representative crack types;
- Sealed cracks;
- Different surface types, textures in particular;
- Bleeding and aggregate loss;
- Patches and potholes;
- Road markings;
- Bridge joints, grid inlets etc. and
- Longitudinal and transverse joints where concrete pavements form part of the network.

No data shall be collected during inclement weather or under wet pavement conditions. Although systems equipped with artificial illumination may be able to collect data at night, basic ROW imaging may still be required. Care shall be taken to ascertain sufficient lighting conditions for all surveys at all times.

Table G6 summarises validation test requirements for pavement distress imaging systems. General requirements are provided as well as specific requirements for Class 1 systems, i.e. with semi-automated and automated processing capabilities. For Class 1 systems, the collection lane is divided into five strips or zones to complement the analysis process. Whilst default widths are provided for Zones 2, 3, and 4 (inside, between, and outside wheel paths, respectively), Zones 1 and 5 will vary depending on the lane width under consideration.

Validation of Class 1 systems is divided into two parts: The ability of the system to detect cracks and secondly, the ability to properly analyse the cracks or crack map. To validate *system detection capability*, actual field measurements (and not measurements from images) shall be used as a reference. Whilst THM 9 field distress ratings are not required in this part of the method, compilation of a database with this level of ground truth data can be utilised effectively to continually improve confidence in these systems by scrutinizing, calibrating, and developing distress analysis algorithms.

Validation of the Class 1 *system analysis capability* uses imagery collected for the validation sections as the reference data set. The primary data obtained during this process are software facilitated detail distress dimension measurements and mapping. TMH 9 visual ratings shall also be reported for relevant distresses typically detectable by automated systems as outlined in **Appendix G-2**. In addition, the full record of relevant visual surface data and distresses as defined in TMH 9 shall be recorded. The latter may require supplemental manual reviews and recording of distresses that are not automatically detected.

Table G.6 Validation Test Requirements for Pavement Distress Imaging

Site Feature or Test Description	Requirement
General (Class 1 and 2)	
Number of Sites	5
Site Length	1 km
Segment length for recording and processing	0.1 km
Segment width for recording and processing	100% of lane width[1] + 300 mm
Class1 (Systems with semi- automated and automated processing capabilities)	
Repeat runs per section	6 (3 runs each at 40 and 80 km/hr)
Transversal lane zones[2]	Zone 1: Between inside wheel path and lane edge Zone 2: Inside wheel path = 0.75 m Zone 3: Space between wheel paths = 1.0 m Zone 4: Outside wheel path = 0.75 m Zone 5: Between outside wheel path and lane edge/ shoulder
Field visual assessment reference[3] (FVR) (System detection validation)	FVR1: Absolute degree and extent measurements for distresses listed and defined in **Appendix G-2** per zone per lane segment FVR 2: Relative TMH 9 visual assessment, reporting degree and extent ratings for distresses listed in **Appendix G-2** per lane segment FVR 3: Relative TMH 9 visual assessment, reporting degree and extent ratings for all relevant distresses per lane segment
Imaging system reference (ISR) (Image analysis validation)	ISR1: Absolute degree and extent measurements for distresses listed and defined in **Appendix G-2** per zone per lane segment ISR 2: Relative TMH 9 visual assessment, reporting degree and extent ratings for distresses listed in **Appendix G-2** per lane segment ISR 3: Relative TMH 9 visual assessment, reporting degree and extent ratings for all relevant distresses per lane segment

Notes:

1) Also See Table G.3. An additional 300 mm makes provision for vehicle wander and imaging of edge distress crossing the edge/marking
2) The widths of Zones 1 and 5 to be determined from total lane width under consideration positioned with centreline coinciding with centreline of the survey vehicle
3) FVR 2 and FVR 3 may be omitted for system collection and detection validation on the Network Level. However, this data can provide more insight and may be valuable in calibrating distress analysis algorithms used by agencies.

Since Class 2 systems essentially involves the application of the THM 9 visual assessment process utilising pavement imagery, the reference survey is conducted manually by assessment of the reference imagery. The requirements included in TMH 9 for the visual assessment procedure, training and certification of assessors, and quality plans shall apply. Due to the subjective nature of distress rating methods in general, it is particularly challenging to establish reference values. For this reason, the reference ratings may be a consensus-based ground truth estimate (Pierce et al, 2013).

It should be noted that the reference survey is only temporarily accurate as conditions change with time. Validation sections should therefore be surveyed at least every six months, or if specifically required at the commencement of large scale data collection surveys (Austroads, 2006).

G.3.4 Validation Criteria

Criteria for validation of ROW imaging and pavement distress imaging are presented in the following paragraphs. Whilst imaging systems need to pass the validation process, continued monitoring through control testing (see Section G.3.5), and operational and quality control processes (see Section G.4) are critical since many aspects of imaging quality can only be evaluated subjectively.

G.3.4.1 General Validation of ROW Imaging

The following items are checked to ensure correctness, completeness and acceptable quality levels:

- Images shall correspond to the correct segment, including start and end locations. Where relevant, the recording interval shall also be verified.
- Image visual quality must be acceptable. The following items shall be checked as a minimum:
    - Orientation and field of view as required under Section G.3.3.1;
    - Clarity, including focus, sharpness and colour balance. All views shall be clear with no debris in the viewing path and all signs easily readable. Most pavement distresses should be evident in front views.
    - Exposure: Acceptable image brightness/ darkness especially where extreme ambient light or surface colour changes occur.
- Image replay: Images should play sequentially in correct order, representing a vehicle travelling in forward direction.
- Image compression and resulting file sizes should be acceptable.

Discrete items such as the number of legible signs may be used to validate image quality on a more quantitative basis (Pierce et al, 2013). Where specifications make provision for pavement visual distress ratings (i.e. TMH 9) from ROW images, the validation criteria for Class 2 systems shall apply (Refer to Section G.3.4.3, Table G.7).

Apart from the criteria outlined above further validation is required for scaled frame imaging where item dimension measurement are specified. Using the proposed system measuring software, the following criteria shall apply:

- Horizontal, vertical and longitudinal measurements shall comply with a local accuracy (refer to Section G.3.4.2) of ±30 mm. Measurements at the extreme grade and cross fall positions shall be included.
- Position measurements shall have a sub-metre network accuracy (refer to Section G.3.4.2).

G.3.4.2 Validation of 3D ROW Imaging

Validation criteria for point cloud data include:

- Positioning accuracy requirements
- Point density requirements

The number and distribution of control and validation points for validation purposes were presented in Section G.3.3.2.

a) Positioning Accuracy

Two types of point cloud accuracy exist and are used for accuracy specification purposes, namely Network Accuracy and Local Accuracy (Olsen et al, 2013; Faber, 2014).

The Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards Document (# FGDC-STD-007) definesthese types of accuracy as follows:

- The network accuracy of a control point is a value that represents the uncertainty in the coordinates of the control point with respect to the geodetic datum at the 95 percent confidence level.
- The local accuracy of a control point is a value that represents the uncertainty in the coordinates of the control point relative to the coordinates of other directly connected, adjacent control points at the 95 percent confidence level. The reported local accuracy is an approximate average of the individual local accuracy values between this control point and other observed control points used to establish the coordinates of the control point.

Accuracy Testing and Reporting

- Network Accuracy refers to the absolute positioning within a coordinate system
- Local Accuracy refers to relative measurements within the dataset and is a measure of precision.
- The National Standard for Spatial Data Accuracy (NSSDA) developed by the FGDC (1998) provides the foundation for the reporting found in most available standards and guidelines

Whilst traditional survey accuracies are typically expressed in terms of horizontal (2D) and vertical (1D) components, point cloud data intrinsically allows assessment of true 3D error vectors. This is because GPS uses the International Terrestrial Reference Frame (ITRF) realization of the WGS84 (Word Geodetic System 1984) datum (see Part B), which does not require a projection.

The National Standard for Spatial Data Accuracy (NSSDA) developed by the FGDC (1998) provides the foundation for the reporting found in most available standards and guidelines (Olsen et al, 2013; Faber, 2014). In line with the NSSDA, differences between known control locations and/or control surfaces and the point clouds shall be computed as root mean square error (RSME) values.

For point cloud accuracy, 3D accuracy values shall be reported in ground distances (m) at a 95 percent confidence level and based on datasets with a minimum of 20 control points. Ranges of point densities typically required for different applications are shown in the application matrix introduced in Section G.2.6.1 and attached as **Appendix G-1**. Figure G.13 provides refined accuracies (local) and point density values for different transportation applications.

In order to scale RMSE values to a 95 percent confidence level, the conversion shown in Equation 1 should be used. Conversions for 2D (horizontal) and 1D (vertical) accuracy are also shown. Conversions are based on the assumption that the errors are normally distributed (Olsen et al, 2013):

$$\text{3D 95\% confidence} = \text{3D-RMSE} \times 1.6166 \qquad (1)$$

$$\text{2D 95\% confidence} = \text{2D-RMSE} \times 1.7308 \qquad (2)$$

$$\text{1D 95\% confidence} = \text{1D-RMSE} \times 1.9600 \qquad (3)$$

b) Point Cloud Density

The point density should be sufficient to achieve extraction of objects at the level of detail needed for the project. Moreover, cylindrical, spherical, and planar objects must be scanned with sufficient density to model their centres (Austroads: Faber, 2014).

Depending on the system used, point cloud density is influenced by factors such as the nominal distance to the target object, angle of incidence, measurement rate and vehicle speed. For this reason, the specification should include feature types to be surveyed and the point densities to achieve (NCHRP Project 15-44: Olsen et al, 2013).

Ranges of point densities typically required for different applications are shown in the application matrix introduced in Section G.2.6.1 and attached as **Appendix G-1**. Figure G.13 provides refined accuracies (local) and point density values for different transportation applications. When specifying these values it should be considered that obtaining very high point densities on objects that are further than 50 meters away may not be economically feasible or realistic.

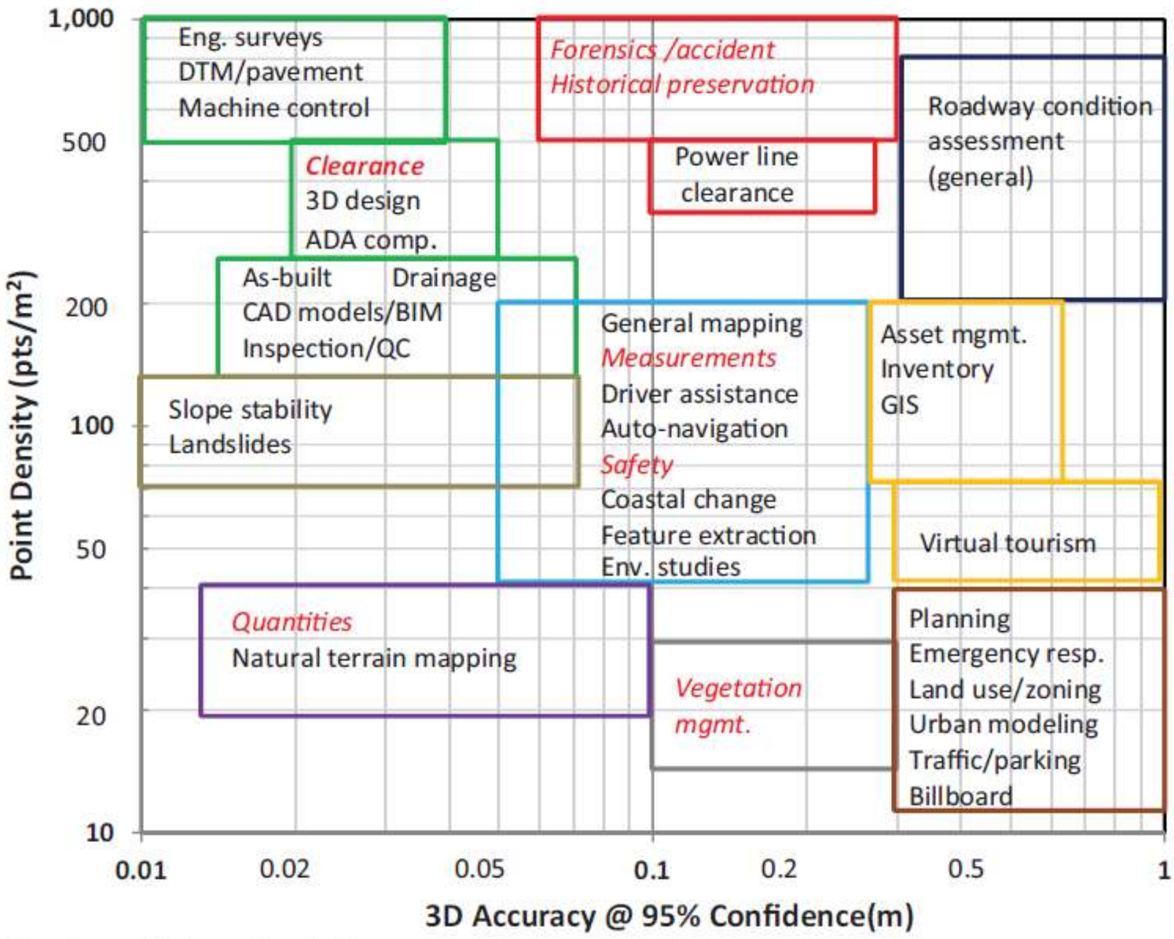
The sample spacing (average distance between coordinates in point cloud) can be calculated using Equation 4, and used to complement point density specifications (Olsen et al, 2013).

