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FINAL REPORT

Monitoring Highway Assets with Remote Technology

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This report identifies and summarizes useful, feasible, and cost-effective remote technologies available for use when collecting data about attributes of twenty-seven MDOT priority assets. In this report, Dye Management Group, Inc. (DMG) presents recommendations to MDOT to provide guidance in the acquisition of such technologies. The recommendations were based on costs, benefits, and technology limitations.

16. Abstract

The purpose of this research was to evaluate the benefits and costs of various remote sensing technology options and compare them to the currently used manual data collection alternative. The DMG's evaluation was used to determine how useful and feasible it would be to perform inventory collection of the Michigan Department of Transportation's (MDOT's) twenty-seven high/medium priority assets. DMG performed a pilot project; using several selected routes in MDOT's Southwest Region, to evaluate different remote technologies and to provide recommendations for how best to implement the most viable of these technologies as data collection tools and data centralization methods.

Results and recommendations include:

- Remote technologies are capable of gathering highway asset data on most MDOT assets. Notable exceptions include assets not readily visible from the roadway (e.g. culverts).
- LiDAR technology, while useful in the appropriate application, produces a level of detail beyond that necessary for the assets identified under this study and was not considered a cost-effective alternative.
- Mobile imaging technology offers an opportunity to effectively gather highway asset data while decreasing worker exposure to traffic, increasing data accuracy and quality, speeding

data collection, and reducing overall costs relative to manual data collection methods.

- DMG recommends that MDOT outsource data collection using mobile imaging technology to a vendor that can handle a project of this magnitude.

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Michigan Department of Transportation

Monitoring Highway Assets with Remote Technology
Final Report

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A. Background

In recent years, the Michigan Department of Transportation (MDOT), which maintains nearly 10,000 miles of trunkline highways throughout the state, has faced challenges related to system maintenance. These include an aging system, a decline in available resources,[1] an increase in asset inventory, a reduction in the workforce, and an increase in maintenance costs. To address these challenges while remaining effective stewards of the statewide resources for which it is responsible, MDOT seeks innovative solutions and tools to facilitate its asset management activities. MDOT partnered with Dye Management Group, Inc. (DMG) to explore the potential benefits and costs of utilizing remote technologies for inventory data collection. Developing a complete and accurate inventory of its assets will assist MDOT in asset management.

B. Objective

MDOT is not alone in its search for more effective approaches to managing its assets. Our research results showed that many agencies are considering, or have already begun to, use remote technologies for asset monitoring. In light of the aforementioned challenges, MDOT has identified the need to collect inventory data more quickly, all the while lowering risk and worker exposure. In the past, MDOT has utilized manual data collection to inventory assets. The use of remote technologies for collecting asset inventory data could provide the type of innovative, cost-effective solution that will help MDOT better fulfill its asset management duties. By decreasing the time spent on data collection, agencies are able to save money, improve accuracy, and most importantly, reduce the number of hours workers spend next to live traffic.

C. Work Plan

To address the project's objectives, DMG formulated a work plan that contains the following components:

- **Literature Review.** To identify potential remote technologies that could be applied toward inventory data collection, we conducted a literature review of a wide array of national and international transportation resources and trade publications. The technologies included Light Detection and Ranging (LiDAR), aerial photography, satellite imagery, ground-based video or photo logging (mobile imaging), and manual data collection.

According to *Risk-Based Transportation Asset Management: Managing Risks to Networks, Corridors, and Critical Structures* (FHWA, March 2013), total gross revenue levels in Michigan's Transportation Fund (MTF) declined between 2004 and 2011. MTF gross revenue declined from just over \$2 billion in 2004 to \$1.85 billion in 2011.

- **Technologies Selection for Use in Study.** Once we identified possible technologies, we evaluated their feasibility for their use in collecting information on twenty-seven (27) different MDOT priority assets. These assets included total lane miles, number of pump stations, and number of signs. We then prepared an approach for data collection, given the different characteristics of each asset.

- **Pilot Study.** We executed a pilot study in MDOT's Southwest Region in and around Kalamazoo. Using the technologies selected based on the literature review—manual data collection, ***Fugro*** mobile imaging, ***Aerometric*** mobile LiDAR, and ***Aerometric*** helicopter LiDAR—we validated the capability of each technology to collect highway asset inventory data. For the pilot, we divided an overall study route into five sections. Each section was assigned a specific technology to collect asset data. Along, the fifth section, called the "overlap" section, we used all four technologies to collect data. This section served as a means to compare data collected via the different technologies. We also used the pilot study to validate our hypotheses that, compared to manual data collection, the use of remote sensing technologies would decrease worker exposure; increase data accuracy and quality; speed data collection; and reduce overall costs. The results of the data collection were recorded and presented in a comprehensive summary.

- **Conclusions and Recommendations.** Finally, we presented the study conclusions, including strengths and weaknesses of each technology, followed by our recommendations for implementation.

D. Results

The results of the pilot study were conclusive. While each data collection technology had strengths and weaknesses, ground-based mobile video/photo logging stood out as the most effective approach. Mobile imaging provided the broadest coverage of the priority assets, minimized worker exposure in the field, and provided the means to collect the data at a much faster rate than a manual process. Aerial imaging with LiDAR supplementation provided adequate coverage of many of the priority assets, but lacked the capability to provide accurate inventory for signs and fence.

Following the pilot study, DMG requested that the vendors provide cost estimates (see Table 1) for a statewide data collection effort on MDOT's trunkline network. The cost estimates for each technology range from $89 to $933 per trunkline mile, which includes both data acquisition and extraction of the assets into a geodatabase file.

Based on our own manual data collection process performed during the pilot, DMG determined that manual data collection would cost MDOT approximately $429 per trunkline mile. This rate is based on the number of hours required to collect and process the data using an MDOT employee fully loaded labor rate. The manual data collection rate also includes the estimated cost to use MDOT vehicles for transportation and collection.

Table 1: Cost per Mile by Technology

Technology	Cost per Mile
Mobile Imaging (Fugro Roadware)	$88.50
Manual (DMG)	$428.77
Mobile Imaging w/LiDAR (Mandli Communications)	$541.00
Aerial Imaging w/LiDAR (AeroMetric)	$818.00
Mobile Imaging w/LiDAR (AeroMetric)	$933.00

Table 1 indicates mobile imaging was by far the lowest cost technology. We found that the primary reason for the wide range of costs is that each vendor proposed a technology and approach that they felt was necessary to meet the needs of the study. Two vendors chose to propose LiDAR to supplement mobile imaging to collect data in greater detail, while another vendor relied on still photos taken along the roadway for data.

It became clear during our review of the pilot data that LiDAR supplementation, while useful for locating some assets, did not improve the accuracy or precision of the asset data collected; mobile imaging by itself provided sufficient accuracy in locating assets for inventory purposes. The use of LiDAR did, however, significantly increase the cost when compared to mobile imaging by itself, which helps explain the wide range of costs the vendors presented.

To improve the cost effectiveness of a future statewide inventory data collection effort, DMG identified several assets that do not require remote technology to be inventoried. MDOT currently tracks bridges, weigh stations, and tourist facilities, and these can be easily located without the need to pay for additional remote sensing.

Based on our research and the results of our pilot study, DMG recommends that MDOT use mobile imaging technology, with a blend of manual field data collection quality assurance, to pursue a statewide data collection effort.

E. Next Steps

Based on our research and validation of the technologies, DMG has defined an implementation plan for MDOT. The recommended steps of that plan are: summarized below.

1. **Develop a request for proposal (RFP) for statewide data collection:** MDOT will develop the requirements for a statewide data acquisition and extraction RFP that focuses on collecting inventory for prioritized assets using mobile imagery or video technology, possibly with LiDAR supplementation, and supported by a manual quality assurance (QA) process. Suggested RFP requirements are presented in the Recommendations for Implementation section (Chapter VII, Section H.5.a.). Also, the suitability of using various technologies and frequency of asset inventory updates is included in the recommendations.

2. **Review proposals**: MDOT will review the vendors and develop a shortlist of potential vendors to invite to demonstrate their proposed approaches. Suggested criteria for selecting the short list are presented in the Recommendations for Implementation (Chapter VII, Section H.5.b.).

3. **Conduct demonstration of approach with vendors:** MDOT will provide the opportunity for the shortlisted vendors to demonstrate their approaches on a designated route, as specified in the RFP.

4. **Review vendor demonstration results:** MDOT will review and conduct QA on the vendor demonstration results, including the vendor-provided geodatabase, for the following:

   - Accuracy of asset location is within allowable tolerance
   - Precision of defined assets (e.g., is guardrail identified as guardrail, not curb?)
   - The structure of the geodatabase accommodates complete integration into the enterprise GIS

5. **Select vendor for contract:** Based on a blend of RFP responses, demonstrated capabilities, and cost, MDOT will select a vendor for contract award. Suggested criteria and rating points for vendor selection are presented in the Recommendations for Implementation (Chapter VII, Section H.5.e.).

I. Introduction

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A. Background

The Michigan Department of Transportation (MDOT) was interested in evaluating the benefits and costs of remote highway asset sensing technology options. Dye Management Group, Inc. (DMG) worked with MDOT to develop and execute a pilot project to perform that evaluation.

The project team aimed to accomplish two main goals. First, the team wanted to lower worker exposure, creating a safer environment in which MDOT employees can work. Second, the team sought to gain the efficiencies presented by remote data collection. These goals were challenged by the reduction in work force, as fewer employees are available to perform the collection. In addition, the team hoped to utilize remote data collection to not just replace the current data, but to improve the data quality.

Early in the project, DMG prepared a literature review in which we researched and summarized the technologies that are currently used by other agencies to remotely acquire and manage roadway and roadside asset data. Technologies that we researched and considered for evaluation included LiDAR (light detection and ranging), aerial photography, satellite imagery, ground-based video or photo-logging (mobile imaging), and manual data collection. Next, we identified and recommended the remote sensing technologies to be used in MDOT's pilot project. We selected these specific technologies because of their usefulness to high priority and medium priority assets and to best achieve MDOT's project goals: to lower risk, worker exposure, and address the challenge of fulfilling its duties with a reduced workforce.

This report identifies and summarizes the useful, feasible, and cost-effective remote technologies that can be used to collect information about attributes of the twenty-seven prioritized MDOT assets. DMG provides a comparison of cost and labor requirements of remote sensing technologies versus manual data-collection efforts in sections V and VI of this report, and takes into account the overall cost savings of collecting several assets/attributes simultaneously, rather than individually. In addition, a matrix of prioritized assets based on metrics specific to MDOT expenditures and practices is included.

As noted in the literature review, the use of remote data collection technologies to measure asset attributes has not been specifically researched for each of the twenty-seven assets. In particular, culverts, which are not readily visible from the roadway or above, pose unique challenges for any line-of-sight technology. As such, using satellite imagery, aerial photography, or LiDAR to measure culverts is considered impractical. Manual data collection therefore provided the most accurate results for culverts.

Each remote sensing technology has inherent strengths and weaknesses. This report investigates the capabilities and limitations of each technology, provides a summary of the costs to use each technology, and explores the limitations of each technology in gathering data on specific assets.

Based on the costs, benefits, and limitations we observed, DMG recommended using a combination of mobile imaging and aerial LiDAR technology for the approximately 176 miles included in the pilot project. As costs allowed, manual data collection was used on the remainder of the pilot route. For quality control and quality assurance purposes, DMG used all three data collection methods to evaluate a five-mile control section of the pilot route.

B. Statement of Hypotheses

DMG hypothesized a combination of remote sensing technologies that would allow MDOT to locate and measure highway assets in a manner that would decrease worker exposure, expedite data collection, increase data accuracy and quality, and reduce overall costs.

II. Literature Review

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A. Review of Previous Research

1. Literature Review Objectives

Our literature review primarily focused on known sources of the most up-to-date information about the usage of remote data-collection technology in other state transportation agencies. These sources were in the form of reports, case studies, and similar documentation. DMG has summarized and presented the results of the literature review in this section of the report to show the technologies that are currently being used to remotely acquire and manage roadway and roadside asset data. We describe each technology in sufficient detail to provide a full understanding of the technology's methodology, equipment involved, advantages, disadvantages, and associated costs.

2. Research Methodology

DMG has conducted a thorough literature search of multiple sources to research current technologies and their applications in order to identify the current state of the practice. We consulted the Transportation Research Board's (TRB) Transport Research International Documentation (TRID), which combines the US Transportation Research Information Service (TRIS) and the European Organization for Economic Cooperation and Development (OECD) International Transport Research Documentation (ITRD) databases. We also searched the U.S. Department of Transportation's National Transportation Library (NTL), the Library of Congress, and trade publications such as *Better Roads* and *Roads and Bridges*.

Our search results were conclusive; many agencies are using or are looking to use remote technologies to monitor transportation assets. By decreasing the hours spent on tedious manual data collection, agencies can save money, improve accuracy, and, most importantly, reduce the number of hours workers spend in the field. It is our ultimate goal that MDOT realizes these same benefits.

3. Description of Technologies

The technologies considered for evaluation within this literature review are:

a. LiDAR (light detection and ranging)

LiDAR is an optical remote sensing technology used to measure the distance and direction between a surface and the LiDAR instrument's sensing unit. As computing power and storage has advanced, LiDAR has gained popularity as a means to create accurate three-dimensional models of any surface within visual sight of the sensing unit. A LiDAR system can be attached to a vehicle and driven with the flow of traffic, it can be attached to an aircraft and flown over the target area, or it can be set up in a single location, like a traditional survey instrument. LiDAR can be used to collect location data on assets that are visible from the roadway, which allows for rapid data collection. However, LiDAR equipment is expensive, and the large amount of data produced is sometimes difficult to process and manage long-term.

The research that we conducted for the Michigan DOT highlights some of the benefits of implementing LiDAR for asset monitoring. First and foremost, LiDAR significantly reduces worker exposure, which creates a safer roadway for DOT personnel and the driving public. Secondly, detailed accuracy of LiDAR data allows end-users to filter and extract data based on their unique needs. As a result, multiple agencies can use the same LiDAR data each for their own application.

Based on the literature review, vehicle-attached mobile LiDAR technology should be able to capture all of MDOT's prioritized assets, with the exception of culverts. Since culverts are sometimes not visible from either the roadway or from above, no research was found to suggest that culverts could be measured remotely. Aerial LiDAR, in contrast, shows slightly less ability to measure the same number of assets as mobile LiDAR. Guardrails, fences, signs, and lights are all difficult to measure with aerial LiDAR. However, aerial LiDAR is cheaper than mobile LiDAR; it can collect data in about sixty percent of the time, and for about sixty percent of the cost of mobile LiDAR.

b. Aerial photography

Aerial photography involves the acquisition of line-of-sight images from above the roadway at a sufficient resolution to identify the targeted assets. A traditional aircraft (e.g., airplane or helicopter) or an unmanned aerial vehicle (UAV) are two approaches for capturing these images. Unlike LiDAR however, aerial photography can be used to identify guardrail, fences, and high-mast lights, as long as image resolution allows it. Higher resolution images are more expensive to acquire, process, and store, but offer the most useful application of the technology across the widest range of assets.

c. Satellite imagery

The use of satellite imagery is similar in many ways to aerial photography and can be an effective way to quickly identify and locate assets over a large area. Previously captured satellite images are typically available off-the-shelf. However, if an image is not available, or too old to be useful, a new image would have to be captured. Renting a satellite for repositioning is expensive, which drives the cost for newly-acquired images significantly higher than for those images available off-the-shelf.

Certain assets (e.g., curbs, guardrails, small signs, catch basins, fences, sound walls, freeway lights, and signals) could not be identified in satellite imagery, even at the highest resolution of 0.61 meters per pixel. However, other assets (lane miles, shoulder miles, bridges, tourist facilities, pump stations, and weigh stations) could be identified. Smaller assets could eventually be identified if higher resolution images become available.

d. Mobile imaging

Mobile imaging typically contains pictures of the roadway that are taken every fifty feet. The images are data-rich, and a review can provide information relating to the type and location of signs, signals, and roadside hardware, and in most cases, the condition of the assets. This data can be manually gathered as needed from the image records for individual or groups of assets. The process can also be automated for the entire image set to perform a roadway asset inventory scan.

While many of the mobile imaging technologies currently used to collect roadway and roadside information utilize an automated process to identify assets within the image set, some systems only collect images. These systems require personnel to review the photos and to manually record the content of the images. This process is tedious, and every effort should be made to move toward automation, provided that the process produces accurate data.

e. Manual data collection

Manual data collection includes any asset inspection that involves personnel in the field manually recording the necessary information to provide a description and location for each asset. Even with the wide array of technologies available, manual data collection can still sometimes be the most efficient and accurate approach for some assets. Technology, such as handheld GPS units and handheld laser or infrared range finders, is often used to supplement the manual collection of data to increase efficiency and accuracy.

While manual data collection can be used to inventory and assess each of the twenty-seven assets included in our pilot, it is best suited for assets that are difficult to measure with more efficient technologies. Culverts are one example. Culverts are difficult to identify from aerial photography, and quite often, aren't visible from the driving lanes, which renders mobile imaging and LiDAR ineffective.

The feasibility of using each technology to collect data remotely is asset-dependent. Within this report, our comparisons between the twenty-seven assets and the technology used to sense them were limited to the research that has already been completed in the reviewed literature. Not all assets were measured with all technologies within the available research.

B. Summary of State-of-the-Art

1. Summary of Multiple Technology Studies

Most of the research included in this synthesis focused on the use of one specific technology to remotely monitor assets; those studies are summarized in the technology-specific portion of this report. However, some literature summarizes agencies' efforts to use several technologies at once to investigate. This section focuses on some of the general work that has been done to simultaneously evaluate multiple technologies.

Clemson University produced a synthesis of safety data collection practices for the National Cooperative Highway Research Program's (NCHRP) *NCHRP Synthesis 367: Technologies for Improving Safety Data*. The study looked at data sources for crash records, road inventories, and traffic operations. The portion of this study that is most applicable to our project is the analysis of road inventories. *NCHRP Synthesis 367* evaluates three different technologies of interest: mobile imaging, digital highway measurement vehicles, and satellite imagery. The technology-specific results of this synthesis are included in section 2. Some of the general findings of this synthesis are listed below.

- Most roadway inventory data is collected in the districts or by headquarters staff that is dedicated to this function.
- Many states collect road inventory data on an annual basis for some characteristics, whereas the time needed to complete a full re-inventory usually approaches three to five years.
- Road pavement data is usually collected annually.
- Both in-house staff and contractors collect pavement data.

The synthesis also contains data requirements and a technology matrix, which compares several of the twenty-seven assets that DMG evaluated to some of the available technologies. Assets analyzed in *NCHRP Synthesis 367* that are also included in the MDOT evaluation are total lane miles, concrete surface lane miles, bituminous surface lane miles, paved shoulder miles, gravel shoulder miles, curb miles, number of sweepable approaches, and ditch miles.

