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A Comprehensive Assessment of Highway Inventory Data Collection Methods

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The implementation of the Highway Safety Manual (HSM) at the state level has the potential to allow transportation agencies to proactively address safety concerns. However, the widespread utilization of HSM faces significant barriers as many state departments of transportations (DOTs) do not have sufficient HSM-required highway inventory data. Many techniques have been utilized by state DOTs and local agencies to collect highway inventory data for other purposes. Nevertheless, it is unknown which of these methods or any combination of them is capable of efficiently collecting the required dataset while minimizing cost and safety concerns. The focus of this study is to characterize the capability of existing methods for collecting highway inventory data vital to the implementation of the recently published HSM. More specifically, this study evaluated existing highway inventory methods through a nationwide survey and a field trial of identified promising highway inventory data collection (HIDC) methods on various types of highway segments. A comparative analysis was conducted to present an example on how to incorporate weights provided by state DOT stakeholders to select the most suitable HIDC method for the specific purpose.

INTRODUCTION

The Highway Safety Manual (HSM) provides decision makers and engineers with the information and tools to improve roadway safety performance. In the first edition of the HSM, predictive methods, which can be employed to quantitatively estimate the safety of a transportation facility in terms of number of crashes, were provided for three types of facilities: rural two-lane roadways, rural multi-lane highways, and urban/suburban arterials. A National Cooperative Highway Research Program (NCHRP) 17-45 project recently developed safety prediction models for freeways and interchanges as well (Bonneson et al. 2012). Since the release of the HSM in 2010, many states have sought to tailor the various safety measures and functions within the report to better reflect road safety in their specific locations. This manual provides valuable insight that can help practitioners to prioritize projects, compare alternatives, and select the most appropriate countermeasures in the planning/ design/ construction/ maintenance process.

To implement methods presented in the HSM, a major challenge for state and local agencies is the collection of necessary roadway information along thousands of miles of highways. Collecting roadway asset inventory data often incurs significant but unknown cost. To date, state departments of transportations (DOTs) and local agencies have employed a variety of methods to collect the roadway inventory data, including field inventory, photo/video log, integrated GPS/GIS mapping systems, aerial photography, satellite imagery, airborne Light Detection and Ranging (LiDAR), static terrestrial laser scanning, and mobile LiDAR. These methods vary based on equipment needed, time required for both collecting data and reducing data, and costs. Each method has its specific advantages and limitations. Particularly, vehicle-mounted LiDAR, a relatively new type of mobile mapping system, is capable of collecting a large amount of detailed 3D highway inventory data, but it requires expensive equipment and significant data reduction efforts to extract the desired highway inventory data. On the other hand, a traditional field survey requires less equipment investment, training, and data reduction efforts. However, this method is not only time-consuming and labor-intensive, but also exposes data collection crews to dangerous roadway environments.

The efforts and costs associated with collecting various data with different techniques vary greatly. Therefore, there is a need to understand the application of existing highway inventory data collection (HIDC) methods for gathering HSM-related roadway inventory data. This study sought to present an in-depth review of various roadway asset inventory data collection methods and to compare the quality and desirability of these methods. A national survey was conducted to all the state DOTs to collect the related information toward these various data collection techniques. Additionally, field trials were conducted to identify the most promising methods for collecting and recording highway inventory data to support HSM implementation. By virtue of the fact that many state DOTs are currently redesigning their asset management plans to meet MAP-21 requirements, the outcomes of this research effort may provide a resource for saving money and time.

RESEARCH BACKGROUND

Highway Inventory Data for Highway Safety Manual

The HSM can be utilized to predict the safety performance of a roadway segment or an intersection. The safety performance is evaluated by using a system of equations, known as Safety Performance Functions (SPFs), to estimate the average crash frequency based upon roadway characteristics and traffic conditions. The input data for different types of roadway segments and intersections are quite different. Tables 1 and 2 summarize the required input data for the safety predictive models in the HSM. The check mark indicates the required variables for roadway segments and intersections.

Currently, few states have existing highway inventory databases that contain all the required variables for the input of the HSM models. Particularly, a significant amount of roadside information, such as roadside slope, grade, roadside fixed objects and their density, and offset to the edge of travel way are missing in the current Illinois Department of Transportation (IDOT) databases. Therefore, the main objective of this study is to evaluate which data collection method is able to collect those roadside features in the most economical and effective way. Because these features are also absent in many state DOT databases, the findings of this study will be helpful to provide guidance for other states.

Review of Highway Inventory Data Collection Methods

HIDC methods can be broadly divided into two different categories: land-based and air- or space-based methods as shown in Table 3 (Gong et al. 2012). These methods vary in equipment used, data collection time, data reduction time, accuracy, and cost. A brief description of the available data collection methods and related studies is provided in Table 4.

In general, it can be noted that although there are a considerable number of studies on various HIDC methods, none of them have solely focused on supporting HSM implementation. Therefore, the challenge is to match the best methods to HSM-oriented highway inventory applications. Additionally, it is not clear to what extent these methods have been implemented by various state DOTs. Such information might aid other state DOTs and teach valuable lessons regarding which methods are preferred. This study was aimed at characterizing the utility of these existing HIDC methods for collecting HSM-required road inventory data through a national survey and field evaluation of selected HIDC methods.