$$\text{sample spacing} = \sqrt{\frac{1}{point\ density}} \qquad (4)$$

c) Criteria

As indicated previously, Figure G.13 contains refined ranges of local accuracies and point density values. The following should be considered for selecting appropriate criteria (NCHRP project 15-44: Olsen et al, 2013):

- Values are suggested as a starting point to be evaluated considering specific project needs;
- The values were compiled to ensure that the data can support different applications. In some cases, the need for workability may warrant delivery of point clouds or models at reduced density;
- Local (or relative) accuracies are shown. Where red italics are shown, relaxed network accuracies may be specified;
- Values are for accuracy expressed at the 95 percent confidence level;
- Accuracy values shown are 3D (not just horizontal or vertical components as explained above);
- Point density values are to be evaluated on the targets of interest, positioned at a maximum distance range of 75 to 100 m from the target;
- In cases of uncertainty, more conservative/ higher point density and/or accuracy should be specified.



Note the use of a log scale on both axes.

Network accuracies may be relaxed for applications identified in red italics.

Figure G.13 Suggested local accuracies and point densities for several transportation applications (Olsen et al, 2013)

The notation recommended by NCHRP Project 15-44 to specify point cloud accuracy and density for a particular project is adopted in TMH 13:

N – **…**(mm) – **L** – **...**(mm) – **D** – **...**(points/m^2)

Where criteria are included in open spaces provided, N notates the required network accuracy, L the required local accuracy, and D the required point density. Note that the value of L will always be less than or equal to the required accuracy for N.

As an example, typical criteria for a point cloud dataset with application that requires Accuracy Level 3 will include: 3D network accuracy of 1.0 m at 95% confidence level, 3D relative accuracy of 0.3 m at 95% confidence level, and a minimum point density of 10 points/m^2. Using the notation introduced above, the specification would be:

N – 1000 – L – 0300 – D – 0010

G.3.4.3 Validation of Pavement Distress Imaging

The general requirements under Section G.3.4.1 for clarity, colour balance, proper exposure and sequencing shall apply. Where stitching of images is relevant for systems with two or more cameras, the final product shall be seamless both transversely and longitudinally. Image location shall be ascertained, and images from dedicated pavement imaging systems shall be accurately synchronized with ROW images.

Table G.7 presents criteria for the two system classes. It is reiterated that Class 1 essentially represents a systems with crack width measurement capabilities, while Class 2 represents systems with visual review capabilities only or with basic measurement capabilities. Similar to the validation test requirements, validation criteria for Class 1 systems are divided into system detection and system analysis validation.

The criteria included in Table G.7 represent performance measures relative to the reference values or ratings established by independent surveys. Validation and reference test requirements are provided in Table G.6 of Section G.3.3.3.

Table G.7 System Detection and Analysis Validation Criteria

Imaging System Class	Parameter(s)	Acceptance Criterion	Description
1. Automated and Semi-Automated[1]	**System Detection Validation**		
	Individual crack length	≥ 85%	% of reference crack length
	Cracks detected : width < 3 mm 3 ≤ width < 5 mm ≥ 5 mm wide	 ≥ 30% ≥ 50% ≥ 85%	% cracks detected in each range relative to total reference percentage over all sections for each speed
	False cracks/ 50m^2	< 3 m	Validated for five segments without cracks
	System Analysis Validation		
	Crack type identification	≥ 95%	% success identifications
	Crack Degree (width, mm) and Extent (length, m), respectively:		
	R^2 of linear regression Slope of liner regression Intercept of linear regression	≥ 0.95 Between 0.9 and 1.1 Between -0.1 and 0.1	Data set including all segments (of all sections) at each speed, followed by set including all speeds
	Coefficient of variation	< 3%	Repeat runs for individual segments
2. Manual (TMH 9 equivalent)	Distress Type identification Degree and Extent ratings	≥ 95% ≥ 90%	% success identifications % success ratings

Note: [1]Adapted from AASHTO PP 67-10 & PP68-10 (AASHTO, 2014a and 2014b)

G.3.5 Control Testing

Control testing should be performed from time to time during the survey to ensure continued validity of the systems and methods. Daily and weekly quality control procedures complement control testing through early detection and correction of quality issues. Operational and quality control procedures are provided in Section G.4.

Control testing should be performed on validation sections and the same criteria as used for validation shall apply. However, control testing need not be performed on all validation sections, and normally control testing on two or three sites would suffice.

Control testing for systems producing 3D point clouds, shall be performed on validation datasets that consist of more than 20 *validation points*.

Whilst it should be attempted to position validation sites close to the centre of operations, control testing using these sites may not always be practical for large networks. In such cases, dedicated control sections may be established at strategic positions spread geographically throughout the survey area. In addition, for control testing where manual distress ratings are involved, the use of different control sites and rotation of these sites are recommended to reduce the influence of human subjectivity. Similar to validation sites, agencies (or third parties) are responsible for the selection and characterisation of dedicated control sites.

Control testing should be performed on a regular basis as part of the survey process. If control testing shows that the collected data are no longer valid, the survey shall be ceased until the cause of the problem can be identified. Any data collected since the last successful control test should be discarded and re-collected.

It should be obvious that the cost and time implications of a failed control test are severe. For this reason, control testing should be carried out as frequently as possible within the constraints of the network and survey budget.

The frequency of testing is basically a compromise between the cost of control testing (which not only delays the survey, but requires additional time and travel), and the risk of re-collecting all data collected since the last control test. As a minimum for large projects, control testing shall be conducted on a monthly basis. For smaller projects control testing shall be conducted in five stages (equally spaced in terms of length surveyed) during the survey process.

G.4 Operational and Quality Control Procedures

G.4.1 Introduction

Part A addresses the need for a quality control plan as an aid in achieving reliable, accurate, and complete surveillance data. Previous sections introduced calibration, validation and control testing which are key imaging systems related quality control activities. This section deals with timely operational and data checks and methods to mitigate the risk of producing data of unacceptable quality.

It should be noted that while basic operational aspects and their influence on imaging are included, operators of imaging systems should – in addition to the elements covered in this section – have an in-depth understanding of the influence of all operational elements on the imaging process. Relevant standards and operational manuals should be consulted for detailed operational procedures.