The synthesis continues by pointing out several questions that an agency should ask when it implements a new data-collection technology. The questions are thorough; however, their answers will vary from one agency to the next, depending on the status of existing data collection efforts in the state. These questions include:

- If multiple technologies are feasible, which specific technology should be chosen?
- Which vendor should be chosen?
- What are the costs, including capital, operating, and maintenance costs?

- What are the system benefits and how can they be measured?
- How do we ensure complete system integration?

There are many challenges to evaluating multiple technologies that must be overcome while keeping down costs. These challenges range from improving data accuracy to increasing data collection speed. While each of the evaluated technologies can be used independently, it is most efficient to combine data collection activities. For example, a photolog system can be mounted on a digital highway measurement vehicle, which allows the use of both technologies with just one driving pass of a road segment. *NCHRP Synthesis 367* considers the option to contract out the data collection process. Depending on the technologies deployed, the total cost of each data collection vehicle can exceed $1 million, which makes the purchase of such equipment cost prohibitive. In addition, technologies constantly improve, which leaves the purchasing agency at risk of the technology becoming obsolete. By contracting out data collection to contractors that already own the equipment, initial investment and liability both decrease.

In August 2011, the Wyoming DOT and the Wyoming T^2/LTAP Center (T^2/LTAP) released the report *Asset Management for Wyoming Counties*. Some Wyoming counties were experiencing rapid roadway deterioration, due to an increase in oil field truck and equipment traffic. The objectives of the study were to develop an inventory of the counties' roads, bridges, culverts, signs, cattleguards, and approaches; evaluate and assess the condition of those assets; and estimate the counties' financial needs. The only remote technology evaluated in this study was handheld mapping-grade global positioning system (GPS) receivers, into which inspectors manually entered data. The data was then downloaded into and mapped by geographic information systems (GIS) software.

The Texas Transportation Institute's (TTI) report, *Research on Asset Management for Safety and Operations*, cosponsored by the Texas DOT (TxDOT) and the Federal Highway Administration (FHWA), discusses several successful applications of focused transportation asset management systems. The Minnesota, California, South Dakota, and Florida DOTs all use the Pontis bridge management system for database collection of bridge inventory and condition information. Pontis can estimate deterioration and service life for bridge structures and assets. The California DOT (Caltrans)'s department personnel enter information from statewide inspections into the main bridge management database to collect its bridge assessment data. Caltrans also uses a custom-made inspection collection and report generation software called SMART, which gives bridge inspectors access to the main bridge database from a remote location. The Colorado DOT uses Pontis for its bridge data collection and is also working to develop its GIS services. The Florida DOT uses Pontis through the web tool Citrix MetaFrame, which allows any number of DOT personnel to enter inspection data over any number of devices from any single location.

The TTI report also discusses several data-collection methods for hydraulic features. In Maryland, the Highway Hydraulics Division (HHD) created a custom-made, access-based GIS for pipe and culvert inventory. Due to the large amount of data in the inventory, the HHD will soon go to an Oracle-based GIS for data storage. The Minnesota DOT uses the HYDINFRA system to inspect and inventory data for hydraulic features. The state has effectively used the system to precisely map culvert locations. Inspectors record the date of an inspection or maintenance and record the data with global positioning receivers to operate HYDINFRA. Data is then stored in an Oracle database. Minnesota DOT users can upload information onto the system, based on a feature's location, condition, need for repair, or need for cleaning.

The Remote Sensing for Transportation conference in Washington DC, which was attended by eighty personnel from the transportation field, addressed the application of remote sensing technology within transportation infrastructure management. The conference was reported as "positive" overall, and participants were acceptant of for the use of remote sensing in transportation management. Among the topics discussed were pavement, traffic control and road inventories, drainage structure inventory, and the adoption of airborne and ground-based remote sensing data. During the conference, the Federal Geographic Data Committee officially adopted a national standard for data accuracy.

Wide discussions were held on infrastructure business needs that could benefit from remote sensing technology. A variety of remote sensing applications were brought to the table, including the most commonly identified application: the development and maintenance of data and information inventories for different infrastructure elements, including route inventory and condition information. Remote sensing data for route inventory could be used for such purposes as the identification of the most cost-effective route design. Condition information could be used to identify pavement type and road dimensions.

The conference groups established that the infrastructure management process begins during planning and continues into the development of statewide transportation improvement programs. Attendees agreed that data access, data knowledge, and data integration were the most important areas of technical needs, and that continued efforts are considered necessary in order to incorporate these needs with the technical infrastructure application of remote sensing technology. The conference also highlighted the lack of connection between some remote sensing data and design software. The creation of this connection would be of great value to the transportation field. Mapping remote sensing technology was also highlighted for use in transportation applications as a way to introduce transportation agencies to the remote sensing field. Additionally, conference attendees discussed the automation of data extraction, suggesting that the process would benefit agencies because it would reduce the reliance of data post-processing on manual labor, and thus accelerate the use of remote sensing technology.

Potential obstacles to the implementation of remote sensing technology were also identified and discussed. Conference attendees determined that the main obstacle to implementation is a lack of knowledge among transportation personnel about remote sensing techniques, capabilities, costs, and reasonable expectations. Other obstacles include reluctance to change, licensing issues, and workforce and staffing problems. The need for improved information on available remote sensing techniques, substantial products and services, and effective demonstration projects is paramount to the transportation industry. Attendees discussed the creation of sets of standards and addressed the fact that integration as critical for the widespread implementation of the technology. Attendees agreed that there must be an established quality, accuracy, and resolution for the various applications of remote sensing technology.

Other important issues discussed at the conference included the relationship with the private sector. Many state transportation agencies had limited familiarity working with the private sector. Attendees suggested that agencies look into new public-private partnerships that may help share knowledge and create solutions within transportation operations. Members of the conference strongly suggested that an NCHRP synthesis be written on remote sensing applications in order to improve knowledge and create a better understanding of what the technology can do for the transportation field. Such syntheses have worked in the past to advance the implementation of GIS.

2. Research Results by Technology

a. LiDAR

LiDAR, an acronym derived from the term "Light Detection and Ranging," is an optical remote sensing technology used to measure the distance and direction between a surface and the LiDAR instrument's sensing unit. As computing power and storage has advanced, LiDAR has gained popularity as a means to create accurate three-dimensional models of any surface or surfaces within visual sight of the sensing unit. The unit's output is a point cloud, with millions of data points spatially located within a three-dimensional file. By defining the precise location of the LiDAR instrument's sensing unit, the location of objects within the point cloud can be precisely defined and compared. A LiDAR instrument can be attached to a vehicle and driven with the flow of traffic to collect location data on assets that are visible from the roadway, which allows for massive amounts of rapid data collection.

As explained in NCHRP Synthesis 367, digital highway measurement vehicles can be used to measure pavement markings and pavement cross sections, including shoulders and curbs. Each vehicle is equipped with a network of sensors (e.g., LiDAR, inertial navigation systems, and differentially corrected GPS) that work together to accurately define the vehicle's precise location and direction of motion. The vehicle's location is then used to measure the horizontal and vertical alignment of the roadway. As of 2007, the estimated cost of such a vehicle was approximately $1 million.

A research study performed for the Missouri DOT reviewed the use of LiDAR for the remote data collection of assets along Route A in Franklin County (Vincent, 2010). The study evaluated three LiDAR applications: airborne, static, and mobile. Static LiDAR, while highly accurate, is comparatively much slower than mobile and aerial LiDAR and exposes DOT personnel to significantly more traffic risk. Given that MDOT is interested in collecting data over long stretches of roadway, the static LiDAR evaluation has been omitted from this report. As with other remote data-collection technologies, LiDAR's greatest benefit is the speed at which data can be collected. Both aerial and mobile LiDAR provide mapping-grade accuracy at high rates of travel.

The Missouri DOT's aerial LiDAR system was a Leica ALS50II MPIA system, combined with an Applanix DSS 439 medium-format 39-megapixel digital camera. By combining the LiDAR system with a camera, the total system was able to overlay the point cloud with the images, which increased the accuracy of data point identification.

The aircraft used to carry the aerial LiDAR equipment traveled at 115 miles per hour at an elevation of roughly 500 meters (1,640 feet). At that height, the measured ground footprint was 105 meters wide (345 feet). The system was configured to measure approximately fifteen data points per square meter, and the flight path was flown twice (once from each direction) to ensure full coverage.

Once the routes were flown and the data was collected, Leica's ALS post-processing SW software and Applanix's POSPAC MMS program was used to download and calibrate the .las output file to known survey points. The files were then loaded into a GeoCue project environment, which is a data management software system used to process LiDAR datasets. Within this software package, filters were applied that allowed the data points to be classified as bare earth, vegetation, or buildings, or to remain unclassified. Once the filters were applied, the resulting output was checked for accuracy.

An Optech Lynx system was deployed for mobile LiDAR data collection, which consisted of Dual 200 kHz lasers, two GPS antennae, and an inertial measurement unit (IMU). The system was configured to collect 400,000 data points per second. It is recommended that data collection be broken into small sections less than 0.5 miles long to decrease the risk of a period of poor GPS reception that adversely affects post-processing. In addition, the smaller the data file, the more manageable it is for post-processing programs. In order to minimize the effect of data cloud "shadows," the route was driven once in each direction. Data cloud shadows can occur behind an object if the LiDAR laser is unable to see behind or around the object (e.g., a semi truck driving by could obstruct the view of a speed limit sign). Once the route was driven and the data points were collected, the next step was to post-process the GPS and IMU data into trajectories, which were then used to reference the data cloud that the LiDAR system collected.

The dataset for the mobile LiDAR process was significantly larger than that of the aerial LiDAR process, due to the fact that aerial LiDAR is aimed downward and captures a smaller range of data. In contrast, mobile LiDAR creates a much larger dataset because of the larger angle at which data is collected. Depending on the application, mobile LiDAR's greater detail may be beneficial. In other applications, smaller data files from the aerial LiDAR process may be sufficient.

The research conducted for the Missouri DOT highlights some of the benefits of the implementation of LiDAR for asset monitoring. First and foremost, LiDAR significantly reduces worker exposure, which creates a safer roadway for DOT personnel and the driving public. Secondly, the accuracy and detail of LiDAR data allows end-users to filter and extract data in an almost infinite number of ways, which allows multiple agencies to use the dataset for multiple reasons.

MDOT has asked DMG to evaluate remote technologies as they relate to the collection of data on twenty-seven predetermined assets. In Table 2, we present a list of the assets that MDOT requested and that were also mentioned in the Missouri DOT's research. (Not all twenty-seven assets were included in the Missouri DOT study.) Table 3 shows each data-collection technology's ability to collect data for the corresponding asset. The most noteworthy observation pertains to mobile LiDAR, which can be used to measure data for each asset listed.

Table 2: MDOT Asset List

Asset	Asset Group
Atlas miles (map miles)	Roadway
Total lane miles	Roadway
Bituminous surface lane miles	Roadway
Number of bridges	Large assets
Number of tourist facilities	Large assets
Number of signals	Overhead
Number of freeway lights	Overhead
Gravel shoulder miles	Roadside
Mowable acres	In ROW
Number of culverts	Under roadway
Number of catch basins	Roadside
Number of signs	Roadside
Lineal feet of guardrail	Roadside
Concrete surface lane miles	Roadway
Number of sweepable approaches	Roadside
Paved shoulder miles	Roadside
Number of pump stations	Large assets

Asset	Asset Group
Curb miles	Roadside
Ditch miles	In ROW
Number of attenuators	Roadside
Lineal feet of existing ROW fence	In ROW
Number of delineators	Roadside
Number of guardrail endings	Roadside
Number of designated snowmobile crossings	Roadside
Number of weigh stations	Large assets
Non-motorized trail	In ROW
Lineal feet of soundwall	In ROW

Table 3: Feasibility of Asset Data Collection, by Technology

Description	Aerial LiDAR	Mobile LiDAR	Traditional Aerial
Total lane miles	Yes	Yes	Yes
Concrete surface lane miles	Yes	Yes	Yes
Bituminous surface lane miles	Yes	Yes	Yes
A miles (map miles)	Yes	Yes	Yes
Paved shoulder miles	Yes	Yes	Yes
Gravel shoulder miles	Yes	Yes	Yes
Curb miles	Restricted	Yes	Yes
Number of sweepable approaches	Yes	Yes	Yes
Lineal feet of guardrail	No	Yes	Yes
Number of guardrail endings	No	Yes	Yes
Number of catch basins	Yes	Yes	Yes
Lineal feet of existing ROW fence	No	Yes	Restricted
Mowable acres	Restricted	Yes	Restricted
Lineal feet of soundwall	Yes	Yes	Yes
Number of freeway lights	No	Yes	Yes
Number of signals	No	Yes	No

The third benefit mentioned is increased collection speed. Consider collecting data inside a tunnel: with traditional survey methods, the LiDAR is set up on a single point and traffic must be diverted, which increases costs and causes long detours and delays. By using mobile LiDAR instead of traditional survey methods, the tunnel is surveyed while driving with the flow of traffic, which virtually eliminates any traffic impact.

As previously mentioned, data-collection costs are reduced through the use of LiDAR. Based on this study, aerial LiDAR and mobile LiDAR each cost roughly half of the cost per mile of traditional surveying, as shown in Table 4.

Table 4: Missouri DOT Cost and Labor Information for Remote Asset Monitoring

Summary	Hours	Labor Cost	Person Days	Dollars per Mile
Traditional survey design	1,281	$131,585	160.1	$18,798
Aerial LiDAR	444	$58,250	55.5	$8,321
Mobile LiDAR	726	$81,688	90.8	$9,933
Static LiDAR	1,700	$204,805	212.5	$29,258
Conventional aerial mapping	548	$55,234	68.5	$7,891

The Missouri DOT study also considered the economic impact of each of the data-collection methods. As seen in

Table 4, for a seven mile stretch of roadway, conventional aerial mapping was the cheapest option, and aerial LiDAR was only slightly more expensive. Because of the increased granularity of the data that aerial LiDAR produces, it is reasonable to conclude that aerial LiDAR provided the best value of all the tested methods.

Note that the “Labor Cost” column includes all material and equipment, as well as the labor costs. The column represents the total costs for the seven-mile test section. It should also be noted that aerial LiDAR required the fewest labor hours, which indicates the greatest reduction in worker exposure.

b. Aerial photography

Iowa State University’s (ISU) Center for Transportation Research and Education published a report titled *Evaluating Remotely Sensed Images for Use in Inventorying Roadway Infrastructure Features*, which focused on how remotely sensed images can be used to facilitate the accurate and rapid collection of large quantities of inventory data. The research team members first compiled data on inventory elements that state transportation agencies currently used. They then compiled data on current methodologies for inventory data collection and found the benefits and limitations of each. They conducted a pilot study on inventory elements and evaluated which ones could be found or measured from aerial photographs by using a variety of image resolutions. They then made evaluations and recommendations, based on the spatial accuracy of aerial photographs at different resolutions. Finally, they evaluated the overall advantages and disadvantages of using remotely sensed images for data collection.

The study was conducted in Iowa on US Route 69 along three roadway segments. Four resolutions were used during data collection: two-inch resolution, six-inch resolution, twenty-four-inch resolution, and one-meter resolution. The team used performance measures for feature-recognition accuracy, linear measurement accuracy, and positional accuracy to evaluate each resolution's ability to accurately identify individual features and linear or positional measurements. The results showed that features could be directly identified in most instances, especially among higher-resolution datasets.

The research also uncovered a lack of commonly accepted standards for acceptable errors in locating various types of assets. Some transportation assets are located at one specific point (e.g., signs, attenuators, and driveway entrances), while other assets are linear in nature. Some linear assets include guardrail, mainline pavement, shoulders, and pavement striping. Linear measurements can sometimes be used to estimate a variety of factors (e.g., the length and width of roadways can be used to evaluate the chances of accidents). However, despite the various uses of linear measurements, there is no generally accepted standard for linear measurement accuracy. Agencies use different applications for the measurement of particular roadway features, so accuracy varies. In order to find the expected linear accuracy for each dataset, the ISU team worked in the field to measure lane widths, turn-lane widths and lengths, median widths, and total roadway widths at locations in the study area. These measurements were then compared with those obtained from the imagery. The team recorded the difference between the field lengths and photo lengths for specific features and then performed a t-test to estimate the 95 percent confidence intervals. The results defined acceptable accuracy estimates for the location of each linear asset for the ISU study.

The data showed that higher-resolution imagery performs much better than lower-resolution imagery. Length measurements greatly relied on the ability to identify a feature's begin and end points. Only the two-inch dataset consistently gave the accuracy required in order for the collection of data for roadway features to support the highway safety design decisions described in *NCHRP Synthesis 430: Cost-Effective and Sustainable Road Slope Stabilization and Erosion Control*.

ISU's work indicated that the greatest difference between the resolutions was their accuracy in the visual identification of inventory features. The two-inch and six-inch resolutions performed consistently better in feature identification than twenty-four-inch and one-meter resolutions. The ability to locate and measure features was very often dependent on whether the feature could be identified. The location of an unidentified feature could be easily defined; however, the asset type and description of the feature were in some cases difficult to determine. Therefore, with the lower-resolution databases, the challenge became the ability to accurately a feature, much more so than the ability to accurately measure it.

Driveways, two-way left-turn lanes, and raised medians were all clearly visible in the six-inch resolution image. In addition, it took five hours to obtain the data from the images, which is a significant reduction from the ten hours required to collect the same data in the field.

ISU's report states that aerial photography has significant advantages over GPS and mobile imaging in its ability to reduce data collection time. Unlike field date collection, the use of aerial photography doesn't endanger workers' safety by requiring them to work next to a busy road or create the potential to disrupt traffic. The main disadvantage of remote sensing technology is its cost. A source from the Iowa DOT estimated the cost to obtain aerial or satellite images from a vendor at about $100 per linear mile. Mobile imaging, on the other hand, was estimated at $11 per mile, not including the cost to buy the van and equipment.

An alternative to the traditional means to capture aerial photographs exists, in which unmanned aerial vehicles (UAV) are used to fly the route and take pictures. Ohio DOT personnel delivered a presentation at the ninth National Conference on Transportation Asset Management in 2012 that summarized the DOT's recent improvements in asset management. One of the new technologies discussed was the use of UAVs for asset inventory purposes. This alternative, which costs $120 per hour to operate the UAV, is much less expensive than traditional aerial photography, which costs around $450 per hour. The study reports that the highest-possible resolution for UAV scanning is 0.75 inches per pixel.

The Texas Transportation Institute also released a report, *Use of Micro Unmanned Aerial Vehicles for Roadside Condition Assessment* (Hart, 2010). The study's most significant finding was the effect wind had on the quality of images and the operator's ability to control the device, once airborne. In favorable site conditions (low traffic and winds less than five miles per hour), the UAV was faster and safer than manual surveys. However, winds above fifteen miles per hour rendered the UAV unable to fly. Winds from five to fifteen miles per hour allowed for flight, but produced low-quality images. Manufacturers will need to address this limitation before the use of UAVs for asset monitoring can be considered for widespread implementation.

c. Satellite imagery

Purdue University produced a publication in 2005, titled *Modern Technology for Design Data Collection*, in which the research team evaluated the usefulness and accuracy of satellite images for roadway feature identification (Bethel et al., 2005). The research describes some of the steps in the process of taking a raw, unprocessed satellite image and creating a useful "rectified" image. The research also considers the use of satellite imagery not only for asset identification, but also as a substitution for traditional topographical surveys that are used throughout the design process. While design input data is outside the scope of this project, if the data collection technology chosen for implementation provides data that could be useful to other units within MDOT, it would be fiscally responsible to share those benefits. Such shared benefits could lead to other units eventually sharing some of the cost of data collection.