SURVEY DATA COLLECTION AND ANALYSIS

In many states, there is a lack of worthy highway databases that include all the required variables as inputs for the HSM predictive models. On the other hand, many state DOTs do have road inventory databases that provide some data elements that can be used in the HSM predictive models. A

Table 1: Highway Inventory Data Required for Road Segments in the Highway Safety Manual

Variables	Rural Two-lane Highways	Rural Multilane Highways	Urban/ Suburban Arterials	Descriptions
Number of through lanes	√	√	√	
Lane width	√	√		
Shoulder width	√	√		
Shoulder type	√	√		
Presence of median		√	√	
Median width		√		
Presence of passing lane	√			
Presence of rumble strips	√			A road safety feature that alert inattentive drivers by causing a tactile vibration
Presence of two-way left-turn lane	√		√	
Driveway density	√			
Number of major/minor commercial driveways			√	
Number of major/minor residential driveways			√	
Number of major/minor industrial/institutional driveways			√	
Number of other driveways			√	
Horizontal curve length	√			A feature that increases road safety and comfort in the design of horizontal curves
Horizontal curve radius	√			A feature that increases road safety and comfort in the design of horizontal curves
Horizontal curve superelevation	√			A feature that allows a driver to negotiate a curve at a higher speed and more convenient
Presence of spiral transition	√			A feature used to gradually change the curvature and superelevation of a roadway
Grade	√			A feature determined by the percent grade for the roadway between each point of change in grade
Roadside hazard rating	√			A feature is used to characterize the potential hazard related to roadside environment

Table 1: continued

Variables	Rural Two-lane Highways	Rural Multilane Highways	Urban/ Suburban Arterials	Descriptions
Roadside slope		√		Features determined by the slope ratio (the vertical rise divided by horizontal run) for the foreslope (the slope extends from the outside of the shoulder to the bottom of the ditch)immediately outside the roadway shoulder
Roadside fixed object density/offset			√	A feature determined by the number of roadside fixed objects on both sides of the roadway segments divided by the length of the segment
Percent of length with on-street parking			√	
Type of on-street parking			√	
Presence of lighting	√	√	√	
Presence of auto speed enforcement	√	√	√	

Source: AASHTO (2010)

Table 2: Highway Inventory Data Required for Intersections in the Highway Safety Manual

Variables	Rural Two-lane Highways	Rural Multilane Highways	Urban/ Suburban Arterials	Descriptions
Number of intersection legs	√	√	√	A feature determined by the number of approaches in each intersection
Number of approaches with left-turn lane(s)	√	√	√	
Number of approaches with right-turn lane(s)	√	√	√	
Intersection skew angle	√	√		A feature determined by angle at which the legs of an intersection meet
Presence of lighting		√	√	
Pedestrian volume/lane			√	
Number of bus stop within 1000 ft			√	
Number of alcohol sales within 1000 ft			√	
Presence of schools within 1000 ft			√	

Source: AASHTO (2010)

Table 3: Categorization of Highway Inventory Data Collection Methods

	Land Based	Air or Space Based
GPS	Field Inventory Integrated GPS/GIS Mapping	
GPS + Imaging	Photo/Video Log	Satellite Imagery Aerial Imagery
GPS + Imaging + LiDAR (Using a laser to illuminate a target and measure the reflected light)	Static Terrestrial Laser Scanning (Using direct 3D precision point information acquired from stationary 3D laser scanners to extract highway inventory data) Mobile LiDAR (Driving an instrumented vehicle while collecting direct 3D precision point information using either land-based LiDAR systems or photogrammetry systems while traveling at highway speeds)	Airborne LiDAR (Using direct 3D precision point information acquired from aircraft-based LiDAR systems to derive highway inventory data)

question is how different state DOTs have collected these inventory data and is there any lesson that can be learned from them. In order to gain an understanding of the implementation status of various HIDC methods and their perceived strengths and shortcomings, a web-based survey was developed and sent to 50 state DOTs and seven Canadian provinces. More specifically, the respondents were asked to indicate their primary data collection methods and their opinions on the adopted methods regarding cost, time, accuracy, safety, and data storage requirements. The survey focused on a few roadside features that are known to be difficult to collect but play an important role in the HSM models.

The survey analysis results, based upon 30 respondent states, demonstrated that over 50% of responding states use field inventory, integrated GPS/GIS mapping, video log, and aerial imagery for collecting roadside feature data. In truth, the field inventory method is still required for many roadway features due to equipment limitations since new technologies may not be suitable for all assets. According to the survey results, it is evident that satellite imagery and airborne LiDAR are less popular choices among state DOTs because it is difficult to identify small objects using these methods. Additionally, mobile LiDAR is uncommon but appears to be growing and most popular. Figure 1 depicts the percentage of states using each type of HIDC method.