The network manager is not responsible for performing daily checks or following of proper operational procedures. However, a proper understanding of the elements that influence measurement and of the procedures that a contractor should perform each day, will allow the network manager to exercise better control over the measurement process. The guidelines in this section thus focus on how operational procedures can be controlled during the survey to ensure data quality.

G.4.2 Operational Procedures for Imaging Systems

Before a survey can start each day, specific system checks should be performed in an official and orderly way at the hand of an official “Check List”. The operator will sign the check list at the end of the procedure and thereby generate a traceable quality assurance record as part of the Quality Control Plan (See Part A).

The contractor’s check list will depend on the survey vehicle and imaging system type, and the recommendations from the manufacturers. As a minimum, the check list shall include:

- Vehicle: The general condition of the vehicle and functioning of components shall be checked. Safety related aspects, such as indicators, hazards, dedicated safety lights, arrows and other signs shall be visible, in good condition and working order. Check the condition and pressure of the vehicle tyres and all spare tyres.
- Batteries/ Power Supply/ Cabling: Where applicable, ensure that batteries are fully charged for both computers and the measuring device. Check that power supplies and all cabling are on board and that all connections are good.
- Imaging Hardware: All cameras, other imaging components and enclosures, should be securely mounted, correctly aligned, and clean. Check that all imaging components and the computer system with monitors are functioning properly.
- Imaging Software: Onboard systems for data acquisition and real-time monitoring (of imaging and other data types) should be ascertained for proper functioning and integration. Where used, reference data bases and shape files for storing geometric location and associated attribute information should also be loaded and checked.
- Warm-up Time: The measuring and data acquisition systems should be subjected to sufficient warm-up time according to the manufacturer’s recommendations.

Imagery and associated data shall be monitored periodically throughout the day for completeness and to detect any changes in quality. At the end of each day of survey, back-up of data and a review of imagery and other data are required. This allows the operators to identify issues, take corrective action, and re-collect the problem segments before leaving an area. The operators shall keep daily logs of activities, including all quality control activities. The Network Manager shall be notified of any unusual circumstances.

Whilst the network manager cannot ensure that all checks are rigorously performed each day, spot checks shall be performed from time to time. These checks should be performed randomly on a weekly or two-weekly basis. During each check, the operator should be asked to stop the vehicle and a control check should be performed. Control checks may include inspection of system calibration and validation certificates, the condition and functioning of the survey vehicle and imaging system, as well as inspection of collected imagery and other data.

G.4.3 Data Capturing, Processing, Management and Documentation

G.4.3.1 Data Capturing and Processing

The contract specifications should provide details on the format required for the captured data. As a minimum, the specifications should state the format of the required files (e.g. ASCII, JPEG, MOV, LAS, spreadsheet format) and the required data fields for processed data deliverables.

In addition to the requirements of TMH 13 (See Section G.3), TMH 18 and TMH 22 should be consulted for items to be collected and reported. The agency may provide database shells or shape files to streamline data capturing and facilitate identification of network segments, thereby reducing any associated errors. The contractor should also provide a definition sheet to define any codes or abbreviations used in the file and column naming. Details of the format in which the output will be provided should ideally be submitted with the contractor's quality control plan.

Digital video and/or photo mosaic should be provided in a common format. For photos, these would typically be supplied as TIFF, JPEG or PNG and for video as AVI or MOV with a common, near-lossless compression code (if applicable). Apart from essential inventory and/or condition data, the following should be reported as a minimum (AASHTO, 2014a):

- Asset identifier (ID), road number, link and segment identification, and other details (e.g. lane, direction)
- Unique image identifier together with image location (latitude and longitude) using the first shoulder side data point;
- Image scale, which should be equal in both directions;

For 3D imaging used for asset management or inventory mapping, a geo-referenced point cloud should always be delivered. Classification of data points is encouraged and can simplify the use of data. However, classification types and categories should be established and clearly specified by the agency. It is recommended that the LAS format or other approved format be used for point cloud delivery. The use of multiple formats and data transfers shall be minimized during workflows (Olsen et al, 2013).

Digital video or photo imagery shall be co-acquired with 3D imaging by laser scanners or any non-photogrammetric systems. Imagery should preferably be geo-referenced to point clouds as a visual reference, especially for feature extraction and validation.

Point clouds shall be obtained using the optimum navigation trajectory of the vehicle that has had each imaging pass shifted via rigid body translation to fit local transformation (or control) points for the project. Survey control point locations and accuracy shall be reported (X,Y Z, ID, standard deviations, residuals, etc.). Trajectories for each pass of the imaging survey vehicle should be provided in common format, typically KMZ or SHP. A field with modelled error estimates throughout the trajectory should be included with the trajectory data (Olsen et al, 2013).

Outputs from modelling of registered point clouds will depend on the project requirements and should be specified to conform to the agency's graphic standards. Features are typically extracted and modelled as 3D CAD, GIS, or BIM objects. Modelling requirements should be clearly specified including file size limitations, desired data density, and completion of optimization procedures. Details of the modelling procedures and quality control of the results should ideally be submitted with the contractor's quality control plan.

Any useful comments that may affect image analysis should be reported. As an example for pavement distress imaging analysis, aspects such as crack seals, railroad tracks, and excessive pavement marking should be reported. The operator should flag any data files or parts thereof for which measurements are regarded as unusual or files recorded under non-optimal conditions. Operators should therefore be trained not only in the system operation aspects, but also in the interpretation of data and the potential impact of pavement, environmental and other parameters on data accuracy and precision.

G.4.3.2 Data Management

A copy of the dataset (video, point cloud etc.) at the highest level of processing should always be requested from service providers for future reference or data mining. Attention should be given to handling of large and complex datasets generated by imaging systems. Aspects of data management included in this section were largely obtained from NCHRP 15-44 (Olsen et al, 2013).

It should be recognised that the bulk of the data falls into two categories, namely read-only and mutable data. Read-only refers to data that do not or should not change, typically large files containing raw measurements or imagery. Mutable refers to changeable or derived data, typically much smaller files containing extracted and processed information.

After initial processing, e.g. geo-referencing and classification, the core imagery should not change and can be considered read-only. Once stored in the appropriate format and location and backed up, these data do not need to be part of the incremental backups or version management.

By separating these large sets of static data from other data, management is simplified. Special consideration should be given to protection of read-only files because much of this data may operate outside usual IT channels. In particular, read-only files must be guaranteed to remain immutable and should be protected from accidental editing, deletion, renaming, or relocation.