Satellite images must be acquired, typically through a commercial vendor. These images must then be rectified or processed to be aligned on one continuous surface. While this process is generally automated by image-processing software, error can creep into the data at this point. The amount of error ranges in significance and is dependent upon several factors, including the amount of relief in an area, the degrees from nadir that the satellite captured the image, and the clarity and accuracy of the terrestrial control points. Errors in the data are not necessarily inevitable or even statistically relevant, if present; however, errors can be introduced through the process of rectification, and as such, the process should be closely monitored.

The satellite used to collect the original image in the Purdue research was Digital Globe’s QuickBird 2 satellite. The image dimensions were approximately 30,000 pixels by 27,500 pixels, with an average ground scale sample distance of approximately 0.61 meters per pixel.

While Purdue University did not evaluate specific assets, the research allows MDOT to estimate the appropriateness of using satellite images to identify specific transportation assets. From the satellite images used in this research, certain assets (curb, guardrail, catch basins, fence, sound walls, freeway lights, and signals) could not be identified at a resolution of 0.61 meters per pixel. However, other assets (lane miles, shoulder miles, bridges, tourist facilities, pump stations, and weigh stations) could likely be identified. If higher-resolution images are available, increased granularity could allow these images to be used to identify smaller assets.

d. Mobile imaging

Mobile imaging typically contains images of the roadway that are taken every fifty feet. Information obtained from an image set can include data for the type and location of signs, signals, and roadside hardware. Information can be pulled as needed from the image records, or the entire file can be processed for a roadway inventory file.

NCHRP Synthesis 367 evaluates mobile imaging as one of its technologies for remote data collection (Ogle, 2007). A survey was sent out to state DOTs, and out of the twenty state agencies that responded, five reported using mobile image data to capture roadway geometry. Several state DOTs, including those in California, Oregon, and Washington State, have given the public full use of their mobile image databases. Users can search for a specific point or virtually “drive” any route captured within the log. The primary benefit of a mobile image record is its ability to let users view a roadway or roadside remotely, without the safety hazard or time spent visiting the site in person.

While many of the mobile imaging technologies currently used to collect roadway and roadside information utilize an automated process to identify assets within the mobile image set, some systems only collect images. These systems require personnel to review the photos and manually record the content of the images. This process is tedious, and every effort should be made to move toward automation, provided the process produces accurate data.

The Connecticut DOT has developed a method of data collection and quality control for inventorying roadway assets, as summarized in the January 2008 edition of TR News, *A Roadway Photolog Goes High-Definition: Connecticut Expands User Network, Realizes Cost Savings*. The method uses enhanced images to collect inventory data aboard a moving vehicle to improve the agency's photolog program. The new photologging system uses high-definition (HD) images that are clear enough to capture even small details on assets such as signs, bridges, and posts. This advancement in data collection is combined with a unique image-editing and -distribution system to make up Connecticut DOT's new DigitalHIWAY system. In 2006, Connecticut became the first state to collect automated HD images from a ground-based vehicle for an entire roadway. HD images were taken on every ten-meter section of Connecticut highway.

The DigitalHIWAY system's photologging is performed with two Roadware Automatic Road Analyzer vans. A large box atop the van allows enough space for a variety of vehicle system modules and generators. The attached camera is the Thomas Grass Valley LDK 6000 MK II WorldCam. The camera performs on a high level, and takes 9.2-million-pixel progressive-scan HD images. The camera can also use multiple HD formats. The Grass Valley camera hardware eliminated the need to attach a dual-camera system to the vehicle. Roadware created its Harvest software to collect the images, which can be configured to retain images at interval distances of five to twenty meters. The images are automatically saved to an eighty-gigabyte removable hard drive and a backup hard drive, when taken. The van's onboard system also uses a GPS, a gyroscope that accurately measures roadway shape and grade, a laser module that measures structures, and a module for pavement crack detection.

Three system modules make up the DigitalHIWAY system: the incremental index and editor, the image server, and the client. Fresh streams of collected data are post-processed on the incremental index and editor. Once there, the images are sent to the server, where they are then viewable by the software client, which allows the end user to view the images from his or her desktop. During the post-processing phase, image data that has been streamed in are checked for quality. Images are then compiled, based on route index, into a JPEG library (CJL) file. Once formatted, the image server sends CJL files of images to users on the DigitalHIWAY system protocol software, which can be run on any Microsoft server. The images are then distributed to the client workstations throughout the Connecticut DOT's office.

The DigitalHIWAY system is used throughout the Connecticut DOT's offices for activities related to permits, GIS, project planning, maintenance management, traffic signals, traffic engineering, right-of-way, central surveys, research, materials testing, bridge design, bridge safety, and incident management. The benefits of using the system can be divided into five categories: review, confirmation, familiarization, documentation, and presentation. Reviewing the data in the system allows DOT workers to virtually access field conditions in order to make assessment decisions. Documentation allows access to the data for every inventoried roadway. Familiarization with the roadway allows workers to safely and effectively plan their trips into the field. The roadway data can be confirmed by accessing annual data, which goes back to 1985, through the online storage. Finally, the system's images and data can be used for presentation, which allows the DOT to demonstrate to the public a clear understanding of roadway impacts and changes.

Responses to system implementation have been very positive. After the Connecticut DOT received feedback and performed cost-saving analysis on the system, it concluded that agencies can save millions of dollars in costs by implementing the technology. The ability to view roadway pictures from a screen can drastically reduce the need to collect data in the field. The reduced usage of fleet vehicles and hours worked by field personnel also translates into dollars saved. The Connecticut DOT reported that it has five hundred personnel that use the DigitalHIWAY system, which saved the state an estimated $2 million per year in field trip costs. The photologging system is becoming a well-established tool that all Connecticut DOT bureaus are using on a regular basis.

Mobile imaging was further examined in *NCHRP Synthesis 367: Technologies for Improving Safety Data*. Mobile imaging allows an inspector to view roadways all over the state from a centralized location. One example of automated image capturing used a mobile image set with an image resolution of 1,300 pixels by 1,024 pixels to capture data for a stretch of Georgia roadway. A Pentium-IV 3.06GHz central processing unit was used to recognize and locate stop signs and speed limit signs from mobile images on approximately two miles of roadway (two hundred images) in less than three minutes.

By capturing GPS location data to link to roadside and roadway assets during data collection, the method can move toward automation within a GIS system. Defining the position of an asset allows the end user to create a "playback" experience while that person reviews a given section of roadway. Processing the data in this way can lead to a more thorough and accurate review of asset information.

A Study of Implementation of IP-S2 Mobile Mapping Technology for Highway Asset Condition Assessment discusses a preliminary study done on Topcon's Integrated Positioning Mobile Mapping System (IP-S2) at Virginia Polytechnic Institute and State University's (Virginia Tech) Center for Highway Assets Program. The objective of the research was to measure the speed and accuracy of using this mobile mapping technology to collect data and to compare it with the traditional human collection method. The study also measured the clarity of the collected data, based on the effects of speed, distance, and lighting. System testing was completed on Virginia Tech's Smart Road, which contains eighteen miles of segments marked at one tenth of a mile each. Each segment contained a variety of roadway assets that were evaluated during the testing, including object markers, signs, and guardrails.

The IP-S2 uses three technologies to accurately maps linear corridors: the Global Navigation Satellite System (GNSS), which gives a geospatial position; IMU, which gives roll, pitch, and heading information; and the Controller Area Network (CAN), which tracks vehicle odometry. These three technologies allow the system to maintain a 3D position even when the satellite signal is obstructed. The system incorporates three high-resolution laser scanners that scan the area adjacent to the vehicle's path up to thirty meters on each side. A 360 degree spherical view is captured by a high-resolution digital camera at a rate of 15 frames per second. The system can also be configured to include other sensors, depending on the needed application. Included with the system is the software GeoClean, which is used to transfer the data from a vehicle and sensors into a stream that can be exported into a format that meets industry standards. The software also allows users to view point cloud data produced from laser scanners to find linear measurements. Dashboard software is also provided, which displays sensor, position, and vehicle status information. During the Virginia Tech study, the system was placed atop a Dodge Caravan and used on the Smart Road.

The study compared the speed and accuracy of using human inspection and the IP-S2, which operated at various speeds, to complete data collection. Two different methods can be used to process data: a four step interactive process and a batch process, which can operate without oversight. The batch process allows crews to process data at a later time. The time evaluation determined which method performed faster under different processing workflows. The data was assessed based on the collected assets and the processing time needed while using GeoClean software. During the time analysis of interactive processing, the researchers found that on average, human inspection was faster than the IP-S2, at both fast and slow speeds. In the batch-processing analysis, the IP-S2 analyzed data faster than human inspection. The IP-S2–based technology performed faster analysis of data than manual collection did, but the overall process was slowed, due to the amount of time it took for data to be processed into a viewable visual format. IP-S2 analyzed data better because it wasn't slowed by travel time, stopping time, or walking time. Its batch-processing mode does not require human inspection, so much less time was required in order to process the data, which significantly increased the overall performance speed of the IP-S2 system.

Field statistics from a scorecard were compared in order to complete the accuracy evaluation. The scorecard evaluated each sample segment by how each collection method fared and also by its accuracy in assessing the assets that were present in the segments. Both IP-S2 speeds performed the same, which resulted in 65 percent of the collected data being perfect matches and all data being statistically accurate. The system was very near a 95 percent confidence level of accuracy for the assets collected. Comparing the IP-S2 to manual inspection resulted in 35 percent of data being perfect matches and only 4 percent of data being statistically different.

In the final test runs, data collection was evaluated based on clarity levels such as speed, distance, and lighting. Speed had little to no effect on the clarity and quality of data. In terms of distance, most assets needed to be within 6.3 meters of the camera to run a condition assessment. Tests conducted at day and at night showed that limited lighting can have a significant effect on the clarity of collected data. Nighttime test runs showed that only assets that contained large reflective areas, such as signs and guardrails, could be seen well enough to be inspected.

Research concluded that in terms of speed, the difference in inspection time between the IP-S2 and traditional manual collection varied, based on the workflow process used. The study claimed that if processing time was eliminated or automated, IP-S2 inspections could be faster than traditional human inspection. The IP-S2 inspection produced a data accuracy of 96 percent, which is on par with the 95 percent confidence level produced in traditional Virginia DOT Turnkey Asset Maintenance Services (TAMS) projects.

e. Three dimensional street-level imaging

earthmine inc. offers a street-level three-dimensional mapping solution that uses technology licensed from the National Aeronautics and Space Administration's (NASA) jet propulsion laboratory and the California Institute of Technology. This is the same technology used on the Mars Exploration Rover missions ("earthmine Signs Exclusive Agreement," 2007). The agreement includes an exclusive and perpetual license for photogrammetric technology, which allows for the creation of very dense and accurate three-dimensional data from stereo panoramic imagery. The technology, called reality indexing, uses an automated vehicle-based camera array that is vertically oriented and works especially well in urban environments. Each pixel in the image contains real-world latitude, longitude, and elevation information. As a result, points, lines, or polygons can be used to accurately locate, measure, or model everything within an image. This data mine can be accessed through a web-based interface where users can identify, view, and extract information as desired (Reuters, 2008).

The system can be mounted on almost any vehicle, and data is collected at regular driving speeds. earthmine also offers a custom pedestrian area platform (e.g., bike-mounted platform). The earthmine system offers 32 megapixel 360-degree (H) by 180-degree (V) stereo panoramic imagery and wide angle 360-degree (H) by 165-degree (V) three-dimensional data capture. earthmine data contains up to 8 million three dimensional points per image and 24 million points per second, depending on the scene (“Mobile Mapping Solutions,” n.d.).

Two hosting options are offered for the earthmine system. The earthmine cloud server is based on Amazon’s web services and provides the ability to store large quantities of data in the cloud. Add-ons are offered to integrate with ArcGIS 10, as well as apps for Apple iPhones and iPads. The benefits of cloud-based services include high availability, low overhead, security, speed, and scalability (meaning the service provided can expand or contract to meet the needs of small- and large-scale user-base applications). The earthmine server uses local computing infrastructure and users can configure earthmine to meet an organization’s security requirements and control data access (“Hosting Options,” n.d.).

Several desktop software options are offered, including earthmine for ArcGIS, earthmine Viewer, and earthmine for AutoCAD Map 3D. earthmine for ArcGIS provides a dockable window within ArcMap that displays the street-level view alongside the traditional two-dimensional map view. Features within the geodatabase are then accurately displayed on top of the panoramic imagery, which enables users to visualize spatial data within its real world context. It also offers users the ability to gather and analyze additional information that may not be contained within GIS. Users can take linear and area measurements and view and edit attribute information within the ArcGIS desktop environment. earthmine viewer offers a “ready-to-go” desktop application built on earthmine’s software development kit (SDK) for Flash developer tool and deployed as an Adobe Integrated Runtime (AIR) application for installation on Windows, OSX, and Linux systems. earthmine viewer integrates satellite and aerial imagery, road data, and address geocoders from Bing Maps and provides an extensive set of measurement tools. earthmine for AutoCAD Map 3D delivers high-resolution and immersive street level imagery alongside the traditional AutoCAD view, and integrates GIS, CAD, and earthmine data into a single solution. Like earthmine viewer, earthmine for AutoCAD is “ready to go out of the box” and requires little to no development expertise (“Desktop Software,” n.d.).

earthmine offers a variety of developer tools, such as earthmine SDK for Flash, which allows developers to use Adobe Flash, Flex, and AIR frameworks to create customized street-level three-dimensional experiences. earthmine widget provides a simple way to use a browser-based interface that is distributed over the web to publish GIS data in conjunction with earthmine imagery to a wide audience. It also includes a set of measurement and feature creation and editing tools. earthmine SDK for iPhone creates iPhone apps and gives developers the core functionality to retrieve and display earthmine’s panoramic imagery, as well as tools to create immersive applications and unique experiences on the iPhone. Users can take measurements, display relevant geo-contextual content, and visualize assets from a geospatial database (“Developer Tools,” n.d.).

Real world applications

(1) Columbia County, Georgia

Columbia County, Georgia, paid $75,000 (an "early adopter" price) to map 1,130 miles of roadway in both rural and urban settings. In addition to the Department of Construction and Maintenance, several departments are using the earthmine data, including the county tax assessor's office and Sign Department (Heaton, 2012). DMG communicated directly with Don Barrow, Columbia County road construction project manager, and Mary Howard, Columbia County GIS manager. Both provided positive feedback on their experiences with earthmine. Mr. Barrow reported that his office has used earthmine data to evaluate the existing road network, damages caused by recent construction, and site conditions for future construction. His office has also used earthmine data to successfully measure shoulder and lane widths and identify areas of failing pavement, cracking, and rutting, among others. Using the earthmine system has enabled the office to increase safety and realize fuel and time savings. Mr. Barrow reported that the data's only drawback is that it is time sensitive. Ms. Howard's office has overlaid its GIS point and line data with earthmine data, which enables staff to quickly evaluate projects such as a street light audit. Ms. Howard stated that the significant cost savings to her office have far outweighed the price of the earthmine data. Both users reported positive experiences with earthmine staff.

(2) Colorado DOT asset collection

The Colorado DOT used earthmine data to map a wide variety of assets, including guardrails, fences, walls, barriers, inlets, snow gates, cattle guards, and game crossings. The earthmine Mars Collection System captured all this information at highway speeds. The DOT integrated the earthmine data into its existing workflow with the earthmine for ArcGIS add-in, and asset identification was done completely in the ArcGIS environment. The images allowed the department to accurately record the locations of assets and to identify their specific construction materials. These inventories gave maintenance divisions a list and location of assets within their regions and theses lists are used to determine the respective monetary values of the inventories ("Mapping and GIS," n.d.).

f. Alternative methods

Researchers at Japan's Osaka University looked at the application of radio-frequency identification (RFID) and personal digital assistants (PDA) to facilitate the inspection and diagnosis of roadside trees as a roadway asset. The resulting report is titled *A Management System of Roadside Trees Using RFID and Ontology*. Planting trees has important effects on an environmental program; it reduces pollution, improves scenery, and manages the ecosystem. Trees can also play an important part in improving traffic safety and decreasing roadway disasters. Based on studies and interviews, some of the current problems with roadside tree management are low accuracy and unproven management systems, a lack of diagnosis data because of the time required to properly fill out the diagnosis forms for individual trees, and difficulties in tree identification. The main objective of the Osaka study was to find a system that uses RFID technology and ontology to diagnosis support and data management to improve the efficiency of tree management.

Research conducted to solve these problems led to the development of the Roadside Tree Diagnosis Support System, which uses RFID technology for visual tree assessment. A tree surgeon installs an RFID tag on each roadside tree, and the RFID reader then identifies the tree from the RFID to perform a diagnosis. After the tree is properly identified, the PDA displays diagnosis forms and the data can be input into the PDA quickly and with ease. Prototype system testing showed that with the new system, it took half as much time to diagnose and make decisions as it did with previous methods.

g. Manual data collection

The Wyoming DOT and the Wyoming T2/LTAP Center (T2/LTAP) released a report titled Asset Management for Wyoming Counties. The objectives of the study were to develop an inventory of the counties’ roads, bridges, culverts, signs, cattleguards, and approaches; evaluate and assess the condition of those assets; and estimate the counties’ financial needs. The research team used laptop computers linked to handheld mapping-grade GPS receivers to collect data. Temporary employees were hired, trained, and then sent out in the field to collect appropriate data on the chosen assets. An inspector saved the asset type, condition data, and asset location on a laptop. T2/LTAP designed forms to facilitate consistent data entry for all inspector teams. The data was then downloaded into GIS software and mapped by GIS.

Tying asset data to geographic coordinates can create numerous benefits. One such benefit is it empowers maintenance personnel to more efficiently manage their time and resources. By providing asset location and type information, maintenance personnel are better prepared to make necessary asset repairs. Asset-specific information (e.g., type of sign, size of culvert, and road width) is sometimes just as important as asset location. Wyoming has a comparatively sparse population, and as such, its maintenance crews sometimes spend several hours driving to a location within their areas of responsibility. When crews have the proper information about an asset in need of repair before they leave the maintenance facility, this can make a substantial difference. In some cases, it can be the difference between taking one trip and two trips—and two days—to complete a maintenance task. Asset management systems sometimes pay for themselves in the hours and miles saved. The systems are also beneficial because by documenting the overall condition of a highway system, agencies can base funding requests on measured needs rather than on unsubstantiated estimates.