Figure 1: Technology Adoption Percentage in Respondent States

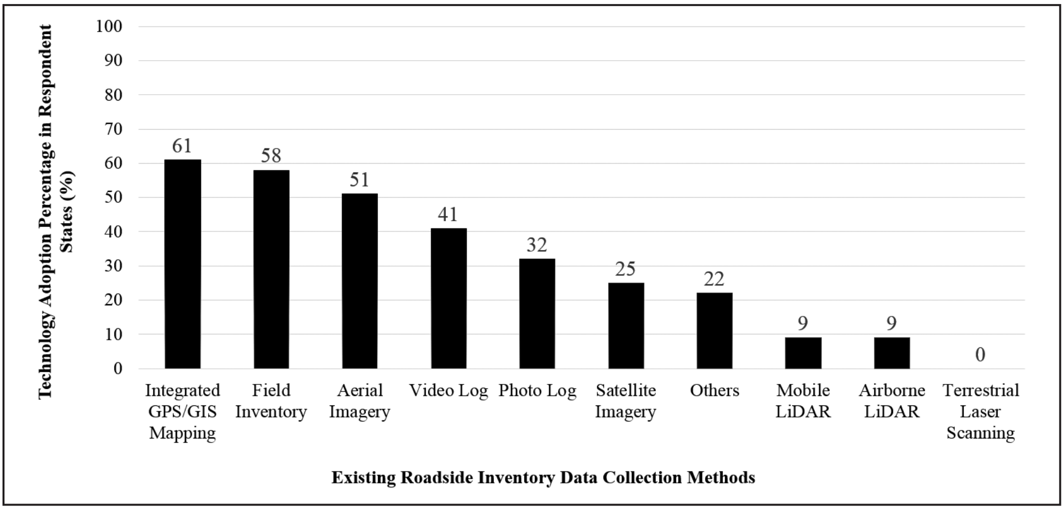


Table 4: Existing Highway Inventory Data Collection Methods and Related Studies

	Methods						
	Field Inventory	**Photo/Video Log**	**Integrated GPS/GIS Mapping Systems**	**Aerial/Satellite Photography**	**Terrestrial Laser Scanning**	**Mobile LiDAR**	**Airborne LiDAR**
Description	Uses GPS survey equipment and conventional optical to collect desired information in the field.	Driving a vehicle along the roadway while automatically recording photos/videos which can be examined later to extract information	Using an integrated GPS/GIS field data logger to record and store inventory information	Analyzing high resolution images taken from aircraft or satellite to identify and extract highway inventory information	Using direct 3D precision point information (3D point clouds) acquired from stationary 3D laser scanners to extract highway inventory data.	Driving an instrumented vehicle while collecting direct 3D precision point information using either land-based LiDAR systems or photogrammetry systems while traveling at highway speeds	Using direct 3D precision point information acquired from aircraft-based LiDAR systems to derive highway inventory data
Advantages	Low initial cost, low data reduction effort, and capability of collecting rich and highly accurate roadway inventory data	Less exposure to traffic and short field data collection time	Low initial cost, low data reduction effort, and the ability to transfer inventory data back to the home office through a wireless connection	Elimination of field work and data collection time, no traffic exposure, no disruption to traffic, and compatibility of images with GPS	Operating in daylight or darkness, high data accuracy and extremely rich and accurate data collection that is valuable to multiple DOT programs	Collecting huge amounts of data in a very short time, survey crew safety is superior compared with traditional survey methods	No exposure to traffic, short field data collection time, and collection of rich data in a short amount of time
Disadvantages	Crew exposure to traffic and long field data collection time	Inability to measure feature dimensions and need for large data reduction efforts	Crew exposure to traffic, long field collection time, and GPS outage problems due to trees	Difficulty to identify features such as signs or traffic signals from overhead imagery	Long field data collection time, exposure to traffic, high initial cost, long data reduction time, and large data set size	The need for expensive equipment, long data extraction time, and large data set size	High initial cost, large data set size, and long data reduction time
Related Studies	Khattak et al. (2000)	Maerz and McKenna (1999), Hu et al. (2002), Degray and Hancock (2002), Jeyapalan and Jaselskis (2002), Jeyapalan (2004), Robyak and Orvets (2004), Wu and Tsai (2006), Tsai (2009), Wang et al. (2010), Balali et al. (2013)	Caddell et al. (2009)	Hallmark et al. (2001) Veneziao (2001)	Pagounis et al. (2009), Slattery and Slattery (2010), Caltran (2011)	Tao (2000), Vosselman et al. (2004), Laflamme et al. (2006), Pfeifer and Briese (2007), Kampchen (2007), Barber et al. (2008), Huber et al. (2008), Lato et al. (2009), Garza et al. (2009), Lehtomaki et al. (2010), Graham (2010), Tang and Zakhor (2011), Yen et al. (2011a), and Yen et al. (2011b)	Jensen and Cowen (1999), Hu et al. (2002), Hatger and Brenner (2003), Souleyrette et al. (2003), Shamayleh and Khattak (2003), Zhang and Frey (2006), Pfeifer and Briese (2007), McCarthy et al. (2007), Uddin (2008), Chow and Hodgson (2009)

It should be noted that most of the respondent states indicated that they use a combination of several data collection methods to meet their roadside inventory data needs. The results revealed that guardrails, shoulders, and mileposts are the most predominant objects being collected but using different methods. Moreover, only 9% of states collected roadside slope and curvature alignments.

Additionally, the survey respondents were requested to indicate their level of satisfaction with their primary collection method using a scale of 1 to 5 (representing unacceptable, fair, good, very good, and excellent, respectively) where one is worst and five is the best. Table 5 illustrates the results for the nine satisfaction indicators considered in the survey, including equipment cost, data accuracy, data completeness, crew hazard exposure, data collection cost, data collection time, data reduction cost, data reduction time, and data storage requirement. Based on these parameters, most states express their level of satisfaction as good for the primary data collection methods, which they have used more frequently to collect the required datasets.

Table 5: Levels of Satisfaction for Primary Data Collection Method of State DOTs

Satisfaction Factors	**Unacceptable (%)**	**Fair (%)**	**Good (%)**	**Very Good (%)**	**Excellent (%)**	**Sum (%)**
Equipment Cost Rating	0	21	58	21	0	100
Data Accuracy Rating	0	7	41	45	7	100
Data Completeness Rating	7	17	34	34	7	100
Crew Hazard Exposure Rating	4	29	39	21	7	100
Data Collection Cost Rating	3	24	55	17	0	100
Data Collection Time Rating	3	34	48	14	0	100
Data Reduction Time Rating	11	26	30	26	7	100
Data Reduction Cost Rating	4	39	29	21	7	100
Data Storage Requirement Rating	0	14	52	31	3	100

The data shown in Table 5 indicate that most agencies rated their current systems from fair to good for most performance categories. Table 6 presents the rating of each satisfaction indicator in Table 5 for each data collection method based on the level of satisfaction with the primary data collection method. It showed that satellite imagery, photo logs, and aerial imagery scored highest on all the evaluation elements. Examination of the scores of different evaluation elements reveals that most methods had lower rankings for data reduction time, data collection time, and data collection cost. This clarifies that the focus of concern of state DOTs is on the time required for data collection and reduction and the associated cost. Moreover, state DOTs that used either airborne LiDAR or mobile LiDAR expressed less satisfaction toward these two methods in equipment cost, data reduction cost, and data reduction time performance categories. Their concerns are clearly related to the data reduction time associated with these two methods. Both methods collect a tremendous volume of data that is difficult to process. Some of the other interesting findings were that the New York State DOT rates its GPS/GIS system as unacceptable to fair in several categories, and the California State DOT appears generally dissatisfied with its photo log system. Overall, no single technology stands out as the obvious choice of methods for roadside feature data collection, and most agencies perceive that their inventory methods could be substantially improved.