Extracted data are derived from imagery or measurement, e.g. locations and dimensions of features such as road markings or signage. Different levels of processing can be facilitated using a variety of potentially manual, semi-automated, and fully automated software tools. With each processing step, the value of the information increases, whilst the incremental storage required normally reduces. Regardless of the extraction and/or higher level processing method used, potential errors may be introduced in each step. Specifications should therefore cater for proper reporting of data lineage. As a minimum for 3D imaging, a metadata file containing project related data (as defined by the agency) should accompany each project file.

Information resulting from these processes is usually mutable, consisting of smaller and more manageable files which should be included in normal agency management, IT procedures and policies.

The medium of data delivery should be specified and is typically via external hard drives which can be used as host drives, eliminating the time required to copy files. Whichever type of drive is used, identical duplicate data should be submitted on a second drive. The backup or second drive should be verified as soon as possible after delivery, before placed in secure storage.

The specifications should stipulate the deadline for delivery of data files on completion of the survey. It is important to minimize delays between the time of survey and data analysis, in order for errors to be identified as soon as possible. Ideally, some data files should be given to the network manager while the survey is in progress, so that the data can be checked and any inconsistencies identified at an early stage.

G.4.3.3 Documentation and Deliverables

Apart from documentation outlined under Part A, imaging surveys, and especially high-end 3D imaging surveys, require clear documentation of the quality and lineage of the data to maximize the return on investment, future use and usability for multiple applications within the agency. As such, this subsection largely focuses on documentation and deliverables typically required after completion of 3D imaging surveys.

In general, all systems included under TMH 13 include cameras. A camera calibration report (interior orientation) and image geo-referencing information (exterior orientation) are required for all cameras and images, respectively.

The outline to follow is an extract from NCHRP 15-44 (Olsen et al, 2013). A survey narrative report should be completed, including the following minimum information:

- Project name and location identifier
- Survey date, time, weather conditions, limits and purpose
- Project datum, epoch and units
- System calibration report
- Survey control points found, held and set (see Control Survey Report)
- Personnel, equipment, and surveying methodology employed
- Problems encountered, if any
- Other supporting survey information such as GPS observation logs
- Dated signature and seal (if licensure is required) of the surveyor/ engineer in charge

Higher order survey control networks may be required depending on the application. Traceability back to the published primary control and reproducibility by an independent 3rd party must be ascertained.

To this end, the data lineage shall be clearly defined and documented in a control survey report containing the following minimum information:

- Primary control held or established
- Project control held or established
- Local transformation/ control points
- Validation points
- Adjustment report for control and validation points
- Base station observation logs (occupation data, obstruction diagram, atmospheric condition, etc.)
- GPS accuracy report with details on time, duration, and location of loss of signal lock
- GPS satellite visibility and PDOP reports
- IMU accuracy report
- Trajectory reports including locations of loss of signal lock exceeding a specified threshold (typically 60 seconds) and operating speeds during acquisition

In addition to the control survey report where the application requires this level of accuracy, the following data processing documentation should be provided:

- Trajectory analysis and quality control
- Adjustment report
- Registration statistics
- System calibration/ model fitting statistics
- Detailed metadata files

Datasets to be delivered include:

- Point cloud
    - Raw data
    - Geo-referenced data
    - Classified data
- Associated imagery:
    - Video
    - Photo mosaic
- Modelled data may include:
    - DTM
    - CADD, BIM
    - GIS database files
    - Other formats
- Survey control points
- Trajectory

G.4.4 Data Checking and Troubleshooting

Periodic testing of control sites is one of the key quality control measures and results are used for both quality control and acceptance (see Section G.3.5). It is reiterated that control testing needs to be performed regularly so that the quantity of collected data is manageable when resurveying is required.

In addition, the network manager should perform a series of acceptance checks on the final condition database or batches of data and imagery received.

a) General

Global database checks may be performed as manual screening, execution of saved queries, or an automated or semi-automated series of error checks. In general, database checks include (Pierce et al, 2013):

- Compliance with required format even if a database shell was provided. Automated checks or queries may not function correctly if formats are incorrect.
- Location accuracy and checks for missing segments using segment files or GIS.
- Data completeness checks. For example by scrutinizing zero or default values, or the number of events recorded by segment.
- Data consistency checks using engineering judgement or doing logic tests to identify data that do not make sense.
- Screening for out of range data using predefined triggers, minimum and maximum values. For example, the area of patching cannot be greater than the segment area.

More detailed checks should be performed on a sample of data. The sample size typically varies between 5 and 10 percent, depending on the network size. Whilst any sampling method may be used (viz. random, systematic, stratified, clustered or a combination), it should be noted that reference values for these sites normally do not exist. Sections with which the manager is familiar with may therefore be selected. The objective of these checks should be to ensure the measurements correspond with basic engineering judgement, and that the data are consistent with that of earlier surveys. Alternatively, blind sites may be selected which are unknown to the contractor but with conditions known to the agency. Independent resurveys of sample sections may also be ordered by the agency.

b) Visual Quality and Distress Rating Checks

In the context of TMH 13, visual quality checks should be performed on imagery. Imagery should be checked for clarity, proper exposure, colour balance, stitching (where applicable) and sequencing (see Section G.3).

Distress ratings from manual (Class 2) processing of imagery should be subjected to inter-rater (or cross-rater) reproducibility and repeat (or intra-rater) test checks. If the ratings do not meet quality standards, further training and re-assessment of batches should be performed.

c) Time-Series Comparisons

If historic survey data exist, then data can be graphically compared to the data collected in previous years, i.e. time-series comparisons. If a data check reveals an inconsistency between measurements (or ratings) of the previous year, then the data file should first be checked for comments from the operator regarding possible contributory factors. TMH 13 Part C, on roughness measurements, includes examples and discussions on time-series comparisons.

d) Confusion Matrices

Semi-automated or automated procedures are used in imaging processing to classify points or pixels into feature or distress categories. A confusion matrix is an effective method to check the performance of classifiers, especially when the number of observations in different categories varies greatly. In this method, a table is constructed where columns represent the observations predicted/recognized by the system classifier, whilst each row represents the actual observations.

As an example, the classification accuracy of a classified point cloud needs to be determined in addition to the geometric accuracy. Point cloud classification categories typically include terrain, vegetation, buildings etc. Manual classification of points in several representative sample sections can be determined and compared with the output from the classifier. The data can then be presented in a confusion matrix indicating how well the points were classified.

Figure G.14 is an example confusion matrix, comparing outputs from the system classifier with actual classifications and providing classification accuracies by category. Where no mis-classifications occur, the matrix should consist of a diagonal with 100% ratings. The recognition rate for different categories can therefore be assessed in detail and used, for example, to determine system calibration issues.