T2/LTAP put much thought into its creation of the forms used to collect the asset data. Consistent, easy-to-use forms allow the greatest efficiency in data collection. Each asset requires different amounts of information to be collected, and as such, the forms need to be unique for each asset type. The PASER road rating system, shown in Table 5, was used to rate gravel roads. The Wisconsin Transportation Information Center developed this system.

Table 5: PASER Gravel Road Overall Rating Standards

Rating	General Condition	Drainage	Maintenance
10: Excellent	New construction or total reconstruction	Excellent drainage	Little or no maintenance needed
8: Good	Recently regarded; adequate gravel for traffic	Good crown and drainage throughout	Routine maintenance may be needed
6: Fair	Shows traffic	Needs some ditch improvement and culvert maintenance	Regrading (reworking) necessary to maintain; some areas may need additional gravel
4: Poor	Travel at slow speeds (less than 25 mph) is required	Major ditch construction and culvert maintenance also required	Needs additional new aggregate
2: Failed	Travel is difficult and road may be closed at times	Needs complete rebuilding and/or new culverts	

The PASER rating system was also used to rate asphalt roadways. Approach type and location were recorded, as were width and gate types. Bridges were located, though no distress measurements were taken, as the Wyoming DOT already manages its bridges with a separate system. Signs were located, measured, and evaluated. By omitting retroreflectivity testing from the measurements, sign measurements could be collected without additional equipment or training. The inspector recorded the size, type, panel condition, support condition, and location of each sign.

Culverts present a unique problem for data collection. Of the twenty-seven assets that MDOT identified for analysis, all but culverts can be located and measured from aerial photography and/or a properly equipped measuring vehicle. Manual data collection is typically the only way to conduct condition assessments of culverts. The Wyoming DOT measured its culverts manually and recorded the types. The condition and flows were rated on a scale that ranged from "failed" to "excellent." This rating system for culverts is subjective and does not significantly improve on other current culvert management methods.

DMG developed *NCHRP Report 677*, in which recommendations are made for the development of a level of service (LOS) performance scale for the Interstate

Highway System. Within the scope of this work, DMG also developed recommendations for equipment and practices used in manual data collection, which account for worker safety, data accuracy, and collection efficiency.

With these considerations in mind, DMG recommends that field data collection teams consist of three individuals for the following reasons:

- One person can drive while the other two record data.
- One person can watch for oncoming traffic while the other two record data.
- One person can take measurements or count while the other two record data.
- Other opinions may be advantageous if a judgment call is necessary.
- Three people are less likely to be accosted by wrongdoers than one person acting alone.

In addition to the organization of the field team, DMG recommends a general list of equipment necessary to complete manual field assessments:

- Notebook, or note pad and clipboard, and several extra pens to use to record pertinent notes about data collection
- Flexible metal measuring tape, three-fourths to one-inch wide by twenty-five feet long, or a six-foot folding ruler, graduated in feet and tenths
- One hundred-foot cloth or metal measuring tape
- Measuring wheel with a capacity of at least 528 feet to measure distances longer than the length of the flexible tape
- Vehicle equipped with:
  - Flashing yellow/orange safety lights on top of vehicle
- Distance measuring instrument (DMI) capable of recording to the nearest 0.01 mile and calibrated for less than 1 percent error under normal operating conditions (e.g., temperature, tire pressure, and vehicle load)
- Handheld laser or infrared range finder, the type commonly used for hunting or golfing (optional)
- Flashlight to use to examine the interiors of catch basins
- Twelve-volt socket “splitter” to allow more than one device to be plugged into the cigarette lighter (available at most automotive supply stores)
- Traffic cones (minimum of three)
- Several cans of orange spray paint to use to mark sample locations
- Protective clothing, such as field boots, jeans, hat, safety glasses, and other outdoor wear appropriate for the season

- Reflective orange or green safety vests, according to agency policy

3. Review of Other DOT GIS Systems

As a part of the research, DMG conducted a review of information currently available from other state DOTs about their asset management systems. Overall, we found that some state DOTs have built systems from commercial off-the-shelf (COTS) asset tracking software in collaboration with other software to predominantly track pavement, culverts, and bridges, while other states have chosen to build their systems from scratch.

Many states have some form of pavement and bridge management systems. However, the tracking and management of other assets is a relatively new concept. From what we found, there is not a great deal of information currently available in this area. During this research initiative, we found information from six state DOTs that pertained to their asset management systems, some of which are less developed and contain fewer assets than others. For the purpose of this report, we have divided these states into two categories: those with systems built with COTS software and those built from scratch.

a. Systems built from COTS software

Each state has its own unique needs, inventory, assets, budgets, and existing business software (to track work orders, employee time, etc.), which needs to be considered when developing a risk-based asset management system. There is COTS software available that can be customized, based on the needs of the DOT. In some cases, states have used multiple software systems in order to develop their management systems.

Table 6 provides the state DOTs included in this research, along with the COTS software they are using and the assets they are tracking.

Table 6: State DOT Systems Built from Commercial Off-the-Shelf (COTS) Software

State	Software Used	Assets Tracked
Minnesota	1. Pontis 2. HYDINFRA with Oracle database	1. Pontis: bridges 2. HYDINFRA: Pipes (including culverts and storm drains), structures (including drop inlets, catch basins and manholes) special structures (including aprons, headwalls, end treatments, weirs, and increasers/reducers), water quality devices (including ponds, ditches, and structural pollution control devices), and virtual features (illicit discharge and outfalls)[1]
Colorado	1. Deighton dTIMS CT 2. Pontis 3. SAP AG	1. Deighton dTIMS CT: Pavements, signs, guardrails, and pavement markings 2. Pontis: Bridges, earth retaining structures, and culverts 3. SAP AG: Maintenance fleet equipment, Intelligent Transportation Systems, and Maintenance LOS[2]
New York	1. Microsoft Access 2. GIS Geodatabases 3. Cartegraph 4. Oracle	Databases contain 90 to 100 percent of all traffic signals, sidewalks, curbs, and small culverts; about 40 percent of all large culverts; and about 15 percent of earth retaining structures, guardrails, and traffic signs[2]

(1) Minnesota

The Minnesota Department of Transportation (MnDOT) uses Pontis to track its bridges. Pontis is a bridge management system that stores inventory and inspection information about an agency's bridges, culverts, and other structures. It also provides a set of modeling and analysis tools to support project development, budgeting, and program development.[3] Agencies can choose to use all or some of the Pontis features. Based on current information, MnDOT uses Pontis for bridge management and a MnDOT-specific hydraulic infrastructure (HYDINFRA) system to manage inspection and inventory data for hydraulic features. Pipes, structures, and water quality devices are all maintained in HYDINFRA. GPS receivers are used to collect data in the field and it is then uploaded into an Oracle database. Users can query the database for specific information, create maps, and run reports. HYDINFRA is updated and enhanced on a regular basis to take advantage of new developments in technology.

Although asset management is divided between two different tools, MnDOT is confident in its small structure inventory. MnDOT feels that the use of Pontis is a practical application of an existing software package and that HYDINFRA can be used as a model to manage drainage systems in other states. MnDOT has expressed a willingness to share information about its HYDINFRA system with other DOTs. [1]

(2) Colorado

According to the Comprehensive Transportation Asset Management Report, [2] the Colorado Department of Transportation (CDOT) uses a combination of Deighton's Total Infrastructure Management System (dTIMS), Pontis, and SAP AG to manage its assets. dTIMS and SAP AG are both decision support tools that relate to asset life cycle.

CDOT uses the dTIMS CT software to track pavements, signs, guardrails, and pavement markings. Pontis is used for bridge, earth retaining structure, and culvert inventory, while SAP AG keeps data for maintenance fleet equipment, Intelligent Transportation Systems, and maintenance LOS. CDOT is interested in transferring all of its asset inventory data to dTIMS CT so that it can cross-manage all the assets in one location, rather than in three different systems.

(3) New York State

In 2011, the New York State Department of Transportation (NYSDOT) was in the beginning stages of the development of its asset management system. Statewide inventory data was available for traffic signals, culverts, sidewalks, and curbs. NYSDOT used a combination of Microsoft Access databases, GIS geodatabases, Cartegraph, and Oracle to track its inventory. These databases contained 90 to 100 percent of all traffic signals, sidewalks, curbs, and small culverts and about 40 percent of all large culverts, but only 15 percent of earth retaining structures, guardrails, and traffic signs.[2] The goal of the system was to eventually obtain a fully integrated asset management program.

Since then, Moving Ahead for Progress in the 21st Century (MAP-21) has gone into effect. NYSDOT's asset management system provided the inventory needed to develop its transportation asset management plan (TAMP). When finalized, the NYSDOT TAMP will address NHS pavements, pavements on other state-owned roadways, all bridges, and large culverts on state-owned roadways.[5] The final TAMP is expected to be completed by May 2014.

b. Custom systems

Because each state has its own unique needs, it is sometimes more fitting to custom-build software than to utilize COTS software. During our research, we found information from three state DOTs that built their asset management systems from scratch. These states and the assets they track are listed in Table 7 and explained in further detail below.

Table 7: State DOT Systems Built from Scratch

State	System Name	Software Used	Assets Tracked
Maryland	**1.** Structure Management Systems (SMS) **2.** Asset Data Warehouse (ADW)	SMS: Access-based GIS	SMS: Culverts and bridges[6] ADW: Bridges, pavement data, highway lighting, ITS devices, mowable areas, and drainage assets
New Mexico	Road Features Inventory (RFI)	Integrated with Highway Maintenance Management System (HMMS)	Roadway signs, signals, supports and structures for signs, signals and lighting, guardrails, barriers, pavement markings, and pavement treatments
Florida	Roadway Characteristics Inventory (RCI)	TransStat GIS Application Manager with ArcMAP	Roadway signs, signals, lighting, supports and structures, guardrails and barriers, pavement markings and treatments, detectors, etc.

(1) Maryland

The Maryland Department of Transportation State Highway Administration (SHA) is responsible for asset management. Its in-house Access-based GIS Structure Management System (SMS) was first developed to track culverts and bridges, and the final plan was to convert over to an Oracle-based GIS system.[6] While SMS tracked culverts and NBIS-length bridges, it did not predict culvert service life as a part of existing or anticipated deterioration. In 2009, the SHA began to create a repository to maintain asset inventory information that would be easily accessible to business units throughout the SHA.[7] The Asset Management Warehouse (AMW), as this repository became known, was built to provide standard and ad-hoc reports for inventory and condition information. The initial assets incorporated in AMW included bridges, pavement data, highway lighting, ITS devices, mowable areas, and drainage assets, and there were plans to build in brush and tree, line striping, retro-reflective pavement, and rumble strips at a future time.[7]

(2) New Mexico

The New Mexico Department of Transportation (NMDOT) developed the Road Features Inventory (RFI) system, which integrates with the Highway Maintenance Management System (HMMS). HMMS is an interactive planning, budgeting, and reporting tool that supports routine operations of the department, as well as helps NMDOT maintenance supervisors make decisions.[8] RFI uses video and database information to catalog thirty-one types of roadway features. Assets tracked include roadway signs; signals; supports and structures for signs, signals, and lighting; guardrails; barriers; and pavement markings and treatments. The system is used for complete asset management throughout the life cycle of design, installation, inventory, condition, performance monitoring, maintenance, and repair. RFI also includes a "virtual drive" feature that allows engineers to check the condition of a roadway remotely, without leaving their offices.

(3) Florida

Based on our research, the Florida Department of Transportation (FDOT) appears to have the most comprehensive asset data set compared to that of other DOTs. FDOT's asset management system is called the Roadway Characteristics Inventory (RCI) and the Transportation Statistics Office (TransStat) developed it. RCI runs from a TransStat GIS application manager with ArcMap.

RCI is the basis for estimating funding needs for FDOT and is the key management tool for deploying and overseeing contract maintenance and other operation services. The system tracks information for roadway signs, signals, lighting supports and structures, guardrails and barriers, pavement markings and treatments, detectors, and several other point and administrative features.[9] The database also records data on 29 asset features, which are described by 118 characteristics.[8] As of July 2013, RCI was the largest FDOT database, with over 12 million records and growing.[9]

Each state has its own unique needs, which should be considered when developing a risk-based asset management system. While COTS software may work well with one DOT, a built-from-scratch approach may be more appropriate for another. We recommend that MDOT reflect on its own inventory size, system needs, and expectations as it considers how to build its risk-based asset management plan.

III. Methodology

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A. Experimental Design

MDOT provided DMG with a list of twenty-seven assets to address within the scope of this project. These assets are listed in Table 8 and organized into six asset groups. The assets are grouped based on their locations with respect to the roadway and their ability to be located with the same technology. For example, paved shoulder miles and gravel shoulder miles were placed in the roadside asset group because MDOT will use the same technology to measure both shoulder types.

MDOT provided the "Notes/Explanation" column to further clarify what should be measured for each asset. We have modified these to provide further clarity.

Table 8: Assets to Be Evaluated

Asset	Asset Group	Notes/Explanation
Total lane miles	Roadway	Total lane miles, including roadway, ramps; turning flares from the edge of median (EOM) to EOM; and passing lanes from start of taper to end of taper. 1. Add one lane mile for each park and ride lot on the route that is being inventoried. 2. Add 3.2 lane miles for each rest area or weigh station. 3. Add one lane mile from EOM to EOM for roadside parks and scenic turnouts.
Concrete surface lane miles	Roadway	Concrete surface lane miles, including lane miles as above
Bituminous surface lane miles	Roadway	Bituminous surface lane miles, including lane miles as above Note: This category includes concrete base surfaces that have been overlaid with bituminous asphalt
A miles (map miles)	Roadway	From control section atlas
Paved shoulder miles	Roadside	Five foot or wider paved shoulders—measure at 100 percent of length Two to five foot paved shoulders—measure at 50 percent of length
Gravel shoulder miles	Roadside	Miles of gravel shoulders (less than two feet paved); two five 5 foot paved shoulders at 50 percent of length
Curb miles	Roadside	Miles of curb and median barrier lengths, including gaps for approaches
Number of sweepable approaches	Roadside	Number of non-curb paved intersection approaches
Lineal feet of guardrail	Roadside	Lineal feet of guardrail from guardrail inventory

Asset	Asset Group	Notes/Explanation
Number of guardrail endings	Roadside	Number of guardrail endings from guardrail inventory
Number of catch basins	Roadside	Catch basins are defined as “brick or concrete structures with a grate opening at the top for maintenance.”
Number of designated snowmobile crossings	Roadside	Number of designated snowmobile crossings (signed on the trail and/or road)
Number of delineators	Roadside	Number of delineator posts along each shoulder
Number of signs	Roadside	Use the Michigan Traffic Sign Inventory System (MTSIS) count for the route that is being inventoried.
Number of attenuators	Roadside	Number of permanently placed ground-mounted attenuators, regardless of type
Number of bridges	Large assets	Bridges and culverts greater than or equal to ten feet listed in the MDOT Design Division Publication, *State Highway Bridges, Culverts and Grade Separations* (MDOT Report 44 95-98)[2]
Number of tourist facilities	Large assets	Includes rest areas, roadside parks, scenic turnouts, and table sites
Number of pump stations	Large assets	Each location
Number of weigh stations	Large assets	Each permanent, operational weigh station location
Ditch miles	In ROW	For inventory purposes, “a ditch is a lineal depression with a back slope designed to channel water.”
Non-motorized trail	In ROW	Miles designated non-motorized trails, separated from the travel lanes, where maintenance funds are used to perform maintenance
Lineal feet of existing ROW fence	In ROW	Include only right-of-way fence that is currently in place or whose trace can be found
Mowable acres	In ROW	Highways without medians (five to twelve feet); highways with medians (twelve feet); medians less than fifty feet—all; medians greater than or equal to fifty feet–twelve feet; clear vision corners Note: See activity 12600, *Area Mowing Performance Guide,* for acreage calculation
Lineal feet of soundwall	In ROW	Lineal feet of soundwall currently in place, regardless of composition
Number of culverts	Under Roadway	Number of culverts less than ten feet in diameter, including driveway culverts
Number of freeway lights	Overhead	Number of bulbs on poles/towers along freeways and in rest areas and weigh stations
Number of signals	Overhead	Use SAFESTAT signal inventory count for the route that is being inventoried

[2] http://www.michigan.gov/documents/mdot/MDOT_Metro_Regn_Report_44_295622_7.pdf

1. Asset Prioritization

This section describes the approach for determining asset priorities for inventory data collection. The approach outlined in this section could be employed by MDOT for selecting the highest priority assets should MDOT elect to not collect all twenty-seven assets included in this research. The approach is based on information from the AASHTO *Asset Management Data Collection Guide*, which helps identify priorities. The guide was developed in 2006 to provide guidance to transportation agencies for planning and conducting data collection efforts in support of asset management processes, as outlined in the AASHTO *Asset Management Guide* (Volume 1, 2002).

Transportation asset management, in this context, promotes more effective resource allocation and utilization that is based on quality information and data. Asset data needs to support a broad array of DOT functions, activities, and decisions, including:

- Transportation investment policies,
- Institutional relationships between DOTs and other public and private groups,
- Multimodal transportation planning,
- Program development for capital projects and for maintenance and operations
- Delivery of agency programs and services
- Real-time and periodic system monitoring

These functions are listed as a reminder that asset data serves a wide variety of needs. MDOT'S asset data collection efforts in the future should be coordinated with the managers of all these functional areas to ensure that all necessary assets and asset features are obtained in an efficient and timely manner. The asset prioritization metrics are as follows:

1. What is the **quantity and dollar value** of the asset category **relative** to that of the entire asset population?

2. What is the **importance of the asset category** to the agency and road users (e.g., what are the safety, congestion, and environmental impacts of it)?

3. What is the **relative cost of data collection** for each asset within the technology?

4. With **what frequency** will data for this asset category need to be collected?

Table 9 details the scoring levels for each of the metrics and an example of the weighting factors that can be applied. A score of 1 to 5, ranging from Not Important to Very Important, is used to rank the various levels of importance for each metric.

Following is an example of how the scores and weighting factors in Table 9 can be applied to an asset to obtain a weighted score. Assuming that an asset was assigned the following scores for the four metrics, the weighted score would be obtained as follows:

Metric	Score		Weighting Factor		Weighted Score
1	3	x	30%	=	0.90
2	5	x	25%	=	1.25
3	4	x	25%	=	1.00
4	3	x	20%	=	0.60
Asset overall weighted score				=	3.75

The weighted score for an asset is assigned a priority rating as follows:

Weighted Score	Priority Rating
3.01 to 5.00	High
2.01 to 3.00	Medium
1.00 to 2.00	Low

The thresholds for each metric as well as the weighting factors and priority thresholds for the different importance levels are somewhat subjective. These are based on our best judgment, having worked with many different assets for several state DOTs. MDOT may choose to assign different thresholds and weighting factors based on its own consideration of assets and priorities in Michigan. Each metric will be discussed in more detail in the following sections.