Table 6: Level of Satisfaction on Adopted Inventory Data Collection Methods by State DOTs

	Highway Inventory Data Collection Methods							
Satisfaction Factors	**Satellite Imagery**	**Photo Log**	**Aerial Imagery**	**Field Inventory**	**Video Log**	**Integrated GPS/GIS Mapping**	**Mobile LiDAR**	**Airborne LiDAR**
Equipment Cost Rating	3.1	3.0	3.1	3.1	3.1	2.9	2.0	2.5
Data Accuracy Rating	3.3	3.5	3.6	3.5	3.4	3.8	3.0	3.0
Data Completeness Rating	3.2	3.3	3.3	3.4	3.3	3.3	3.4	2.8
Crew Hazard Exposure Rating	3.2	3.4	2.9	2.9	2.9	3.0	2.5	3.0
Data Collection Cost Rating	3.2	2.9	3.0	2.8	3.0	2.8	2.5	2.5
Data Collection Time Rating	3.2	2.8	2.9	2.8	2.8	2.7	2.6	2.0
Data Reduction Time Rating	2.8	3.1	2.9	3.1	2.8	2.9	2.0	2.0
Data Reduction Cost Rating	3.2	3.1	2.9	2.7	2.8	2.8	2.5	2.0
Data Storage Requirement Rating	3.2	3.5	3.4	3.3	3.1	3.3	3.0	3.4

FIELD TRIAL AND RESULTS

Based on the literature review and survey, the research team identified five potential methods to be further evaluated: GPS data logger, robotic total station, GPS enabled photo/video log, satellite/aerial imagery, and mobile LiDAR. Four different types of roadway segments, including rural two-lane highway, rural multi-lane highway, urban and suburban arterial, and freeway segment, were chosen as the test sites for these methods. These segments varied in length but were not shorter than one mile.

The data reduction effort required for each data collection technique has a significant impact on the utility of the technique. Specifically, one previous study revealed that the manual data collection was more cost-effective than automated methods such as mobile mapping systems, as the latter incur high equipment costs and a significantly greater data reduction effort (Khattak et al. 2000). However, recent developments in automated data reduction methods and declining equipment costs (e.g., laser, camera) may have changed this conclusion. Given this fact, the research team recorded the time spent conducting data reduction tasks such as extracting objects, and determining clear zone distance, side slope and other parameters from datasets. A list of promising data collection methods and the proposed data reduction methods are provided in Table 7. Moreover, researchers also evaluated the feasibility and training needs for DOT personnel to use these programs. In general, the effort of data reduction was directly proportional to the quantity and richness of data collected in the field (Zhou et al. 2013).

Table 7: Proposed Data Reduction Methods

Data Collection Method	Data Reduction Method (if required)	Descriptions
Field Inventory	N/A	
Photo/Video Log	Manual review, photogrammetry	
Integrated GPS/GIS Mapping Systems	N/A	
Aerial Photography	GIS package (ArcGIS)	
Satellite Imagery	GIS package (Google Earth Pro)	
Mobile LiDAR	Point cloud post-processing software	A software which has a capability to decimate files intelligently without losing the important featured-related information such as locations.

GPS Data Logger

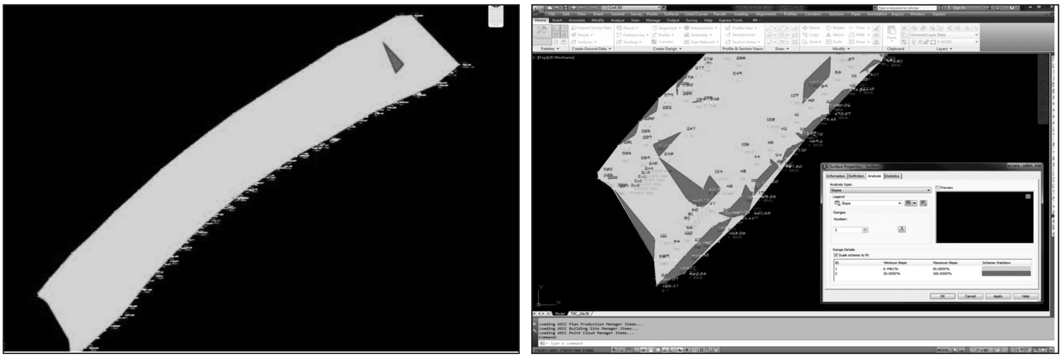
A GPS data logger is a GPS unit that records time of observation, location, elevation, and crew-entered notes. The data logger is equipped with an internal camera, allowing images of recorded locations to be stored and associated with the location data. Output from the data logger may be viewed on a mapping application such as Google Earth. Figure 2 illustrates a sample of this device in use to locate a traffic sign.

Figure 2: A GPS Data Logger Device for Data Collection

In general, the GPS data logger device is very user-friendly, reduces the need for extensive training, and can be operated by one surveyor. As for data collection, the GPS data logging technique is accomplished by placing the device next to the object to be recorded. In doing so, at the beginning of data collection work, the device must be initialized. Initialization refers to the automated startup routine that GPS receivers employ to scan the visible sky, identify observable satellites, and make a location determination. Depending on the number of satellites in view and their geometrical distribution above the target, this process may require from a few minutes to as many as 15 minutes. Once initialization is complete, location data are provided in real time even if the receiver is in motion. Notably, in this method, data collection time is very sensitive to the type of objects, the objects' density, the distance between objects, and the terrain. Therefore, using a four-wheel, all-terrain vehicle can reduce data collection time significantly (Figure 2). In this study, by the help of the aforementioned vehicle, the average times for setting up the device and collecting data per object were five minutes and one minute, respectively.