Classifier Actual	**Ground**	**Vegetation**	**Building**
Ground	90%	10%	0%
Vegetation	15%	80%	5%
Building	0%	5%	95%

Figure G.14 Example Confusion Matrix

All personnel involved in the survey and quality control processes should openly discuss non-compliance or data discrepancies and work together to identify causes and solutions. Equipment or software issues, driver or operator error, weather induced problems, or interferences at control sites or sample sections should be considered. If data quality analyses consistently show discrepancy between the reference data and control survey data, more detailed investigations should be performed. Scrutiny of reference data (or ground truth) and survey methods may be necessary. General considerations for imaging surveys are included in Section G.4.5.

G.4.5 General Considerations

Factors influencing imaging surveys that need consideration during validation, control testing, imaging surveys and quality control processes were highlighted throughout Part G. A number of general considerations and concluding remarks are outlined below that pertain to the expected outcome and/or quality of deliverables from imaging systems.

- While ROW imaging will capture objects within range and line of sight, objects such as drainage ditches and culvert details may be difficult to see or non-visible in the dataset or image.

- Scanning geometry (position and orientation of scanner or camera with respect to object of interest) determines how well objects are captured. For example, dedicated pavement imaging systems capture detailed pavement surface data, but are not configured to acquire data on surrounding features.

- System performance at various sun angles and intensities. Imaging with cameras should be limited to a specific time period of the day (i.e. 9 am to 4 pm) to avoid driving into, or away from the sun which would be at a low altitude. Direct sunlight into the camera will blind the camera and render the images void.

- Performance under various lighting conditions. In general imaging in bad light should be avoided. The camera will try to compensate for the bad light by decreasing the shutter speed. This will lead to “smeared” images of bad quality.

- Performance at various humidity, temperature and wind conditions. Wet pavements or conditions that induce refraction should be avoided, such as precipitation, steam, or heat rising from surfaces.

- Many pavement distress detection and processing algorithms are in research and development and focus primarily on cracks. Systems may vary in terms of their ability to detect crack width and length in all directions; sensitivity of characteristics that define a fissure (crack delineation); minimum resolution versus delineation level and crack angle, and resolution versus position of cracks due to optical distortion (AASHTO, 2014b).

- Data gaps may be caused by visibility constraints during ROW imaging (such as shadows or occlusions). It is therefore recommended that surveys preferably be done during low traffic periods. Alternatively, implementation of a traffic rolling slowdown behind the survey vehicle could be considered to minimize vehicles creating data gaps. Data gaps can also be filled in by doing multiple passes.

- Multiple passes with scanning lasers are often performed. Overlapping scans provide higher point density, remove data gaps, and offer increased reliability from redundancy. In the case of scans in opposite directions, a minimum side overlap of 20 percent may be specified. Comparison of elevation data from side overlaps may be requested as supporting documentation.

- Scanning lasers do not penetrate water. Highly reflective surfaces at close range can be problematic, creating saturation and blooming effects. Dark surfaces do not reflect light well and can be problematic at long ranges for some scanners.

- Not all points in point clouds have the same accuracy which introduces noise. The use of single or isolated points should therefore be avoided when making measurements. However, whilst individual points may have lower accuracies compared to conventional surveying, objects can be modelled more accurately due to the relatively high point density, i.e. capturing of more detail.

- Many algorithms used to process point cloud data are in research and development. The identification of features in point cloud data is usually done by virtual surveying using semi-automated or manual processes which can be time consuming. A few automated processes exist, but are limited to objects with simple, standard geometric shapes (e.g. planes, spheres and cylinders). Co-acquired camera imagery with RGB colour mapped to the point cloud can be valuable during the mapping/ measurement process. Point classification (attributes such as what the point represents) can also be done through manual, semi-automated, and/or automated processing. (Olsen et al, 2013)

G.5 References

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G.6 Glossary

2D: Two-dimensional. Typically referring to data that has been mapped to a plane such as a map or plan (NCHRP 15-44, Olsen et al, 2013, p. 218).

3D: Three-dimensional. In a 3D Cartesian coordinate system (XYZ), there can be multiple Z values at any given XY coordinate (NCHRP 15-44, Olsen et al, 2013, p. 218).

3D imaging system: A non-contact measurement device used to produce a 3D representation (for example a *point cloud*) of an object or a site (ASTM E2544-10).

3D reconstruction: A process of creating a 3D model from data that is not 3D. For example, a series of 2D photographs of an object can be combined to produce a 3D model (NCHRP 15-44, Olsen et al, 2013, p. 218).

Absolute Accuracy: The level of accuracy that can be obtained in a global coordinate system (NCHRP 15-44, Olsen et al, 2013, p. 218).

Accuracy: Closeness of the agreement between the result of a measurement and a true value of the measurement (ASTM E2544-10). The degree to which a measurement, or the mean of a distribution of measurements, tends to coincide with the population mean (FHWA, Pierce et al, 2013, p.85).

Big Data: A popular term used to describe any collection of large structured or unstructured data sets that is difficult to process using traditional database or software techniques.

Blind site: Control site with location unknown to the survey team.

Calibration: "Set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards" (ASTM E2544-10). A system calibration corrects for inherent system characteristic or manufacturing errors and produces a set of parameters that remains constant as long as the hardware is not adjusted or disturbed. In 3D imaging, this should not be confused with geometric correction (sometimes called a site calibration or local transformation (NCHRP 15-44, Olsen et al, 2013, p. 220).

Control network: In 3D imaging: A collection of control points with stated coordinate uncertainties, in a single coordinate system (ASTM E2544-10).

Control point: In 3D imaging: An identifiable point (visible or inferable) which is a member of a control network (ASTM E2544-10).

Control sites: Roadway segments (that may coincide with validation sites) with known condition or other characteristic values of interest, measured by the agency or third party for use as reference values for comparison with data collected from time to time on the designated sections (control testing) during the survey to verify continued use of valid methods and equipment as part of the quality control process (FHWA, Pierce et al, 2013, p. 85).

Confusion matrix: A table to show the effectiveness of an algorithm comparing the algorithms predicted results to actual results and typically used for a classification accuracy assessment (NCHRP 15-44, Olsen et al, 2013, p. 221).

Crack: A discontinuity or break in the integrity of the pavement surface, usually a narrow opening or partial fracture in a pavement surface. Cracks may be transverse, longitudinal, irregular, single, grouped, or interconnected crocodile pattern or blocks with varying space between them. Except on continuously reinforced concrete pavements, cracks almost invariably represent a pavement defect (Austroads, Guide to Asset Management Part 5E: Cracking, 2006).