Table 9: Priority Scoring Method

Metric	Importance Level	Score	Weight
1. What percentage of the total maintenance budget is spent maintaining the asset?	Not important (less than 0.5%)	1	30%
	Somewhat important (0.5%-5%)	2	
	Moderately important (2%-4%)	3	
	Important (4%-8%)	4	
	Very important (greater than 8%)	5	
2. What is the importance of the asset category to the agency and road users?	Not important to majority of users	1	25%
	Somewhat important	2	
	Moderately important	3	
	Important	4	
	Very important	5	
3. What is the relative cost of remote data collection for each asset within the technology?	Greater than 110%	1	25%
	105%-110%	2	
	85%-105%	3	
	70%-85%	4	
	Less than 70%	5	
4. How frequently will data for this asset category need to be collected?	Very infrequently (e.g., five to ten years)	1	20%
	Infrequently (e.g., two to five years)	2	
	Annually	3	
	Frequently (e.g., quarterly)	4	
	Very frequently (e.g., monthly)	5	
TOTAL			100%

a. Metric 1: Maintenance expenditures

DMG analyzed 2010 MDOT maintenance expenditures for each asset's related maintenance activity to evaluate the relative quantity and dollar value of each asset category. We then ranked each asset category by total maintenance expenditures to demonstrate the relative quantity and dollar value of the assets. Table 10 illustrates the results of this analysis. Bituminous (asphalt) and concrete pavement repairs are difficult to separate based on activity codes. To address this, we split total pavement expenditures based on the percent of total lane miles for each pavement type. Asphalt pavement accounts for approximately 80 percent of total lane miles in the state, while concrete pavement accounts for 20 percent of lane miles. We also split maintenance activity costs for paved and gravel shoulders, as well as for signs and signals. Finally, there was no related maintenance activity for sound wall assets. As a result, we assigned it $0.00 and placed it at the bottom of the rankings. Metric 1 carries a 30 percent weighting factor for the final asset prioritization scores.

Table 10: MDOT Maintenance Expenditures by Asset

Asset	Asset Group	Annual Maintenance Expense in Dollars (2010)
Bituminous surface lane miles	Roadway	$14,317,090
Number of bridges	Large assets	$9,206,185
Number of tourist facilities	Large assets	$7,602,608
Number of signals	Overhead	$5,957,803
Number of freeway lights	Overhead	$5,478,819
Gravel shoulder miles	Roadside	$4,891,855
Mowable acres	In ROW	$4,748,301
Number of culverts	Under roadway	$4,530,601
Number of catch basins	Roadside	$4,142,795
Number of signs	Roadside	$3,767,368
Lineal feet of guardrail	Roadside	$3,650,723
Concrete surface lane miles	Roadway	$3,579,273
Number of sweepable approaches	Roadside	$2,991,744
Paved shoulder miles	Roadside	$2,449,067
Number of pump stations	Large assets	$1,558,357

Asset	Asset Group	Annual Maintenance Expense in Dollars (2010)
Curb miles	Roadside	$1,498,180
Ditch miles	In ROW	$1,492,956
Number of attenuators	Roadside	$857,427
Lineal feet of existing ROW fence	In ROW	$799,423
Number of delineators	Roadside	$502,744
Number of guardrail endings	Roadside	$243,832
Number of designated snowmobile crossings	Roadside	$70,511
Number of weigh stations	Large assets	$35,831
Non-motorized trail	In ROW	$329
Lineal feet of sound wall	In ROW	$0
Total		**$84,373,822**

b. Metric 2: Importance of asset to the agency and road users

We used results from a 2011 Alabama DOT report, developed by DMG, as the basis for Metric 2. It is assumed that the relative importance of assets is fairly standard across state DOTs. For example, safety devices are of high importance across all states, while items like fences and litter control are generally of lesser importance, for both the agencies and the public. Updates to the asset prioritization process were made based on the unique characteristics of Michigan highways (e.g., designated snowmobile crossings). The scores serve as a guide and can be edited to meet MDOT's needs. Metric 2 carries a 25 percent weighting factor for the final asset prioritization scores.

c. Metric 3: Relative data collection costs

Metric 3 rates the relative costs associated with remote data collection for each asset within each technology. Because some technologies cost more than others for the extraction of any asset, DMG designed a method to discern the relative cost of extracting one asset to another within the same technology. By comparing the additional cost to extract each asset to the average cost to extract each asset within that same technology, the extraction costs of each asset could be normalized for comparison across assets. Because the fixed portion of the collection/extraction process would be the same, no matter what asset or assets are chosen for evaluation, those costs have been left out of the comparison for Metric 3.

Table 11 provides an explanation of the process used to normalize costs. Each of the four assets below is listed with an extraction cost per mile (these costs would be specific for each technology). The average cost to extract each asset is the average of the values in the second column, or $10 per mile. The third column shows the cost to collect each specific asset as a percentage of the overall average.

For example, Asset 2's extraction cost divided by the average extraction cost, expressed as a percentage, is: **$12 * 100 / $10 = 120%.**

Table 11: Relative Costs for Mobile Data Extraction–Example

Asset Type	Extraction Cost per Mile (Dollars)	Relative Cost (Percent of Average Cost)
Asset 1	$8	80%
Asset 2	$12	120%
Asset 3	$15	150%
Asset 4	$5	50%
Average Cost	**$10**	

The percentages can be compared directly once the relative cost has been calculated as a percent of the average cost for each asset across each technology. If one asset has an average relative cost of 150 percent, for example, that would mean that for all technologies, on average, extraction costs for that asset are 150 percent of the average cost. In this case, Asset 3 would receive a low rating because of its relatively high extraction costs.

Finally, we organized the assets into five priority levels, based on the percentage of average extraction costs. The costs were based on the data extraction costs experienced during the pilot for this project. See Table 12 for the complete rankings. Metric 3 carries a 25 percent weighting factor for the final asset prioritization scores.

Table 12: Normalized Remote Data Extraction Costs

Asset	Percent of Average Extraction Cost	Comment	Importance Score
Number of designated snowmobile crossings	43.90%	Only mobile imaging	**5** (less than70%)
Total lane miles	68.15%		
Concrete surface lane miles	68.15%		
Bituminous surface lane miles	81.68%		**4** (70%-85%)
A miles (map miles)	81.68%		
Number of guardrail endings	81.70%		
Ditch miles	81.70%		
Number of bridges	95.35%		**3** (85%-105%)
Number of attenuators	98.17%		
Paved shoulder miles	98.60%		
Gravel shoulder miles	98.60%		
Curb miles	102.84%		
Lineal feet of guardrail	102.84%		
Number of delineators	103.65%		
Number of signals	103.65%		
Non-motorized trail	105.34%		**2** (105%-110%)
Number of pump stations	106.32%		
Number of weigh stations	106.32%		
Number of sweepable approaches	107.38%		
Number of signs	109.14%		
Lineal feet of existing ROW fence	113.82%		**1** (greater than 110%)
Mowable acres	114.78%		
Number of tourist facilities	114.78%		
Lineal feet of sound wall	114.78%		
Number of catch basins	115.99%		
Number of culverts	116.61%		
Number of freeway lights	153.66%	Only mobile imaging	

d. Metric 4: Data collection frequency required

Metric 4 estimates the frequency that data for the asset needs to be collected. Similar to the process used for Metric 2, DMG used the results from the 2011 Alabama DOT report for MDOT assets. A five-point scale was used, as follows:

1 = Very infrequent (every 5 to 10 years)

2 = Infrequent (every 2 to 5 years)

3 = Annually

4 = Frequent (quarterly)

5 = Very frequent (monthly)

These scores serve as a guide and can be updated to meet MDOT's needs. Metric 4 carries a 20 percent weighting factor for the final asset prioritization scores.

e. Application of the prioritization process

The twenty-seven selected assets were evaluated based on these four metrics, and were assigned a score of between one and five for each metric, where one denotes the lowest level of importance and five denotes the highest level of importance. We calculated a weighted average to determine the final score for each asset category, which we then used to identify whether the asset is considered high, medium, or low priority. Weighted scores between 3.01 and 5.00 are classified as high priority. Scores between 2.01 and 3.00 are classified as medium priority. Scores of 2.0 or below are classified as low priority.

The results of the asset priority ratings are shown in Table 13. Most of the safety-related assets received high ratings, while non-motorized trails, fences, and sound walls received low ratings.

To illustrate how the priority ratings in Table 13 were derived, the weighed score for Total Lane Miles was calculated as follows, using the weighting factors from Table 9:

$$5 * 0.30 + 4 * 0.25 + 5 * 0.25 + 4 * 0.20 = 4.55$$

The weighted score of 4.55 falls in the range of 3.01 to 5.0, so this asset received a High priority rating.

Table 13: Asset Priority Ratings

Asset Group	Asset Category	Scores for Each Metric					Priority Rating		
		1	2	3	4	Weighted Average	High 3.01-5.0	Medium 2.01-3.0	Low <=2.0
Roadway	Total lane miles	5	4	5	4	4.55	X		
	Concrete surface lane miles	3	4	5	4	3.95	X		
	Bituminous surface lane miles	5	4	4	4	4.3	X		
	A miles (map miles)	5	4	4	4	4.3	X		
Roadside	Paved shoulder miles	3	3	3	1	2.6		X	
	Gravel shoulder miles	4	3	3	1	2.9		X	
	Curb miles	2	2	3	2	2.25		X	
	Number of sweepable approaches	3	3	2	3	2.75		X	
	Lineal feet of guardrail	3	3	3	4	3.2	X		
	Number of guardrail endings	1	4	4	4	3.1	X		
	Number of catch basins	3	2	1	2	2.05		X	
	Number of designated snowmobile crossings	1	1	5	2	2.2		X	
	Number of delineators	1	3	3	3	2.4		X	
	Number of signs	3	4	2	3	3.0		X	
	Number of attenuators	2	4	3	4	3.15	X		
Large Assets	Number of bridges	4	4	3	3	3.55	X		
	Number of tourist facilities	4	3	1	3	2.8		X	
	Number of pump stations	2	3	2	3	2.45		X	
	Number of weigh stations	1	3	2	3	2.15		X	
Under Roadway	Number of culverts	3	3	1	3	2.5		X	
In ROW	Ditch miles	2	3	4	3	2.95		X	
	Non-motorized trail	1	1	2	2	1.45			X
	Lineal feet of existing ROW fence	2	1	1	2	1.5			X
	Mowable acres	3	3	1	3	2.5		X	
	Lineal feet of sound wall	1	1	1	2	1.2			X
Overhead	Number of freeway lights	4	2	1	2	2.35		X	
	Number of signals	4	4	3	3	3.55	X		

2. Proposed Pilot Project Route

Due to another research effort on the I-94 corridor, DMG developed a revised route for the pilot that included multiple road functional classes. The initial route measured 125 miles in each direction along I-94 in southwest Michigan, for a total of 250 test miles. The alternate route was comprised of 176 miles. It was a priority to keep data collection costs unchanged when selecting the new route.

The new route included a significant portion of non-interstate roadway. As a result, assets were more densely located within the regions, which increased the cost per mile of data collection. To maintain the proposed project budget, the new route was made to be approximately 200 centerline miles long. Divided highways were counted twice: once for each pass required for data collection. The classifications of the roadways included in the pilot route are separated by National Functional Classification (NFC) in Table 14 below.

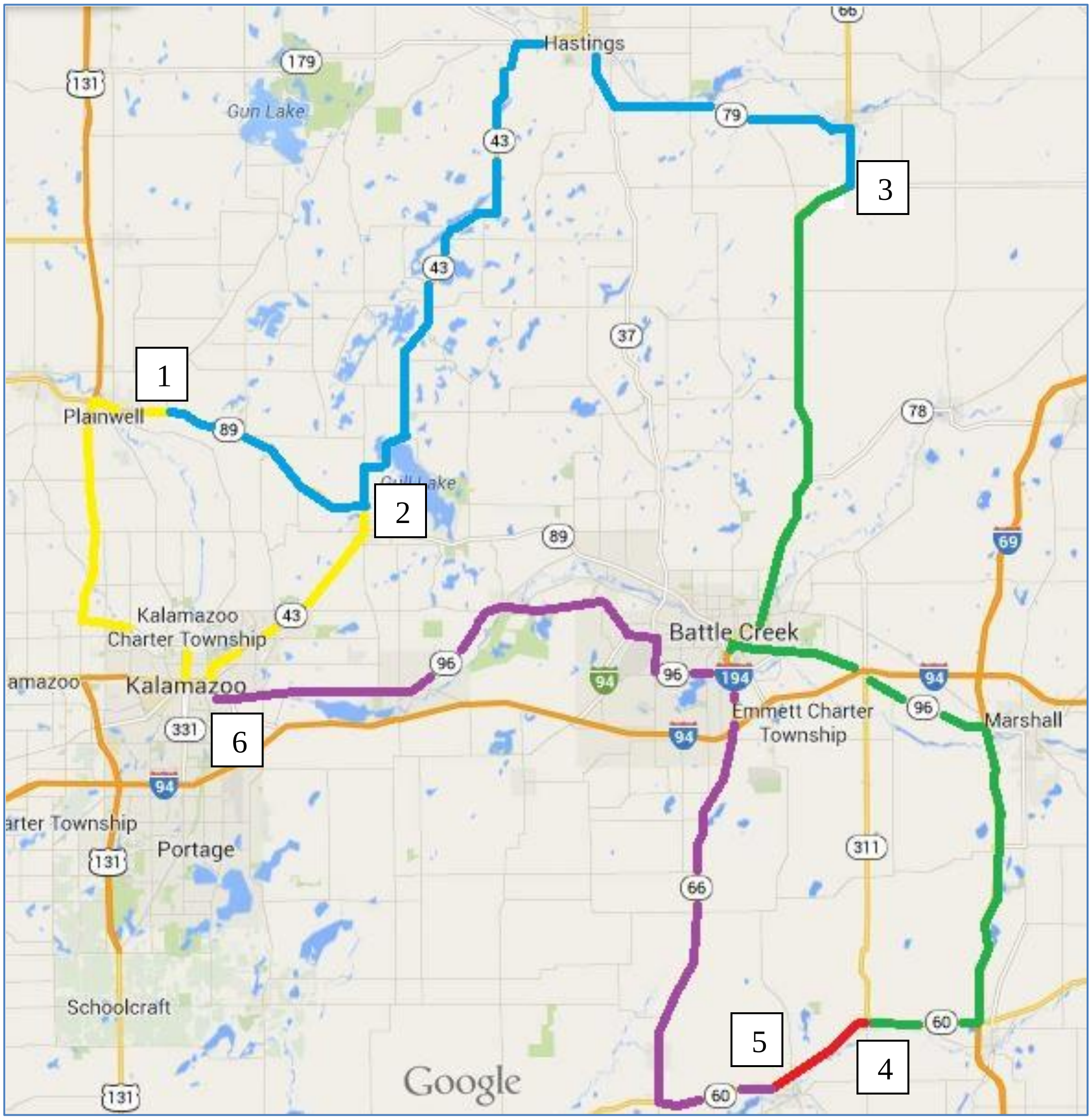
Table 14: Breakdown of Pilot Study Route by NFC

Classification	Approximate Mileage
Principal arterials (NFC 1)	11
Minor arterials (NFC 2)	13
Collectors (NFC 3)	22
Local roads (NFC 4)	130
Total	**176**

The routes for each of the technologies are identified in Figure 1as:

- Yellow: Manual data collection – from box 1 to box 2 (26.2 miles)
- Blue: Fugro mobile imaging – from box 1 to box 3 (47.5 miles)
- Green: Aerometric mobile LiDAR – from box 3 to box 4 (47.5 miles)
- Purple: Aerometric helicopter LiDAR – from box 5 to box 6 (50 miles)
- Red: Technology overlap – from box 4 to box 5 (All technologies for 5 miles)

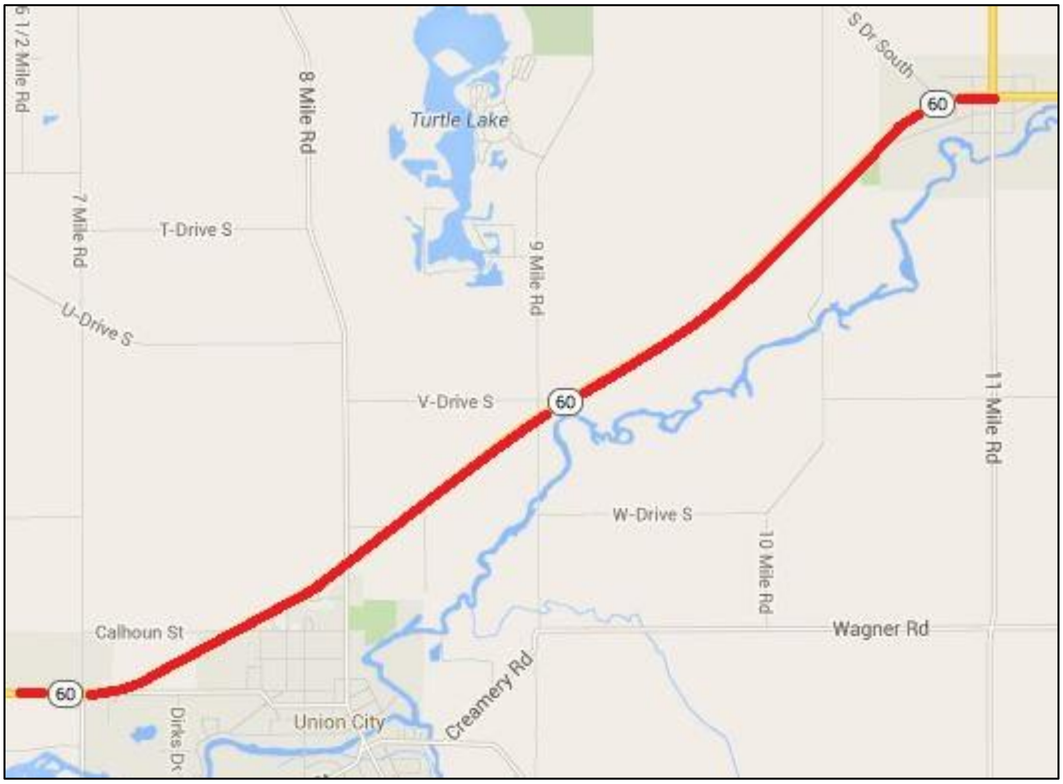
Figure 1: Map of Pilot Study Route (All 5 sections)–Southwestern Michigan



3. Technology Overlap Section

To verify and compare the accuracy of each data collection method, DMG identified a five mile portion of the pilot route, known as the "technology overlap" section. DMG collected asset inventory data along the route and directly compared these results with those obtained by means of the remote technology methods. Figure 2 details the route followed during data collection.

Figure 2: Five Mile Technology Overlap Route



B. Equipment

1. Manual Data Collection

DMG selected the Garmin Dakota 20 global positioning system (GPS) device to locate the assets because it is a lightweight, waterproof field navigation device that has an advertised accuracy of five feet. The GPS device allowed for relatively quick data entry and adequate durability for the field. DMG also utilized two range finder devices to help measure lengths and distances of and between assets:

- Bushnell Yardage Pro Sport 450 Laser Rangefinder
- Bushnell Medalist Laser Rangefinder

A web-based mapping source was useful throughout the entire collection process. In order to obtain a visual account of the route, we used publicly-available mapping data to virtually “drive” the route prior to going into the field. This analysis helped us to plan our approach for each section of the manual collection route. The virtual drive also allowed us to estimate the amount of each asset we would encounter, which helped us to plan the most efficient data collection methods. This analysis also allowed us to identify any possible interference that could affect the collection process, including hazardous areas of the road that could pose safety concerns; obstructions, such as large bridges and overpasses, which could make some assets too difficult to locate and reach; and areas with limited shoulder space, which would make manual data collection difficult.