As to the data reduction effort, one of the primary tasks is the organization of all data collected for the purpose. The data reduction steps required by this method, for this research, included importing the collected data files into a Computer Aided Design (CAD) software program (e.g. AutoCAD Civil 3D), establishing a drawing-file template that includes many of the standard file settings and objects for use in a new file, and importing the resulting data files into the drawing format. The latter consisted of a series of discrete points with associated elevation and description attributes. By virtue of the drawing file, a highway alignment drawing was assembled. Moreover, additional processing using the discrete point elevations to define a surface representing the topography, called "slope banding," was simultaneously employed to identify roadside slope based upon percentage of slope (in dark color) (Figure 3).

Figure 3: A Sample of Slope Banding



Surface Properties - Surface1

Analysis type: Slopes

Legend: Slope

Ranges

Number: 2

Range Details

☑ Scale scheme to fit

ID	Minimum Slope	Maximum Slope	Scheme: Rainbow
1	0.4461%	20.0000%	
2	20.0000%	100.0000%	

In this study, the analysis of results demonstrated that the GPS data logger can not only gather all the objective highway inventory data to be implemented in the HSM but also can meet the accuracy required by the HSM safety predictive models; i.e., four inches accuracy of feature locations can be achieved. One of the shortcomings is the likelihood of GPS outage in areas with tall buildings and significant tree cover. Crew exposure to traffic is another issue that requires mitigation strategies such as setting up warning signs and traffic cones, which consumed a significant percentage of the time required to survey each segment.

Robotic Total Station

During the late 1980s, electronic distance measuring equipment was successfully integrated with electronic theodolites, used for measuring angles in horizontal and vertical planes, to create "total station" surveying instruments. This new generation of surveying instrument directly displays horizontal and vertical angles, slope distance, and derived horizontal distance, vertical distance, and x,y,z coordinates. With the addition of electronic data collection in the early 1990s, survey field work productivity has dramatically improved. A typical survey crew using a total station instrument consists of three people: an instrument person to point the instrument and initiate measurement, a party chief to direct the work and sketch additional data, and a rodman to walk to the object to be recorded and plumb the reflector prism equipped survey rod over the object. Surveying total stations and robotic total stations employ electronic distance measuring systems that measure the time required for light to travel from the instrument to the target and back. A retro-prism mounted on a pole is placed at the target and the instrument's light beam is directed toward it and then sent directly back by the reflective prism. By adding auto tracking of the prism via radio links and robotic servos, total station systems have been developed that automatically continuously track the prism target and transmit data to a data collector and operating controller located on the prism pole. This type of system is referred to as a robotic total station. A robotic total station may be operated by a single person who controls the robotic total station remotely while walking with the prism pole and data collector. During this study, a single surveyor using a robotic total station required an average of one minute to collect information for each object. Figure 4 depicts the robotic total station in use during the data collection activities. Notably, in comparison with the GPS data logging, the initial system setup and data collection time per object were higher.

Figure 4: A Robotic Total Station Device for Data Collection

The robotic total station method requires the same data reduction effort as GPS data logging. A skilled operator, using up-to-date software, has the capability to process survey crew-derived data at rates in excess of 2,000 ft. per hour. The results indicated that this method is able to collect all the required asset roadway inventory data with a precision of 0.01 ft., more than adequate for the accuracy requirements for implementing the HSM. A major deficiency of the robotic total station method is that it has an operating radius of approximately 1,000 ft. from each setup point. Therefore, the robotic total station must be relocated as the survey progresses, a process that requires approximately 15 minutes for each required move. Loss of prism tracking, which is to automatically point the instrument at the prism at all times by a radio link, video imaging system, and light beam recognition system controlled by the instrument's programmable logic system, is an additional issue associated with robotic total stations. Loss of tracking may be caused by line of sight interference due to terrain or highway traffic. Several minutes may be required to re-establish contact with the robotic total station with every loss of tracking event. To operate the system, the surveyor must walk to the object being measured. This exposes the surveyor to traffic, especially when collecting edge of pavement, shoulder, and centerline data. Crew safety must be addressed through warning signs, traffic cones, and high-visibility clothing.

GPS Enabled Photo/Video Logging

The collection of geo-tagged digital videos and photos is carried out using a Red Hen video mapping system (www.redhensystems.com). Equipped with a video camcorder and a GPS antenna, the video mapping system is able to collect geo-tagged digital video with essential locational information, which may be imported into ArcGIS 9.3 software (with a ArcView 9.3 or Arc Editor 9.3 license) using a video for ArcGIS extension (or GeoVideo) (Figure 5). In the instance of data collection time, the GPS enabled photo/video logging requires a relatively short time but an extensive feature extraction effort in the office. In this study, the average time for data collection employing this method was nine minutes per mile.

In respect to the data reduction effort, with the help of high-resolution imagery (e.g., 1-ft digital orthophotos, an undistorted aerial imagery that can be used to measure the true distances, or satellite imagery) as a background and video files collected in the field in MPG format that produces better quality videos than other formats, features in the form of points, lines, and polygons can be traced through on-screen digitizing and saved as feature classes in ArcGIS. In the present research, extraction of required features took an average of 50 minutes per mile or one minute per object. Figure 6 illustrates an example of object extractions using both video logging and high-resolution imagery.