Detectability: The threshold or limiting crack width for detection by a crack/ distress detection system (Austroads, Guide to Asset Management Part 5E: Cracking, 2006).

Data processing: All activities that are conducted to convert the raw data/ imagery collected in the field surveys to useful information. These activities can be manually done by a reviewer/assessor, semi-automated by a reviewer/assessor facilitated by software, or automated by software using algorithms with minimal human involvement.

DGPS/GNSS: Differential GPS/GNSS. A system that uses a network of fixed ground based reference stations to broadcast the difference between the positions indicated by the GPS/GNSS satellite systems and the known fixed positions (definition after Wikepedia, 2007).

Distress rating: A process where the severity (degree) and extent of different types of distresses are visually assessed by a certified assessor. Traditionally this is conducted by a ‘walk over’ or ‘windshield’ assessment. In the context of TMH 13, assessments are performed by a virtual tour using imagery of the road asset.

Distress measurement: Assigning dimensional quantities such as length and width to a distress through manual, semi-automated or automated processing of collected imagery. Manual measurements can also be conducted directly in the field to serve as reference values for validation of system detection capabilities.

Frame imaging: Or are scanning uses a two-dimensional array of pixels in a conventional sequence of snapshots (Wang and Smadi, 2011, p. 4).

Geo-reference: The process of assigning a coordinate system and location information to a point or points in space (NCHRP 15-44, Olsen et al, 2013, p. 224).

Geometric correction: A geometric correction or adjustment is done to correct for errors in the GNSS and IMU positioning information by adjusting the scan data to control or between adjacent passes. This correction would be applied uniquely for each project (NCHRP 15-44, Olsen et al, 2013, p. 223).

IMU: Inertial Measurement Unit. A device which utilises a combination of gyroscopes and accelerometers to provide velocity and orientation information (NCHRP 15-44, Olsen et al, 2013, p. 225).

Line scan imaging: Uses a single line of sensor pixels to build up a two dimensional digital image. The second dimension results from the motion of the sensors/ imaging system or the object (Wang and Smadi, 2011, p. 4).

LIDAR: Light Detection and Ranging. A method of measuring the flight time of a beam of light to calculate range to objects at predetermined angular increments, implemented using a laser scanner and resulting in a point cloud (NCHRP 15-44, Olsen et al, 2013, p. 226).

Mobile LIDAR System (MLS): A mobile ground-based system (as appose to airborne LIDAR systems) utilising the at least one laser scanner.

Pavement image: A presentation of the pavement that describes a characteristic (gray scale, colour, temperature, elevation, etc.) of a matrix of point (pixels) on the pavement (AASHTO PP 68-10).

Photogrammetry: The science of making measurements from photographs, especially for recovering exact positions of surface points (<en.wikipedia.org/wiki/photogrammetry>, 2014).

Precision: See “Repeatability”

Point cloud: A collection of data points in 3D space (frequently in the hundreds of thousands), for example as obtained using a 3D imaging system (ASTM E2544-10).

Range imaging: Produces the 3D structure of a scene by using line projectors and high-speed cameras to construct a depth map of surface points through triangulation techniques. Each pixel of a range image expresses the distance between a known reference frame and a visible point in the scene.

Reference value: A value that serves as an agreed-upon reference for comparison, and which is derived as a theoretical or established value, based on scientific principles, and assigned or certified value, based on experimental work of some national or international organization, or a consensus or certified value, based on collaborative experimental work under the auspices of a scientific or engineering group. Reference value is also known as “ground truth” (FHWA, Pierce et al, 2013, p.88).

Resolution: The resolution of a device specifies the smallest measurement increment that the device is capable of, or the degree of detail that can be seen.

Repeatability: Degree of variation among the results obtained by a single operator using the same test method. The term is also used to designate test precision under a single operator.

Reproducibility: Degree of variation among the results obtained by different operators using the same test method.

Relative Accuracy: The level of accuracy that can be obtained within a local coordinate system (NCHRP 15-44, Olsen et al, 2013, p. 230)

Registration: The process of determining and applying to two or more datasets the transformations that locate each dataset in a common coordinate system so that the datasets are aligned relative to each other (ASTM E2544-10).

RMSE: Root Mean Squared Error. Measures how much error exists between two datasets, usually between predicted values and observed values. For example, results from a LIDAR survey: RMSE takes the difference between each LIDAR value and surveyed value (control point), square the difference, and divide the sum of all values by the number of observations (<http://gisgeography.com/root-mean-square-error-rmse-gis/>, 2014).

RTK GPS: Real time kinematic GPS. An enhancement to satellite navigation that utilised carrier phase measurements for better positioning; allows for GPS corrections in real time (NCHRP 15-44, Olsen et al, 2013, p. 230).

Scaled frame image: An image with assigned horizontal and vertical scales based on known/ reference measurements of objects. More advanced systems use the principles of photogrammetry to geo-reference each pixel in the image.

Time-history: A set of successive periodic measurements of pavement condition over time on the same roadway section, used to evaluate pavement performance and as a data quality check.