2. Fugro Roadware (Fugro)

Fugro utilized Automatic Road Analyzers (ARAN) vehicle to gather pictures of the roadway that are taken at set intervals approximately every twenty-one feet. Information obtained from the mobile images included the type and location of point, linear, and area assets. Inventory data can be pulled, as needed, from the photo records, or the entire file can be processed for a roadway inventory scan.

3. AeroMetric (Quantum Spatial)

AeroMetric (now Quantum Spatial) used a mobile asset collection (MAC) vehicle that utilized mobile LiDAR and right-of-way (ROW) imaging to collect mobile image data. The LiDAR system AeroMetric utilized was a Riegl VMX-450 mobile LiDAR unit capable of scanning 1.1 million points per second while traveling at highway speeds.

AeroMetric's helicopter-based LiDAR system consists of a Riegl VQ-480i laser scanner, a phase one iXA 80 megapixel digital back with a 55mm lens, and a Trimble AP50 GNSS-Inertial original equipment manufacturer board on a rotating turret mount that allows the system to automatically compensate for drift while it acquires the digital data. AeroMetric utilizes a Track'Air GPS guidance system to overlay the precise flight line vectors by importing the centerline shapefile relevant to the project corridor.

C. Procedures

1. Manual Data Collection

DMG utilized manual data collection methods to establish an accurate inventory on a 31.2 mile portion of the pilot route. Because of the amount of time needed to collect the required assets along the entire thirty-one miles, we divided the collection process into multiple trips. During this process, we collected readily-observable condition data for the assets. However, our focus was to establish an accurate inventory count for each of the twenty-seven asset types that MDOT defined.

The planning process for the manual collection phase of the pilot survey began several months before we began collecting data on the pilot route. Our preparation included multiple steps: first, we used a web-based mapping tool to virtually drive the route and determined how to divide the route into daily collection segments; second, we tested and validated the accuracy of our measurement equipment; third, we again used a web-based mapping tool to categorize all of the assets that we would encounter across the route; fourth, we prepared for procedures in the field; and fifth, we took steps to ensure safety throughout the entire process.

As mentioned above, we thoroughly tested the measurement equipment we used to collect data in the field. In order to verify the advertised accuracy, we conducted a field assessment in urban and rural environments. As a result of these tests, we were able to establish a general accuracy baseline for the device, as well as to analyze the effects that possible interferences, such as trees and large buildings, could have on the GPS' accuracy. The device did, at times, show some inconsistencies during testing, as shown in Table 15; it sometimes erred by as much as fifty feet on one test waypoint. However, we concluded that the error was due to the device's proximity to large buildings. Given the lack of large buildings along the pilot route, we determined that the device was sufficient for the requirements of our survey, since only proximity—not exact location—was required.

We also tested the range finders, which use a laser to measure the distance between the unit and an object. We measured a range of distances to validate the accuracy of the device. The range finder was fairly accurate at distances up to 500 feet and erred by 5 percent or less during testing. The accuracy increased proportionally with the distance measured. We used this device sparingly during our actual data collection process, but it served as a back-up if safety issues or obstacles in the roadway prevented us from manually measuring certain linear assets.

Table 15: GPS and Range Finder Accuracy Test

Test Number	GPS Measure (Feet)	Measuring Wheel (Feet)	GPS Percent of Error	Rangefinder Measure (Feet)	Range Finder Percent of Error	Comments/ Notes
1	95.54	100	4.47	105	5	Rural
2	230.49	250	7.81	258	3.2	Rural
3	495.30	500	0.94	504	0.8	Rural
4	115.80	100	15.80	99	1	Urban
5	223.12	250	10.75	243	2.8	Urban
6	450.75	500	9.85	498	0.4	Urban

Table 15 shows the results of the measuring device accuracy test. The pilot route runs through both rural and urban settings, so we elected to test the devices in both settings. We used a measuring wheel to mark off distances of 100, 250, and 500 feet. At the starting location, as well as at each of these distances, we recorded a waypoint with the GPS. In addition, we took measurements with the range finder at each of the three distances. We then uploaded the GPS waypoints into a web-based mapping tool, and we compared the distances between the points to the measuring wheel results.

In order to fully understand the implications of the errors, we evaluated the magnitude of the errors in feet, as well as a percentage of the total length. We divided the length of error by the total length of the measurement to calculate the percent error. We observed a higher degree of error in urban settings, most likely due to interference of large structures. We recommend that MDOT personnel verify that the surrounding buildings do not interfere with the GPS signal before performing the same exercise.

The third step of the process was to use a web-based mapping tool to locate all "large" categorized assets across the entire length of the route. These assets were bridges, tourist facilities, pump stations, rest areas, and weigh stations. Since the assets were permanent and readily visible in a web-based mapping tool, we determined that it would save time to locate all large assets across the 186 mile pilot survey using a manual approach rather than a remote technology. We marked and recorded the GPS coordinates for these assets on a web-based mapping program, which allowed us to quickly locate and validate these assets in the field.

The use of a web-based publicly-available mapping tool would be beneficial to MDOT. It will save time, because MDOT personnel can collect the coordinates on the assets without having to enter the field, thus reducing worker exposure. Also, most of the identified priority assets are not likely to change between the dates that the web-based images were taken and our collection date.

During the fourth step of the planning process, we:

1. Examined manual collection methods we used previously in other state DOTs to refine our MDOT manual process.
2. Leveraged a web-based mapping tool to review previous estimates of our daily routes, which provided a rough estimate of the hours needed in the field. We estimated that our crew needed eight hours to complete five to seven miles daily.

We thoroughly considered possible delay factors, such as safety hazards, weather obstacles, and traffic delays, in order to ensure that we maximized our time in the field and prevented unnecessary delays.

During the fifth and final step of this process, we planned for and addressed safety concerns. To ensure a safe working environment, we equipped our vehicle with a rotating strobe light bar and our team wore proper winter field attire and American National Standards Institute (ANSI) Class 3 vests to ensure maximum visibility. We also checked that we had the proper equipment, including a safety light bar, traffic cones, survey marking paint, a first aid kit, a twenty-five foot measuring tape, a range finder, a laptop and charger, a measuring wheel, a flash light, and a digital camera with GPS.

2. Field Data Collection: Execution

MDOT provided DMG with a list of twenty-seven assets to collect during this project. We categorized these assets as point assets, linear assets, and area assets. Below are the steps we took to collect the data for each type of asset.

3. Manual Asset Data Collection Process

We completed the majority of the manual collection process on foot in order to ensure the most accuracy. However, it was often most practical to complete the data collection from a vehicle. We conducted the vast majority of the collection from a vehicle on a fourteen mile stretch of US Highway 131 for two reasons. First, there was a relatively low density of assets in this section, so we were able to use resources more efficiently from a vehicle. Second, it is a divided highway with a high traffic volume and limited shoulder space in which to park a vehicle safely. To collect data while in the vehicle, we drove on the shoulder at a safe speed and stopped at each asset. While one team member drove, the other two team members recorded the waypoints on both sides of the road.

a. Point assets

Point assets include items such as bridges and culverts. We used a common method of data collection for nearly all point assets. To begin the process, the inspector positioned him or herself as close to the assets as possible; for example, the collector sometimes stood on a catch basin or directly under a freeway light. Once positioned, we saved the coordinates of the asset as a waypoint in the handheld GPS. We named each waypoint with an asset abbreviation. We also gave a quantity after the abbreviation for some assets in order to account for single locations with multiple assets. For example, if one pole had two signs, we named it “SG-2.”

The collector’s proximity to an asset depended on the asset’s location and how safely one could stand next to it. Certain assets, such as culverts, were located off the roadway and therefore a collector could not always be in close. In such cases, we marked the waypoint at the nearest possible point. Other assets, such as signs, were located in the median of the freeway, and also presented safety concerns. Since only an approximate location was required for the purpose of this data collection survey, we marked these assets at a point on the opposite side of the freeway, directly parallel to the asset.

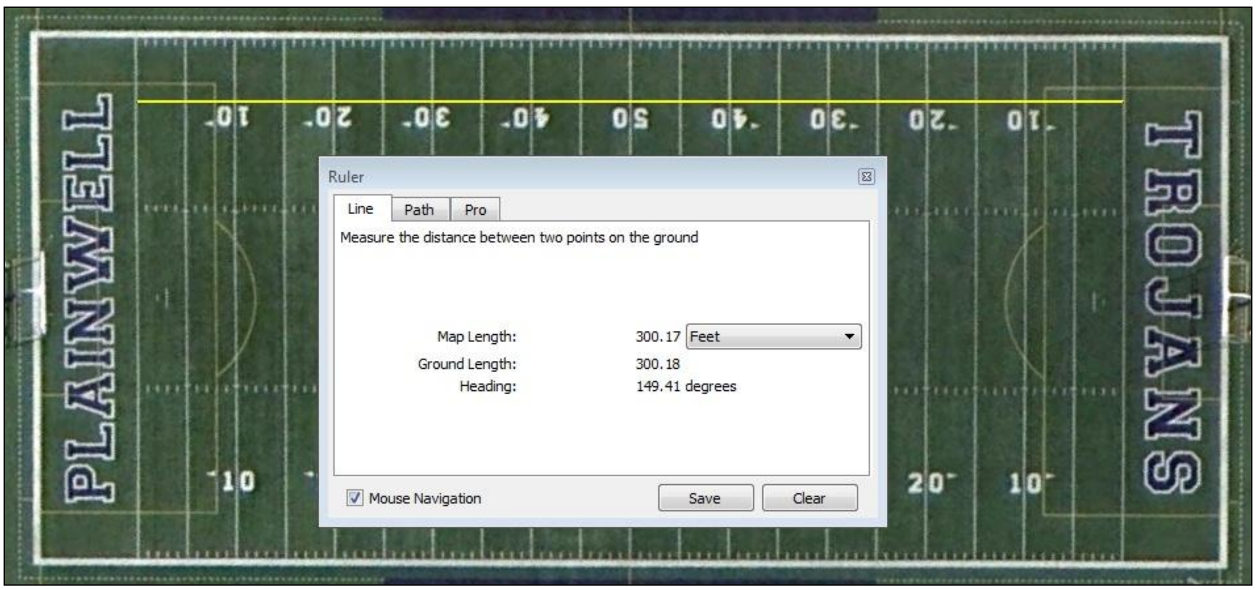
b. Linear assets

MDOT requested that we measure several linear assets, including concrete surface lane miles and linear feet of guardrail. For all linear assets, we used the GPS device to collect data, in order to determine the assets’ lengths. We marked a waypoint at the ends of the asset to collect data for ditches, paved shoulders, gravel shoulders, bituminous surface, roadway, and concrete roadway. We numbered each linear asset’s corresponding waypoints the same so that we could match the data points once uploaded to the data file. We gave the waypoint for each individual asset length corresponding numbers, after the abbreviated name, so that we could pair the data points together to calculate the asset’s length.

For example, one segment of a ditch had two different waypoints, both named “DM2.” Guardrail was similar to those previous assets, but had waypoints specified as “GRS” for guardrail start and “GRP” for guardrail stop. We specified guardrail assets this way in order to distinguish the start and stop points of the guardrail length from the point asset, “GRE,” which identified guardrail endings. To collect data for non-motorized trail and curbs, we traversed the entire length of the asset and periodically marked waypoints every few hundred feet. We then uploaded the data into a Microsoft Excel file to calculate the distances between waypoints, in order to determine the total length of the asset.

Finally, we uploaded the waypoints into a web-based mapping tool, which created a trail of points that we then connected and verified with the web-based mapping tool's path tool. As shown in Figure 3, a web-based mapping tool's linear measurement tool provides a high degree of accuracy. The tool measured the length of the football field in Plainwell, Michigan (along the pilot route), within a 0.06 percent degree of error.

Figure 3: Web-based Mapping Tool Screen Capture, Length Tool Accuracy



We had a greater degree of accuracy when we used the handheld GPS device to mark waypoints to measure distances than when we used the range finder to measure the distances because the range finder only measures straight distances. It was necessary for us to measure several points along most linear assets, due to curves and changes in the direction of the roadway. This method was also more practical than using a measuring wheel, which has limitations in certain settings, such as in steep areas or rough terrain. This method also expedited and simplified the data collection process. The collection process was improved by the use of this method because only one team member needed to drive while another member marked waypoints.

c. Area assets

MDOT defined mowable area for the shoulder and the median by one of two categories, based on measurement. For medians with a width greater than fifty feet, we measured the mowable area's square footage as twelve feet into the median on both sides of the roadway. For medians less than fifty feet in width, we measured the total width of the median and multiplied by the full length of the mowable area. We used the following assumptions to determine which area of the route was mowable:

- Mowable area needed to have a minimum width of twelve feet to allow enough room for the use of mowing equipment.
- Mowable area could not be located adjacent to guard rail, as the guardrail would prevent mowing
- Vegetation within the boundaries of a residential or commercial property was assumed to be maintained by the property owner, and as such was not considered mowable. This included the majority of suburban areas.
- Clear, flat areas between the shoulder and farm land was considered mowable.

The majority of the mowable area was found to be located on the rural portions of the route and on divided highways, which with the addition of the shoulder, had mowable area located within the median. With the exception of the area within the median, the mowable acres were calculated with an assumed mowed width of twelve feet multiplied by the length of the section.

It was necessary to use a combination of field work and a web-based mapping tool to collect the data, due to the fact that a significant portion of the mowable area was located on the divided highway US 131. Due to safety concerns, we were often unable to access and measure the area within the median. We therefore collected data by first driving the eleven mile stretch of the highway and then using a visual estimate to determine which sections were less than fifty feet wide. We marked all mowable areas' starting and ending points with the GPS and then transferred and plotted them on a web-based mapping tool to determine the total square footage.

To validate our data, we used a fee-based advanced measuring tool to verify the marked mowable area and to measure each section. Google Earth Pro is one tool that offers this functionality and costs $400 per year, per user account. These tools can draw a polygon around the entire mowable area, which provides a more exact measurement. Since cost is an important consideration, it should be noted that we only used Google Earth Pro to validate our results and that it is not required to execute our collection method.

While most of the assets are defined in a self-evident manner, for a few of the assets, we needed to further define clarifications and assumptions. Each of these assets is further defined in the following bullets.

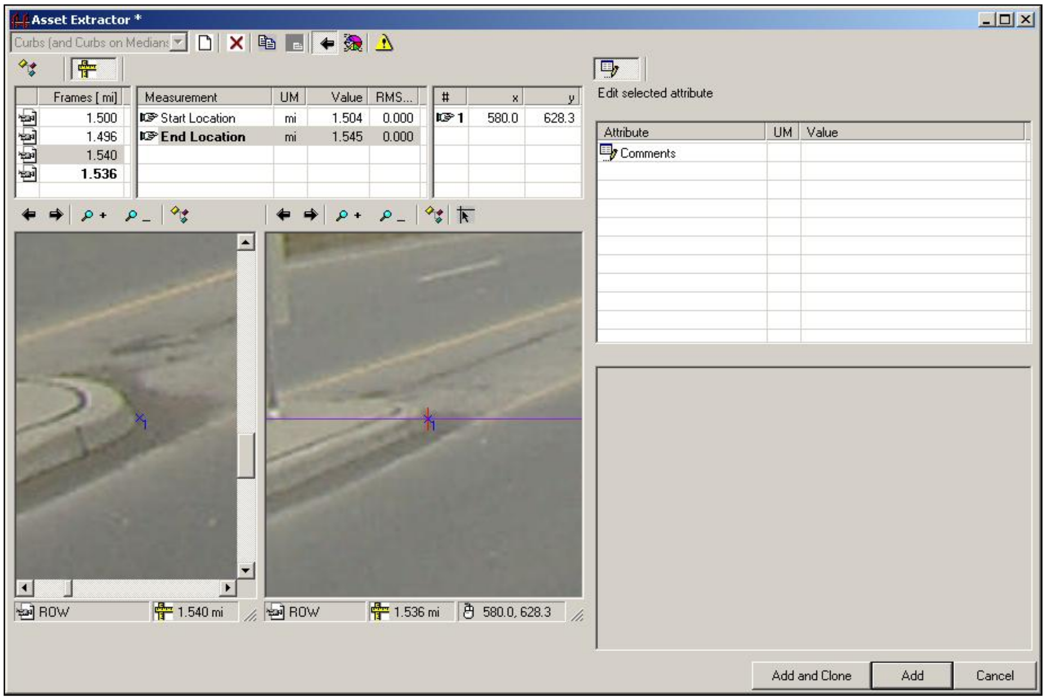
- "A" miles are route miles, or centerline miles. This value is independent of the number of lanes on a given route, and is only dependent on the length of the route, which is determined by looking at the route on a map.

- We recorded a waypoint at any point where the roadway changed number of lanes or material in order to measure bituminous surface lane miles and concrete surface lane miles. For example, at the beginning of a route, the roadway may have two asphalt lanes, in which case we labeled the waypoint “BM-2” to represent two lanes of bituminous surface. Where that route changed to three lanes, we marked a waypoint at the end of the two-lane portion, “BM-2,” and another point adjacent to that one called “BM-3.” To calculate the lane miles, we measured the distance between like points, “BM-2,” for example, and then multiplied the length by the number of lanes.
- Shoulders exist adjacent to the travelling lane and provide support to the roadway structure. When the entire width of the shoulder is paved or gravel, it is easy to identify as “paved shoulder” or “gravel shoulder.” However, for situations where the shoulder is part asphalt and part gravel, MDOT provided clear definitions. If the paved portion was less than two feet wide, we considered the shoulder a full gravel shoulder. If the width of the paved section was greater than five feet, we considered the shoulder a full paved shoulder. If the paved portion fell between two and five feet, we counted the length as 50 percent paved and 50 percent gravel.
- MDOT defined mowable area for the shoulder as a twelve foot width that extends along the road, wherever vegetation is present and able to be mowed. The defined mowable area of the median falls into two categories, based on measurement. For medians greater than fifty feet in width, the square footage is measured twelve feet extended on both inside edges of the median. For medians with widths less than fifty feet, we measured the mowable area as the entire width of the median.
- We counted signs and signals separately. Within the signal count, there were 116 crosswalk signals. We included crosswalk signals in the signals count, since maintenance on these is more similar to that of signals than signs.
- We counted the number of sign faces, not the number of sign posts.

4. Fugro

DMG contracted with Fugro Roadware to provide mobile imaging data collection services for the pilot route. As noted previously, information obtained from the mobile imaging includes the type and location of point, linear, and area assets. Inventory data can be pulled as needed from the photo records, or the entire file can be processed for a roadway inventory scan. See Figure 4 for a screenshot from Fugro’s asset extraction program. The two separate images allow the user to simultaneously zoom in on different points within the same image. Figure 5 provides a sample mage from the photo records.