Figure 5: A Video Logging System Configurations in Use for Data Collection

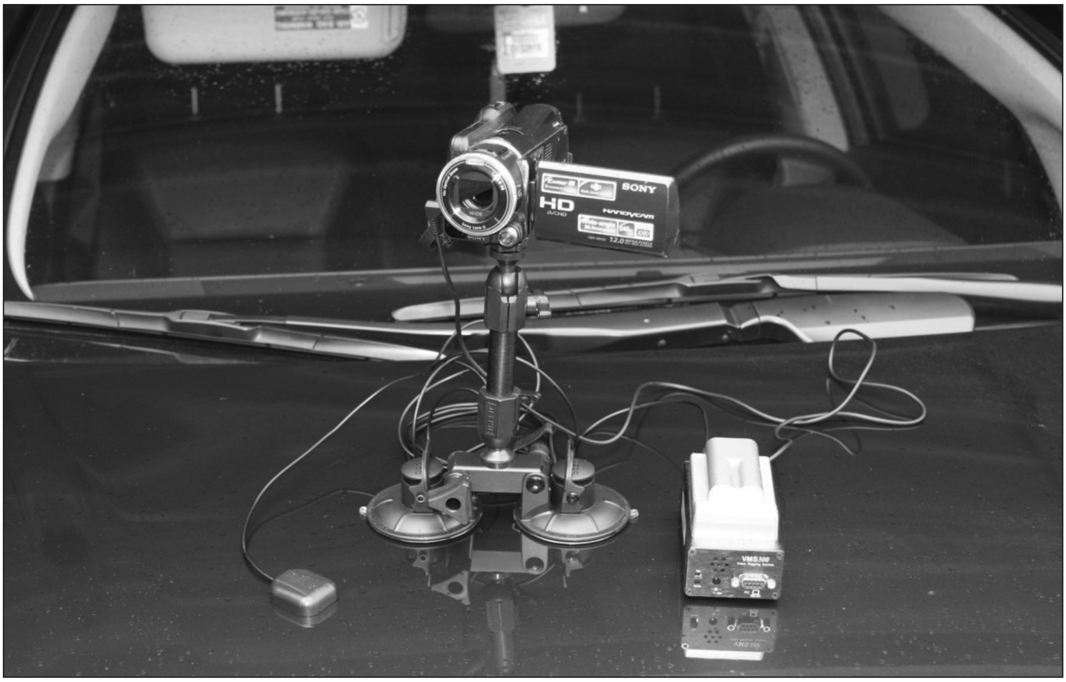
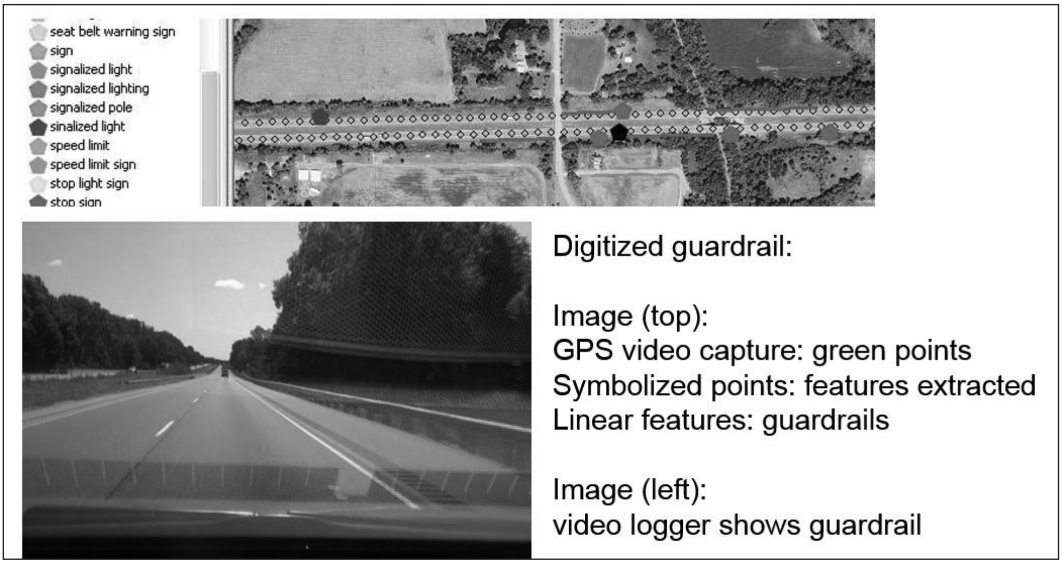


Figure 6: A Sample of Object Extraction Utilizing Both Video Logging and High-Resolution Imagery



Digitized guardrail:

Image (top):
GPS video capture: green points
Symbolized points: features extracted
Linear features: guardrails

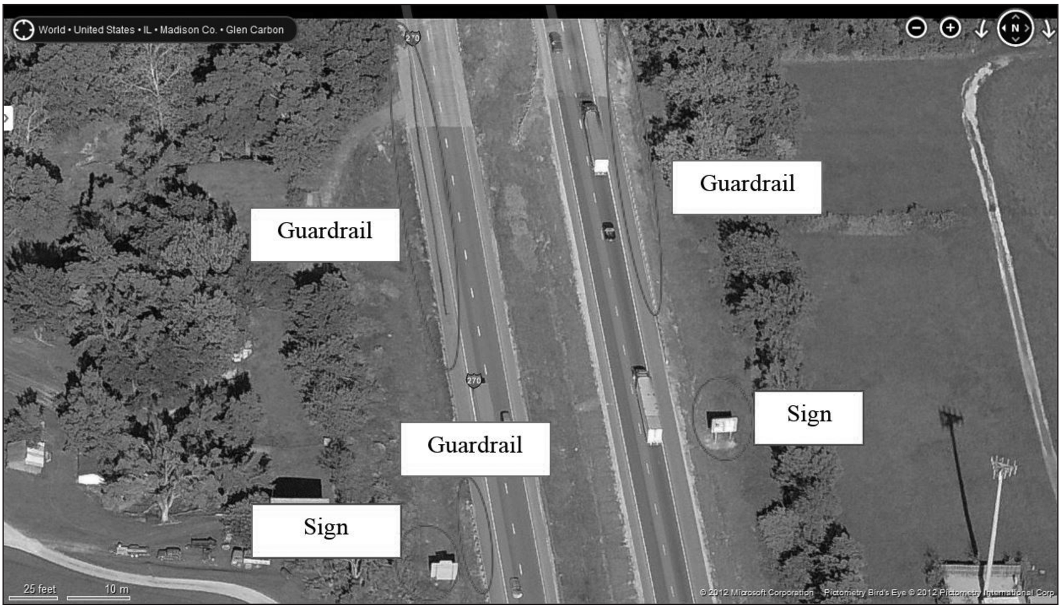
Image (left):
video logger shows guardrail