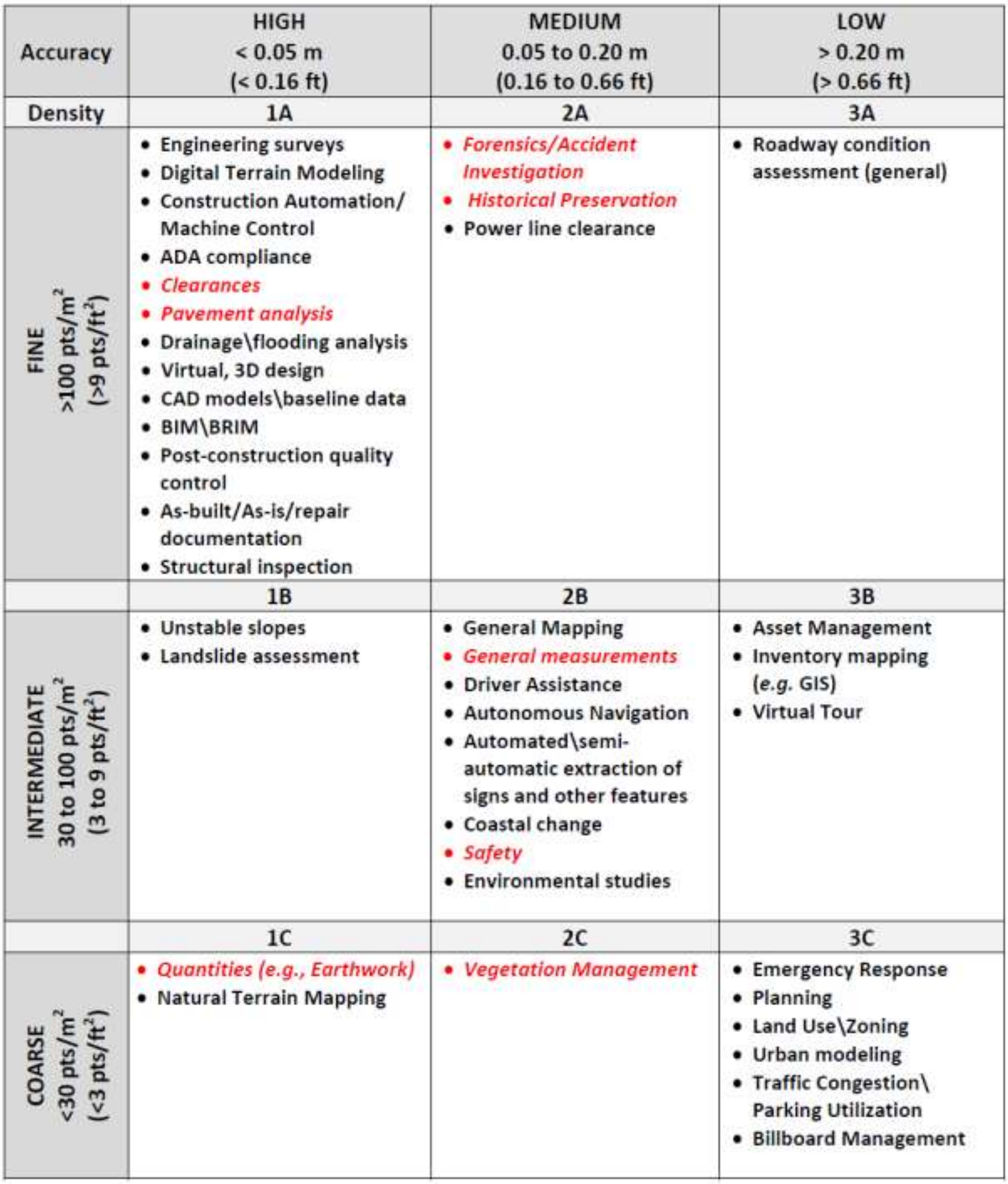
Validation: The process of determining if a measurement device or system, when operated according to an established procedure and within established operating ranges, can operate effectively, reproducibly, delivers data that meet certain criteria.

Validation site: A roadway segment with known condition (or other characteristics) determined by the agency or a third party used to validate measurement devices or systems for acceptance before production measurements starts.

APPENDIX G-1

MOBILE LIDAR SUGGESTED APPLICATION MATRIX

(NCHRP PROJECT 15-44, OLSEN et al, 2013)



Accuracy	HIGH < 0.05 m (< 0.16 ft)	MEDIUM 0.05 to 0.20 m (0.16 to 0.66 ft)	LOW > 0.20 m (> 0.66 ft)
Density	**1A**	**2A**	**3A**
FINE >100 pts/m^2 (>9 pts/ft^2)	• Engineering surveys • Digital Terrain Modeling • Construction Automation/ Machine Control • ADA compliance • *Clearances* • *Pavement analysis* • Drainage\flooding analysis • Virtual, 3D design • CAD models\baseline data • BIM\BRIM • Post-construction quality control • As-built/As-is/repair documentation • Structural inspection	• *Forensics/Accident Investigation* • *Historical Preservation* • Power line clearance	• Roadway condition assessment (general)
	1B	**2B**	**3B**
INTERMEDIATE 30 to 100 pts/m^2 (3 to 9 pts/ft^2)	• Unstable slopes • Landslide assessment	• General Mapping • *General measurements* • Driver Assistance • Autonomous Navigation • Automated\semi-automatic extraction of signs and other features • Coastal change • *Safety* • Environmental studies	• Asset Management • Inventory mapping (*e.g.* GIS) • Virtual Tour
	1C	**2C**	**3C**
COARSE <30 pts/m^2 (<3 pts/ft^2)	• *Quantities (e.g., Earthwork)* • Natural Terrain Mapping	• *Vegetation Management*	• Emergency Response • Planning • Land Use\Zoning • Urban modeling • Traffic Congestion\ Parking Utilization • Billboard Management

Notes:

1) Accuracies may be relaxed for Network Level applications highlighted in red italics
2) The matrix may be adapted based on project needs and specific agency requirements

APPENDIX G-2

CRACK DEFINITIONS FOR AUTOMATED ANALYSIS METHODS

(FLEXIBLE PAVEMENTS)

Summary	Type/ Characteristic	Definition[1]
General (AASHTO PP 67-10, p.67-2)	Crack	A fissure of the pavement material at the surface with a minimum dimension of 1 mm width and 25 mm length.
	Crack position	The coordinates of the midpoint of the crack measured perpendicular to the shoulder edge of the pavement and the longitudinal location relative to the starting collection point.
	Crack orientation	The angular measurement in degrees between the direction of travel and a line drawn between the ends of the crack as measured within the measurement zone (see Table G.6) of interest.
	Crack width	The average gap in millimetres between the two edges of a crack measured at points along the gap with minimum spacing of 3 mm.
	Crack terminus	The point at which the crack width reduces and remains below 1 mm over a 10 mm length, or the intersection with another crack, or when the maximum of 3.67 m is reached or the end of a segment is reached.
	Crack length	Length measured between crack termini. If a terminus was created due to reaching the maximum length, a new crack begins at the terminus
Linear	Longitudinal	• Minimum length: 0.3 m, AND • Orientation between -10 and +10 degrees • Based on position, type can be “edge” or “slip” cracking when e.g. positioned < 0.25 m from pavement edge
	Transverse	• Minimum length: 0.3 m, AND • Orientation between 80 and 100 degrees
Pattern/ Interconnected	Block	• Presence and intersection of transverse and longitudinal cracks, AND • Intersecting distance > 0.3 m
	Crocodile	• Crack that is part of a network of cracks that form an identifiable grouping of shapes, AND • Interconnected or interlaced cracks forming a series of at least 3 polygons with size < 0.3 m, AND • Positioned within the wheel path. • Associated with surface deformation (data from profiler measurements or range imaging can be used)
Other	Surface	• Unconnected irregular cracks varying in line and direction, OR • Transverse or longitudinal cracks with length < 0.3 m, OR • Crack that is part of a network of interconnected or interlaced cracks, forming a series of at least 3 polygons with size < 0.3 m, AND • Randomly positioned. In advanced stage, cracks can cover full width.

Notes: [1] Adapted from AASHTO PP 67-10, 2014, p.PP67-2.