Figure 4: Screenshot from Fugro Asset Extraction Program–Curbs



Fugro collected asset inventories on seventeen MDOT highway assets. Point assets include catch basins/drop inlets, crash attenuators, delineators, signs, sweepable approaches, and traffic signals. Linear assets include curbs, ditches, guardrail, concrete lane miles, bituminous lane miles, ROW fencing, and shoulders. Lastly, MDOT requested data on mowable acres.

Figure 5: Fugro ROW Fence Image from MDOT Data Collection Project

5. AeroMetric

DMG contracted with AeroMetric to provide mobile imaging and helicopter-based LiDAR data collection services for the pilot route. The ROW cameras were triggered at a distance of 13.1 feet (0.0025-mile) and were configured to cover the front and rear of the vehicle's travel. The LiDAR and imaging were collected simultaneously and integrated with a distance measuring instrument (DMI), inertial measurement unit (IMU), and on-board computers to record all measurements in real-time. Figure 6 provides a sample image from AeroMetric's mobile image data collection. Note: AeroMetric did not generate LiDAR images for this project.

Figure 6: ROW Image from AeroMetric's Mobile Image Data Collection

AeroMetric's aerial LiDAR incorporates flight plans to help the pilot and sensor operators to accurately track the center lines of the proposed flight paths. The area was flown at an altitude of 900 feet above ground level (AGL), and the imaging was acquired at a resolution of approximately one inch and the LiDAR at a density of approximately sixteen points per meter (ppm) square. This dual geospatial solution allows for easy identification of the appropriate ground features, as required.

AeroMetric acquired approximately fifty control points to validate the accuracy of both geospatial solutions. They used aerotriangulation to densify the project survey, in order to support the orthophoto rectification process. The aerotriangulation process combines the Airborne GPS and IMU data with ground control data to sufficiently cover each stereo model with accurate control for mapping purposes. The process leverages specialized software that accounts for the shape and distortion of the particular camera lens, as well as target datum and project coordinate system. Horizontal and vertical ground control points collected throughout the project area were identified on their respective aerial images. AeroMetric's aerotriangulation analysts worked to identify at least six additional points per stereo that can be located on the adjacent images.

AeroMetric utilizes Z/I Imaging's ImageStation Automatic Triangulation (ISAT) package. The software computes an aerotriangulation solution in which coordinates are assigned to all identified points based upon the X, Y, and Z values of the ground control points and the X, Y, and Z locations of the camera sensor at each moment of exposure. The analysts then tested the solution against other known ground control points, called check points, to evaluate the accuracy of the solution. When an acceptable level of error, defined as an average root mean square error (RMSE), is reached, the solution is accepted and applied to the entire block of photographs. Each control point and pass point had acceptable X, Y, and Z values in the project coordinate system.

Figure 7: Image from AeroMetric's Helicopter LiDAR Data Collection

AeroMetric collected asset inventories on seventeen MDOT highway assets. Point assets include catch basins/drop inlets, crash attenuators, delineators, signs, sweepable approaches, and traffic signals. Linear assets include curbs, ditches, guardrail, concrete lane miles, bituminous lane miles, ROW fencing, and shoulders. Lastly, MDOT requested data on mowable acres.

IV. Findings

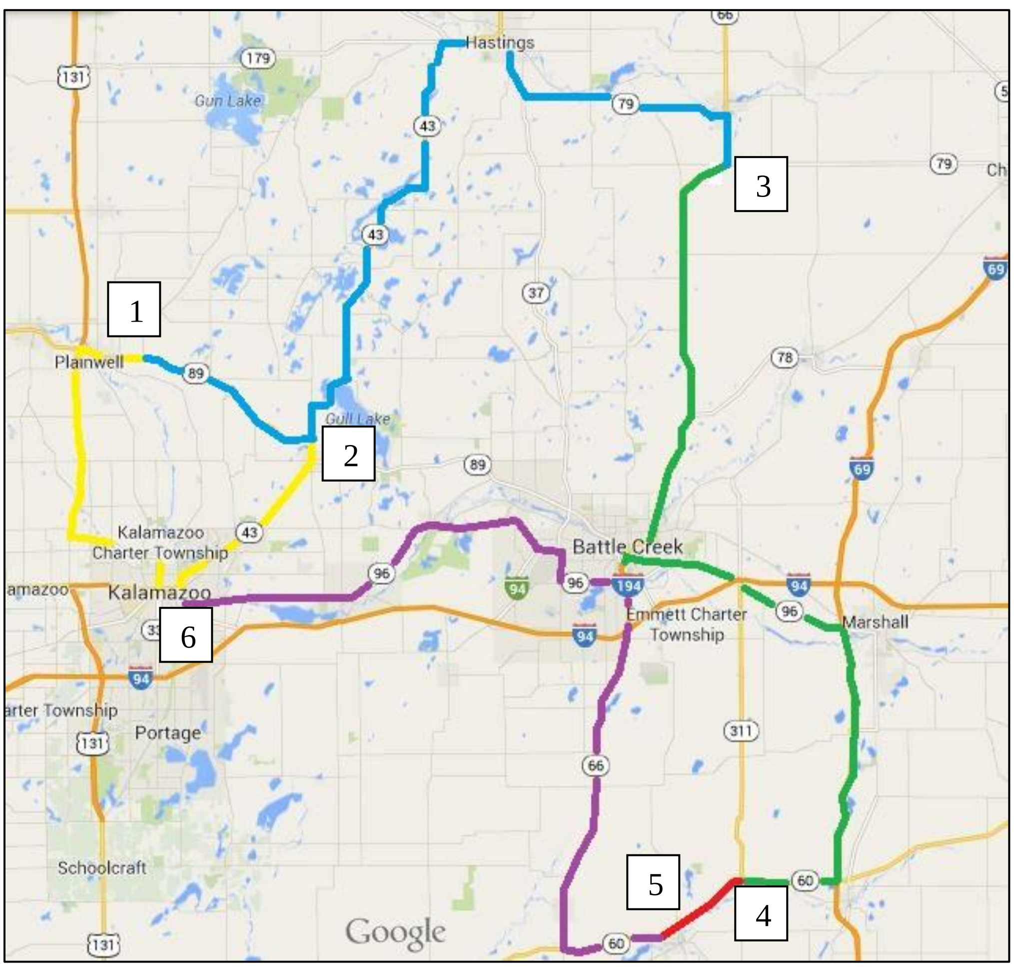
■

The following section summarizes the pilot results from each of the methods of data collection. Results include the asset inventories from the pilot route, as well as from the technology overlap section.

The routes for each of the technologies are identified in Figure 8 as:

- Yellow: Manual data collection – from box 1 to box 2 (26.2 miles)
- Blue: Fugro mobile imaging – from box 1 to box 3 (47.5 miles)
- Green: Aerometric mobile LiDAR – from box 3 to box 4 (47.5 miles)
- Purple: Aerometric helicopter LiDAR – from box 5 to box 6 (50 miles)
- Red: Technology overlap – from box 4 to box 5 (All technologies for 5 miles)

Figure 8: Map of Pilot Study Route – Southwestern Michigan



In addition to presenting how we collected data using each of the three selected methods, this section also assesses each method considering not only efficiency, but also effectiveness. Data is helpful only if it is provided to MDOT in a meaningful way. For example, one of MDOT's tasks is to collect guardrail data. In addition to collecting a guardrail segment's "start" and "stop" points, the person or tool that collects the information must also calculate the distance between the two points. MDOT is interested in the guardrail length; the "start" and "stop" points alone are not helpful. MDOT embarked upon this project to lower risk, worker exposure, and address the challenge of fulfilling its duties with a reduced workforce. To meet these goals, MDOT must consider which technology provides data in the most useful manner, rather than merely the fastest or least expensive.

A. Manual Data Collection (performed by DMG)

1. Summary of Data Collected

DMG manually collected asset data along two distinct segments of the overall route. The first section was a 26.2 mile continuous route, shown Figure 9. The second section includes results from a five mile segment of roadway used to verify the results of each technology, referred to as the "technology overlap" portion of the route. This section presents the results of data collection from the 26.2 mile continuous route, the results from the five mile overlap section, and the combined summary. The results from the technology overlap route are discussed in further detail in a subsequent section. The 26.2 mile route included 132.33 total lane miles; 76.08 concrete lane miles (57 percent); and 56.25 bituminous lane miles (43 percent). DMG identified nearly 39,000 feet (approximately 7.39 miles) of guardrail, over 24,400 feet (4.62 miles) of non-motorized trail, and 12.21 and 40.9 miles of gravel and paved shoulder, respectively (see Table 16).

The manual data collection process resulted in several notable results and observations from field experience:

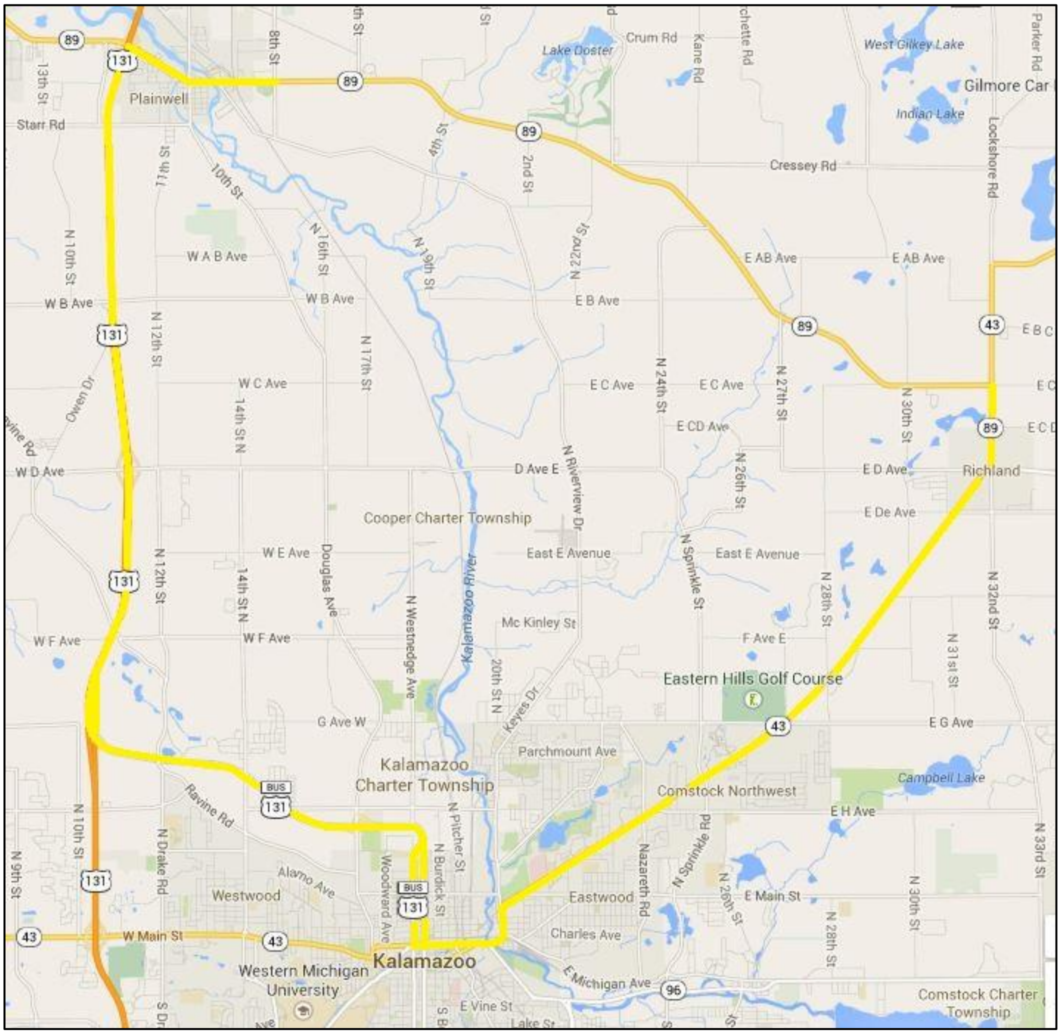
- Manual data collection is a particularly effective method by which to gather data on assets not readily visible from the roadway (e.g., culverts).

- In most instances, two-man teams were utilized to gather asset data. This was an effective method for most assets. However, three-man teams were effective in gathering asset data along higher traffic volume roadways (e.g., US 131). In these cases, one team member drove the vehicle, while the other team members identified and recorded asset data. Safety concerns drove this decision.

- Weather impacted the data collection team's ability to effectively gather asset data, and must be considered as an important factor when developing data collection work plans. In our case, snow was plowed off the immediate driving surface and piled high enough to sufficiently cover most curb, catch basins, and some mowable area. We recommend that the inspector verify that the ground is free from snow before traveling to the collection area.

- Diligent planning, performing, and reporting activities are imperative to a successful data collection effort. Efficient route scheduling, clear and concise naming and numbering conventions, and vigilant reporting are necessary components of a productive asset inventory collection program.

Figure 9: 26.2 Mile Manual Data Collection Route



2. Method of Analysis

Following each manual data collection session, we uploaded the GPS data and converted it to GPX, Excel, and KMZ file formats. The GPX format allowed us to import the GPS data into an Excel file. We also converted the GPX file to a KMZ, which we could then upload into a web-based mapping tool. These KMZ files allowed us to plot and view each asset along the route, and thus gave us a mapped-out view of the entire collection of data. We performed an overview of the KMZ files as a quality control process for all of our collected data. Once we reviewed each data file, we totaled all point assets, summed all linear asset distances, and transferred the results to a master data file. DMG conducted additional in-office data processing as well. We used this process to delete erroneous data entries and verify asset coordinates via the web-based mapping tool in order to verify collected data.

3. Presentation of Results

DMG provided the pilot results to MDOT in several formats, including Excel, .kmz files, and an ArcGIS geodatabase which was developed using ArcMap. Table 16 details the manual data collection asset inventories.

Table 16: Manual Data Collection Asset Inventory Summary

Asset	26.2 Mile Section	Five Mile Technology Overlap	Combined Inventory
"A" miles (CL miles)	26.2	5.1	31.3
Attenuators (each)	0	0	0
Bituminous surface (lane miles)	56.25	10.38	66.63
Bridge (each)	35	0	35
Catch basin (each)	377	22	399
Concrete surface (lane miles)	76.08	0	76.08
Culvert (each)	305	88	393
Curb (miles)	15.51	0.68	15.85
Delineator (each)	683	7	690
Designated snowmobile crossings (each)	0	0	0
Ditch (linear miles)	19.76	7.82	27.58
Freeway light (each)	289	0	289
Gravel shoulder (miles)	12.21	1.35	13.56
Guardrail (linear feet)	38,810.4	2496.56	41,307
Guardrail ending (each)	67	5	72
Lineal feet of existing ROW fence (feet)	129,334	0	129,334
Lineal feet of soundwall (feet)	0	0	0
Mowable acres (acres)	86.36	7.53	93.89
Non-motorized trail (feet)	24,405	0	24,405
Paved shoulder miles (miles)	40.9	7.83	48.73
Pump station (each)	0	0	0
Sign (each)	919	88	1007
Sweepable approach (each)	120	20	140
Total lane miles (miles)	132.33	10.38	142.71

Asset	26.2 Mile Section	Five Mile Technology Overlap	Combined Inventory
Tourist facilities (each)	1	0	1
Traffic signal (each)	348	8	356
Weigh stations (each)	0	0	0

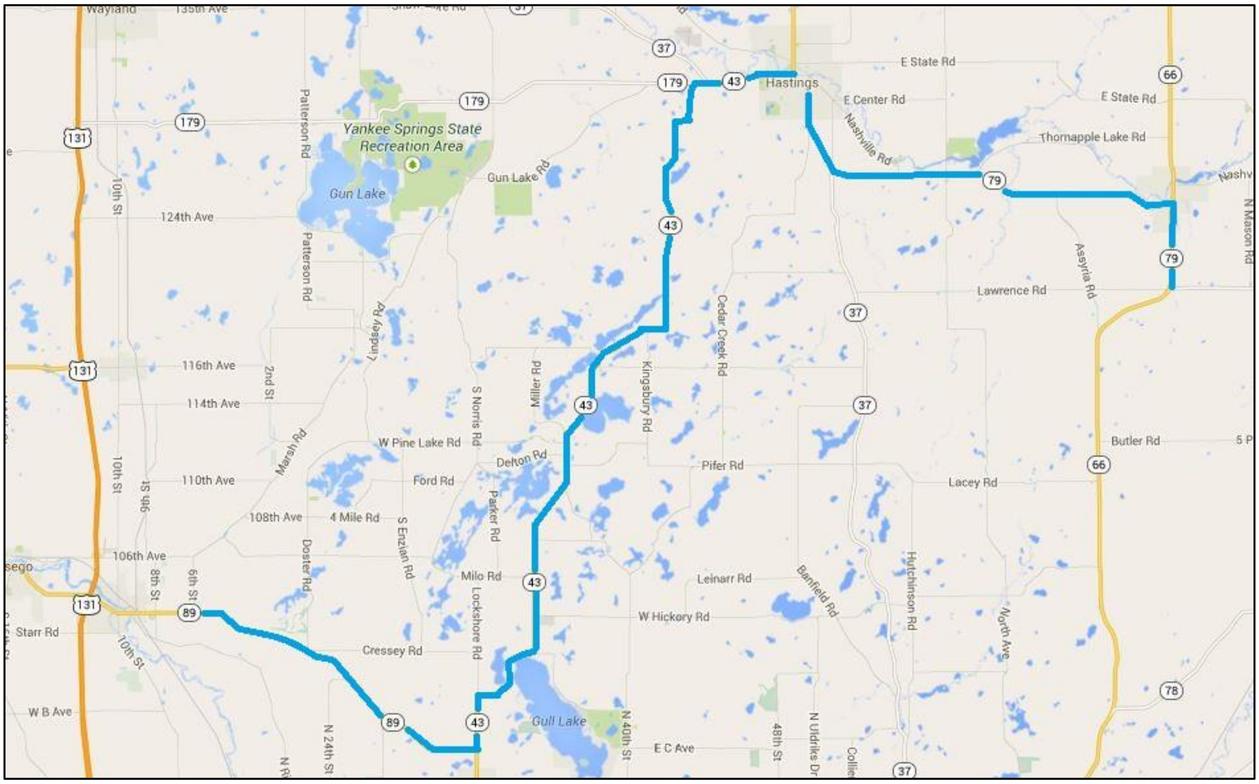
B. Fugro Mobile Imaging

1. Summary of Data

Fugro collected data over a 47.5 mile path along the northern section of the pilot route (Figure 10). Additionally, Fugro collected data along the five mile technology overlap section. In total, Fugro gathered inventory for over 113.75 lane miles. Concrete surface lane miles accounted for 4.6 percent of the route. Bituminous (asphalt) surface lane miles accounted for 92.4 percent of the route. There was an additional 3.4 miles of mixed surface lanes. Fugro stated that these mixed lane miles include lanes with split materials. Fugro identified 55.8 miles of shoulder along the route. Paved shoulders accounted for approximately 76 percent of shoulder miles, while gravel shoulders accounted for approximately 24 percent.