Due to recording videos on a vehicular platform, this method eliminates the risk of exposing the data collection crew to road traffic. Additionally, working with high-resolution aerial photographs or satellite imagery, the photo/video log method can provide all roadside inventory data to be implemented in the HSM, except roadside slope with reasonable accuracy. A locational accuracy of six inches for all roadside objects is achievable with 1-ft spatial resolution images.

Satellite/Aerial Imagery

Satellite/aerial imagery has been employed over the past several decades to obtain a wide variety of information about the earth's surface. High-resolution images taken from satellite/aircraft can be utilized to identify and extract highway inventory data input (Gong et al. 2012, Golparvar-Fard et al. 2012, Zhou et al. 2013, Jalayer et al. 2013). Therefore, Google maps and Bing maps are two beneficial tools for this purpose. The increasing availability of high-resolution images offers the possibility of leveraging these images to extract some HSM-related roadside features as shown in Figure 7. Notably, one of the considerable benefits of the satellite/aerial imagery method is the elimination of data collection efforts since all imagery is already freely accessible. Compared to other methods, therefore, this method is the most economical one due to the absence of the field data collection cost. However, similar to the photo/video log method, the satellite/aerial imagery is not capable of collecting some HSM-related highway inventory data. For instance, extraction of roadside slope information is very difficult from images and small vertical objects are not quite visible. Based on the analysis of results, in this method, the average extraction time was 1.5 minutes per object.

Figure 7: Data Extracted Using Satellite/Aerial Imagery Method (Image: Bing Map)



Mobile LiDAR

Mobile LiDAR is an emerging technology that employs laser scanner technology in combination with Global Navigation Satellite Systems (GNSS) and other sensors to capture accurate and precise geospatial data from a moving vehicle. This system can collect data on approximately 30 miles of highway per day with a high data measurement rate of 50,000 to 500,000 points per second per scanner (Tang and Zakhor 2011, Gong et al. 2012). Figure 8 shows a photo of an outside view of a mobile LiDAR van and a picture of a computer screen inside the van to show the different mounted cameras and data collection progress.

Regarding data collection, this method is capable of collecting a huge amount of data in a very short time, using an equipped vehicle, in comparison with conventional survey methods (Gong et al. 2012, Zhou et al. 2013). Taking advantage of this technology, in this study, an average of 30

Figure 8: A Photo of a Mobile LiDAR Van (left figure) and a Snapshot of the Computer Screen inside the Van (right figure) (Image: Woolpert Co.)

minutes was required to collect information for each mile of segment. However, the data reduction is a major undertaking with mobile LiDAR and the time associated with the data reduction part in this method is significant. Additionally, the processing of and feature extraction from mobile LiDAR data involves a fairly intensive computational effort and requires software and technical expertise. In terms of commercial packages for LiDAR data processing, Terrasolid Suite, Virtual Geomatics, TopoDOT, and QTModeler are found to be applicable for a variety of data extraction purposes. In particular, the Terrasolid Suite is the most commonly used software for airborne and mobile LiDAR data processing. Because of this, it was chosen as the program to benchmark the data reduction time. The data processed during the data reduction steps include point clouds which is a set of data points in some coordinate systems, geo-referenced imagery, data collection path, and an AutoCAD file. One of concerns with the mobile LiDAR method is the need for large data storage space, here 9.3 Gigabyte (GB) of space per mile of roadway. Given this fact, the mobile LiDAR data are typically divided into manageable blocks to reduce any difficulty during the process. For the purpose of this research, a typical block did not exceed 2 GB. As each type of highway segment was broken into equal sized blocks, data extraction was performed on representative blocks and then the results were utilized to infer the data reduction time for the whole highway segment. In this study, determining roadside slope, roadside fixed objects density, super-elevation rate, and grade took 5, 15, 15 and 15 minutes per block, respectively.

The mobile LiDAR has the capability of collecting all categories of HSM highway inventory data. Although the data collection time in this method is short, the cost of field data collection is higher than other methods (Zhou et al. 2013). However, these shortcomings cannot overshadow the potential of this method; it collects survey-grade data, which can only be matched by the robotic total station method, but with no traffic exposure or need for road closures. The main strength of this method also lies in its ability to collect data that are valuable for multiple DOT programs. The rapid development of computing hardware and LiDAR data processing methods indicate that the mobile LiDAR method will soon be comparable to other methods in terms of data reduction time.

Overall, GPS data logger and robotic total station can gather all required feature data, but they impose longer field data collection times and expose data collection crews to dangerous road traffic. Photo/video logging and aerial imagery, when used together, can collect nearly all required feature data, except roadside slope. The mobile LiDAR has the capability to collect all required feature data in a short amount of field time, but the data require extensive reduction efforts.

The results of field trials are summarized in Table 8. In the table, the capability of each HIDC method is evaluated using the metrics, including the capability of collecting HSM-related roadside features, total data collection time, total data reduction time, unit data collection and reduction time, and total cost. For cost analysis, two unit labor costs were assumed: $75 per hour for a person trained at an introductory level and $130 per hour for an expert level person. Based on the quotes from five LiDAR companies, the average data collection cost per mile for mobile LiDAR was considered to be $200. In the present research, the photo/video log method required the least total time (man-hr./mi) and the robotic total station method required the most. Specifically, the mobile LiDAR technology ranked at the median level, with 5.5 man-hr./mile.

Furthermore, based on Table 8, the total cost per mile to prepare the required highway inventory dataset for photo/video log, satellite/aerial imagery, GPS data logger, mobile LiDAR, and robotic total station methods were $72, $107, $700, $915, and $1,075, respectively. In particular, the photo/video log had the lowest cost and the robotic total station had the highest cost.

Table 8: Comparison Between Different Highway Inventory Data Collection Methods

Methods	Type of Segment Selected	Capability of Collecting HSM-related Roadside Features	Total Length (mi)	Total Data Collection Time (man-hr)	Total Data Reduction Time (man-hr)	Total Time (man-hr/mi)	Total Cost ($/mi)
Photo/Video Log	1, 2, 3, 4	Some	28.0	4.0	23.0	0.96	$72
Satellite/Aerial Imagery	1, 2, 3, 4	Some	7.0	---	10.0	1.43	$107
Mobile LiDAR	1, 2, 3, 4	All	14.2	8.0	70.0	5.50	$915
GPS Data Logger	2, 3, 4	All	1.3	6.0	3.5	7.31	$700
Robotic Total Station	1, 3, 4	All	1.3	13.0	3.5	12.70	$1,075

(Note: 1= rural multi-lane highways; 2= freeway segment; 3= rural two-lane highway; 4= urban/suburban arterials)

COMPARATIVE ANALYSIS OF SELECTED DATA COLLECTION METHODS

In addition to unit cost, some other factors are important in selecting data collection methods, such as data quality and completeness, safety, and disruption of traffic. To consider those factors, based on the field trial results, an evaluation matrix was developed to compare different data collection methods, as shown in Table 9. Eleven criteria were utilized to assess the performance of the different technologies. Each criterion was assigned a score of 1 to 5 (5 being the best and 1 the worst) to indicate the relative performance of one method compared to the others. Specifically, the equipment cost for the satellite/aerial imagery method had a score of "5" because it did not incur any field data collection cost. The total weighted score is the summation of scores of each criterion multipled by its corresponding weighing factor. For GPS data logger method, as an example, the total weighted score is 24, which is sum of (3×0.25) + (2×0.25) + (2×0.25) + (2×1.00) + (3×2.00) + (3×2.00) + (2×1.00) + (5×0.25) + (5×0.25) + (5×0.50) + (5×0.25).

For each evaluation criteria, a weighing factor (WF) was designated. These WFs, that imply the relative importance of each data collection method, were identified through discussions with stakeholders at IDOT. A weight of 2.0 was assigned for data completeness and data quality because the highest data quality and completeness were required to have collected data to serve different offices (planning, design, pavement management, and safety) in the agency. Transportation agencies can assign their own WF for each evaluation criteria for their specific purposes. This method, as used in multi-criteria analysis (MCA) approaches, is widely utilized to assess and recognize the importance of one criterion over another in an intuitive manner when quantitative ratings are not available (Dodgson al. 2009). All these criteria were employed to rank various HIDC methods based on the summation of weighted components. The results demonstrated that the mobile LiDAR has the highest overall score when data completeness and data quality are the top priority for the agency.

Table 9: Evaluation Matrix for Highway Inventory Data Collection Methods

	Criteria	GPS Data Logger	Robotic Total Station	GPS Enable Photo/Video Log	Satellite/ Aerial Imagery	Mobile LiDAR	Weighting Factor
Field Data Collection	Equipment Cost	3	2	4	5	1	0.25
	Labor Cost	2	1	4	5	3	0.25
	Data Collection Time	2	1	4	5	3	0.25
	Safety	2	1	4	5	3	1.00
	Data Completeness	3	4	2	1	5	2.00
	Data Quality	3	4	2	1	5	2.00
	Disruption to Traffic	2	1	4	5	3	1.00
Field Data Reduction	Software Cost	5	4	3	2	1	0.25
	Labor Cost	5	3	4	2	1	0.25
	Data Reduction Time	5	3	4	2	1	0.50
	Data Storage Size	5	4	2	3	1	0.25
Total Weighted Score		24	23	23	21	29	

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to identify cost-effective methods for collecting highway inventory data for implementing in the HSM. Several promising methods, including the GPS data logger, robotic total station, GPS-enabled photo/video log, satellite/aerial imagery, and mobile LiDAR, were identified through a comprehensive literature review to compare and determine their capabilities and limitations. Moreover, field trials for collecting HSM-related highway inventory data on four types of roadway segments (rural two-lane two-way roadways, rural multi-lane highways, urban and suburban arterials, and freeway) were performed to evaluate and compare the utility of these methods. The findings of this research indicate that the GPS data logger, robotic total station, mobile LiDAR, and the combination of video/photo log method with aerial imagery are all capable of collecting HSM-related information. Based on the perceived advantages and disadvantages of each data collection method, the following recommendations are made for consideration by state and local transportation agencies:

- The GPS data logger method can be employed for short distances, low speeds, and low to medium traffic volume roadways that are not obstructed by buildings or trees.
- The robotic total station technology can be employed for points of specific interest, such as intersections.
- The photo/video log method, together with high-resolution aerial imagery, can be used to collect roadside inventory data for large-scale statewide data collection.
- The mobile LiDAR technology can be utilized to gather highway inventory data with the highest data quality and completeness for serving multiple offices in state DOTs and local agencies. In order to share the costs of the mobile LiDAR data collection and processing, identifying multiple clients within the DOT is important.

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