Fugro noted difficulties when trying to capture mowable area measurements. Data collectors attempted to use features such as fencing, poles, and visible cut lines as guides to capture the area that MDOT maintains. However, due to a lack of understanding clearly-defined mowable areas, Fugro incorporated a plus and minus 15 percent margin of error in its width measurements.

Figure 10: 47.5 Mile Fugro Data Collection Route



2. Method of Analysis

Fugro collected images while driving the pilot route, and then uploaded those images to its network. Fugro then utilized in-office staff who observed the collected images frame by frame to identify assets and process the data. Fugro used an asset collection manual to help its inspectors to correctly identify the appropriate assets. When identifying the assets, the location and asset information was documented in such a way as to allow the inventory data to be exported to a geodatabase.

3. Presentation of Results

MDOT provided the vendors with an example of its existing GIS infrastructure. Based on this example, Fugro developed a geodatabase of the collected asset inventory for upload to the existing MDOT GIS infrastructure.

Table 17: Fugro Combined Inventory Counts

Asset	Summarized Results
Total lane miles	113.751
Concrete surface lane miles	Total concrete lane miles = 5.309 Average concrete lane width (feet) = 10.583
Bituminous surface lane miles	Total asphalt lane miles = 105.05 Average asphalt lane width (feet) = 13.498
Paved shoulder miles	42.373
Gravel shoulder miles	13.457
Curb miles	9.38
Number of sweepable approaches	115
Linear feet of guardrail	5.908
Number of guardrail endings	150
Number of catch basins	135
Ditch miles	46.892
Linear feet of existing ROW fence	36,606
Mowable acres	123.113
Number of delineators	952
Number of signals	Total number of signals = 67 Total number of lights on signals = 138
Number of signs	1675
Number of attenuators	0

C. AeroMetric Mobile LiDAR and Helicopter LiDAR

1. Summary of Data

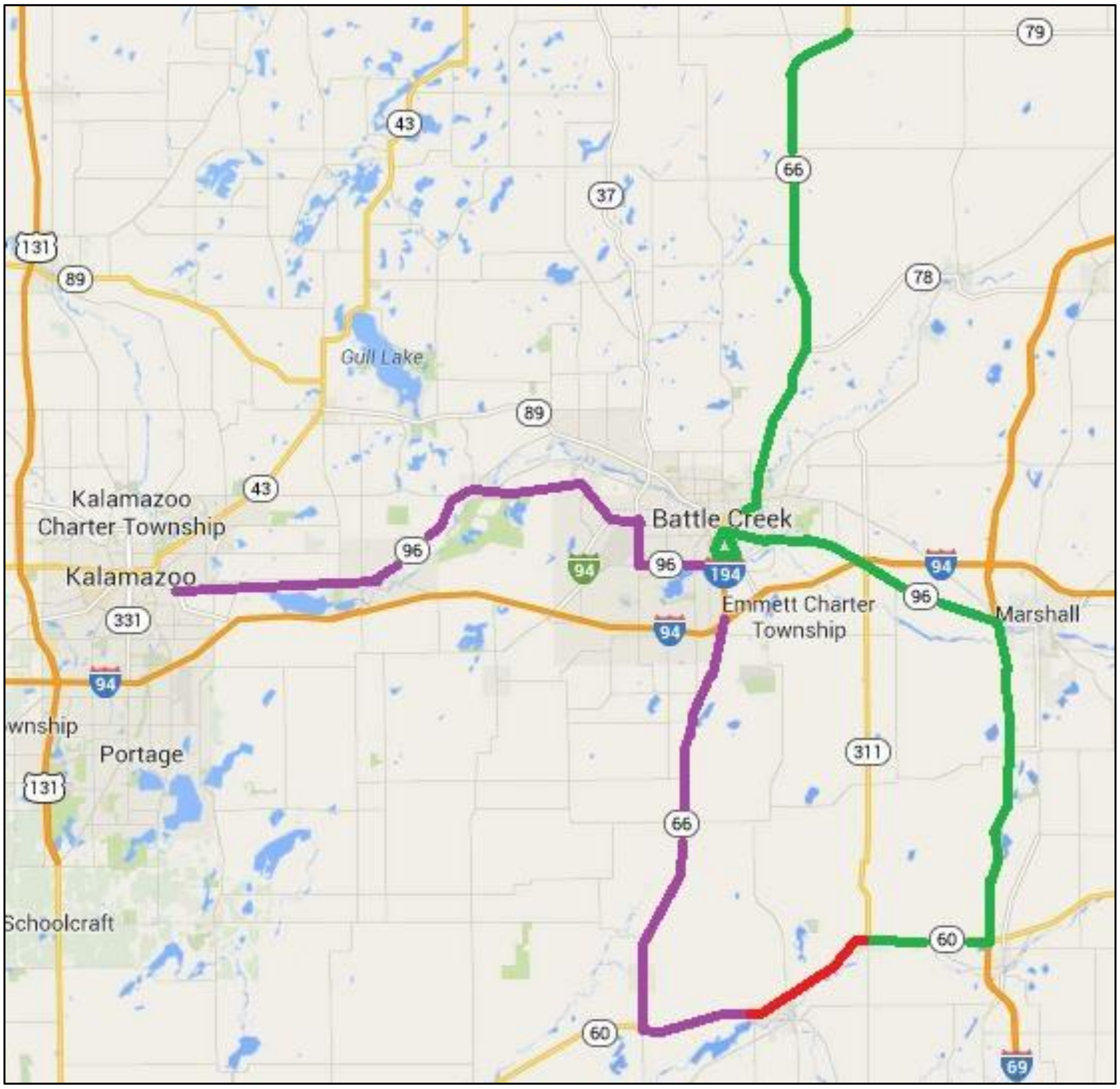
AeroMetric utilized mobile LiDAR and ROW imaging to collect data over a 47.5-mile path along the eastern section of the pilot route (Figure 11 peach line). Additionally, AeroMetric collected data along the five-mile technology overlap section. In total, AeroMetric used mobile technology to gather data over 144.85 lane miles. Concrete surface lane miles accounted for 35 percent of the route. Bituminous (asphalt) surface lane miles accounted for 65 percent of the route. AeroMetric identified 99.68 miles of shoulder along the route. Paved shoulders accounted for approximately 96 percent, while gravel shoulders accounted for approximately four percent of the route. AeroMetric identified 1,211 sweepable approaches. This number appears high and may be a result of asset misidentification. Similarly, AeroMetric inventoried forty-six attenuators. This count is too high and also the result of asset misidentification. See

Table 18 for a complete asset inventory data summary from mobile LiDAR and ROW imaging data collection.

AeroMetric utilized helicopter-mounted LiDAR and ROW imaging to collect data over a fifty mile path along the southern section of the pilot route (Figure 11 white line). Additionally, AeroMetric collected data along the five-mile technology overlap section. In total, AeroMetric used mobile technology to gather inventory over 140.67 lane miles. Concrete surface lane miles accounted for 5 percent of the route. Bituminous (asphalt) surface lane miles accounted for 95 percent of the route. AeroMetric identified 161.05 miles of shoulder along the route. Paved shoulders accounted for approximately 64 percent, while gravel shoulders accounted for approximately 36 percent of the route. AeroMetric identified fifty sweepable approaches and ninety-nine attenuators. These counts are both too high and the result of asset misidentification. See Table 18 for an asset inventory data summary from helicopter LiDAR data collection.

In total, AeroMetric gathered inventory 285.52 lane miles. Concrete surface lane miles accounted for approximately 20 percent of the route. Bituminous (asphalt) surface lane miles accounted for approximately 80 percent of the route. AeroMetric identified 260.73 miles of shoulder along the route. Paved shoulders accounted for 76 percent, while gravel shoulders accounted for 24 percent of the route. The inventory totals for sweepable approaches and attenuators are both too high of counts, due to asset misidentification. Table 18 shows the combined inventory count from AeroMetric's data collection.

Figure 11: Aerometric Mobile (green) and Helicopter (purple) Pilot Route



2. Method of Analysis

AeroMetric used a combination of software, each designed for a specific piece of the processing workflow, to conduct data processing in-office. First, RiAcquire was used on-board the mobile collection vehicle to manage all of the raw sensor data. RiProcess was then used to post-process the trajectory of the vehicle, which includes the creation of a file that represents the position and orientation of the vehicle. This information is then taken into the data extraction software (EarthShaper), which is then used to extract GIS-centric vector data (points, lines, and polygons) that represent asset features in a three-dimensional environment.

Data extraction was conducted in-office over a period of about two weeks. A team of compilers were briefed on the types of assets that were required for extraction, their associated attributes, and the final delivery format of the data. Each compiler was also given a set of instructions from which to determine whether a feature was to be extracted from the LiDAR point cloud or the ROW imagery, or was to utilize a combination of both data sources. For reference, data collected and measured from within the LiDAR point cloud is considered more accurate and precise than the ROW imagery. Therefore, if an object could be compiled from the LiDAR, it would be the first source of data from which to compile an object. If the LiDAR did not contain sufficient resolution to describe an object, it was compiled from the ROW imagery. ROW imagery is typically used to attribute features extracted from the LiDAR because it contains more spectral resolution than can be found in the native LiDAR point clouds.

AeroMetric used an algorithm to convert every pixel in the images from a sample/line location to an X, Y true ground location, based on the projected coordinate system. The images were then projected into the specified map projection and coordinate system. The generated orthoimages were visually checked for accuracy and fidelity on the workstation screen. Selected check points that were visible on the image were visited on the screen and the X and Y coordinates of the location of the check point were displayed. This information was cross-referenced with the X and Y information that the GPS survey provided. Additionally, quality assurance and quality control (QA/QC) analysts reviewed the imagery to ensure that it was free from artifacts or smears caused by changed terrain.

The process of correcting distorted images involved the creation of additional break lines that represent the edges of these above-terrain structures and elevation values for the structure decks, if applicable (such as bridge decks). These lines and points were used to hold the above-terrain structures in their true X, Y positions. This process was followed by interactive image editing to smooth any additional distortions created by the movement of the above-terrain structures to their correct positions. Once the images were successfully orthorectified, AeroMetric imaging specialists used Z/I Imaging OrthoPro software to combine the images, and focused on assuring consistent rendering. Imaging specialists then used Z/I Imaging’s OrthoPro to tile the mosaics according to the defined tile limits. Adjacent image tiles were also tone matched so that the radiometry was similar across the join line between tiles.

AeroMetric mapped the features using heads-up digitization from the generated orthos. AeroMetric utilized its stereo technicians to identify and collect the specific features, as outlined in a Micro Station v8 environment. The features collected corresponded with the final output map scale and the operator’s ability to see and interpret features in the ortho imagery. Following the feature collection, AeroMetric performed an internal QA/QC test. As each tile was completed, it was edge-matched to adjacent tiles. When all tiles were complete in a block, the entire set was externally edited to ensure compliance with all standards and successful tile edge-match. Tiles that passed external QA/QC were stored with the proper naming convention.

Information obtained from both data collection methods includes the type and location of point, linear, and area assets. Inventory data can be pulled, as needed, from the photo and LiDAR records, or the entire file can be processed for a roadway inventory scan.

3. Presentation of Results

MDOT provided the vendors with sample of its existing GIS geodatabase. Based on this, AeroMetric developed a geodatabase of the collected asset inventory for upload into the existing MDOT GIS infrastructure.

Table 18: Aerometric Mobile and Helicopter LiDAR and Roadway and Roadside Imaging Inventory Count

Asset	Mobile LiDAR Results	Helicopter LiDAR Results	Aerometric Combined Results
Total lane miles	144.85	140.67	285.52
Concrete surface lane miles	51.06	6.76	57.82
Bituminous surface lane miles	93.79	133.91	227.7
Paved shoulder miles	95.26	103.19	198.45
Gravel shoulder miles	4.42	57.86	62.28
Curb miles	15.03	25.66	40.69
Number of sweepable approaches	1,211	50	1,261
Linear feet of guardrail	28,403	46,034	74,438.48
Number of guardrail endings	123	259	382
Number of catch basins	379	640	1,019
Ditch miles	80.17	8.24	88.41
Linear feet of existing ROW fence	156,229	13,237	169,467.54
Mowable acres	128.60	136.77	265.37
Number of delineators	710	229	939
Number of signals	141	164	305
Number of signs	1,354	1,335	2,689
Number of attenuators	46	99	145

D. Technology Overlap Section

As noted previously, DMG identified a five mile section of the pilot route to use to verify and compare the accuracy of each data collection method (Figure 2).

1. Summary of Data

The various data collection methods provided fairly consistent asset inventory totals over the five mile technology overlap section, and a few of the assets exhibited variances. Table 19, later in this section, provides a complete summary of technology overlap data. The following section highlights the observed variances and provides explanations for them.

Bituminous lane mile totals from the four data collection methods ranged between 9.9 and 10.38 miles. Much of this variance is explained by slight discrepancies in the start/stop points of data collection for the various technologies. This is unique to the specific technology overlap section and will not be an issue with a statewide data collection effort as the entire trunkline network will be captured.

Curb miles are another example of varying asset definitions and collection processes. Figure 12 illustrates the various interpretations of curb mileage. The blue and green lines both indicate curb features. However, one vendor continued to gather curb mileage totals "around" each intersection. Another vendor continued the curb mileage "through" intersections. Both technologies accurately identified all curb segments; the variance occurred due to differences in where the technician chose to start and stop measuring the curb length for this section. This is another example of a variance that would not be present if the entire system were being collected, as all curb would be collected.

The number of delineators observed in the five mile tech overlap section varied for each technology. Delineators were difficult to measure, mostly due to their small size. Aerial imaging does not easily recognize them, due to their small footprint. In addition, some of the vendors used a broader definition of what encompasses a delineator, which created an elevated inventory count.

A similar variance occurred with guardrail measurements. As can be seen in Figure 13, when considering the points where guardrail ended adjacent to the driving lane, all vendors agreed with the end locations. However, when the guardrail turned at an intersection away from the roadway being measured, the vendors stopped measuring the length of the guardrail at different places, which introduced a variance to the data. One vendor stopped measuring at the physical end of the guardrail wherever it ended (represented by the blue pin), while another vendor stopped measuring the guardrail length at the midpoint of the transition from one road to the other road (the orange pin). Again, this variance isn't a function of the technology, but rather an artifact of the pilot study that will be eliminated when the entire system is collected.

Mowable acre results varied, due to a lack of clarity about which areas were state maintained. This reiterates the need for clearer asset definitions when a statewide RFP is advertised. It also highlights a benefit of the remote technologies, as those assets can be reviewed and extracted even after the initial acquisition.

The accurate identification of right-of-way (ROW) fence and sweepable approaches posed unique challenges. With both of these assets, the definition is dependent on more than just the physical appearance of the asset. Not all fence is dependent on the ROW, which makes discerning ROW fence from privately owned fence difficult in the field. Similarly, sweepable approaches are defined as paved transitions from DOT-maintained roadways to local roads. This distinction is not always apparent in the field and created variance in the pilot inventory results.

Due to its vantage point, aerial imaging did not effectively collect assets with small footprints. Signs, delineators, and fence are all difficult to see from above. Aerial imaging recorded sixty-three signs, while the other technologies averaged ninety-three signs in the tech overlap section. In addition, remote technologies cannot collect data on culverts, as they are not readily visible from the roadway. While there were variances in asset inventory counts between the technologies, many of these discrepancies result from varying asset definitions and collection methods. These variances can be avoided with a uniform collection process and clearly defined asset list, as we have recommended in the implementation plan.

It is critical to note that the technology overlap section provided value in evaluating each technology's ability to measure each asset, and that the results of the pilot are valid despite the variances. The technology overlap also called attention to the areas where asset definitions need to be further articulated. Thoroughly defining each asset will ensure all vendors collect data consistently.

Figure 12: Technology Overlap Curb Mileage Variance

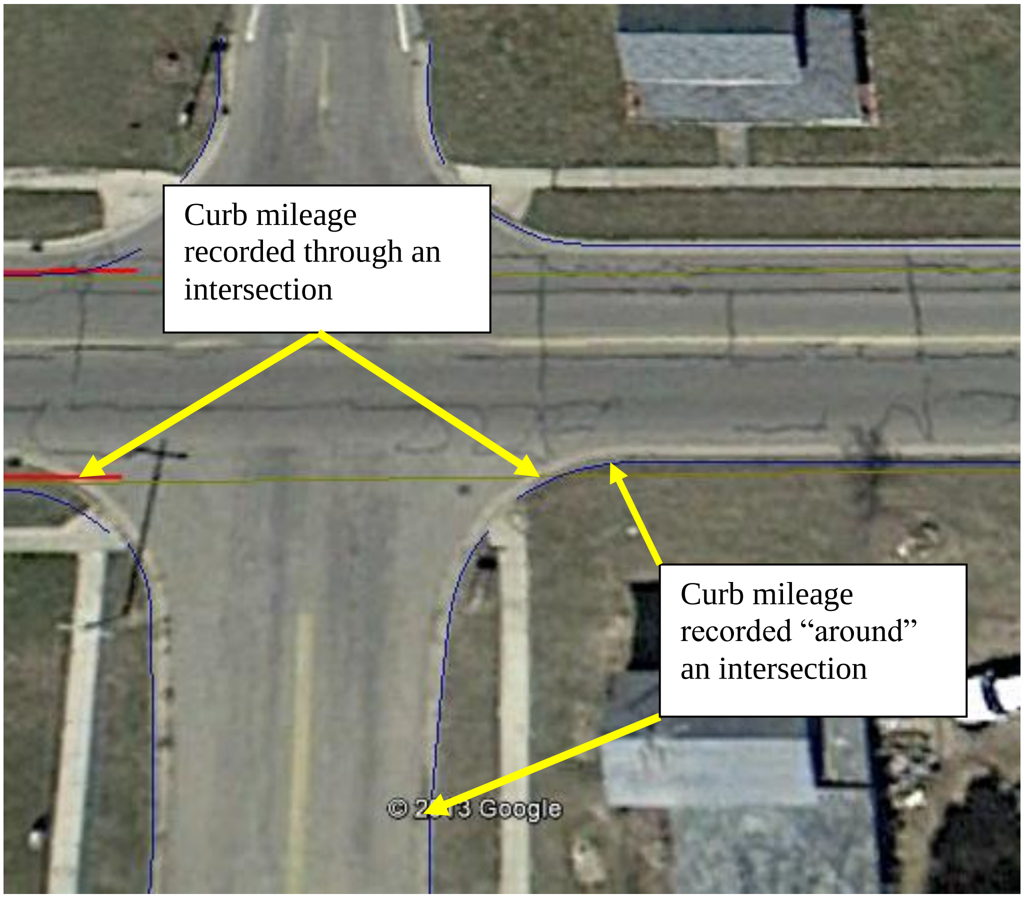
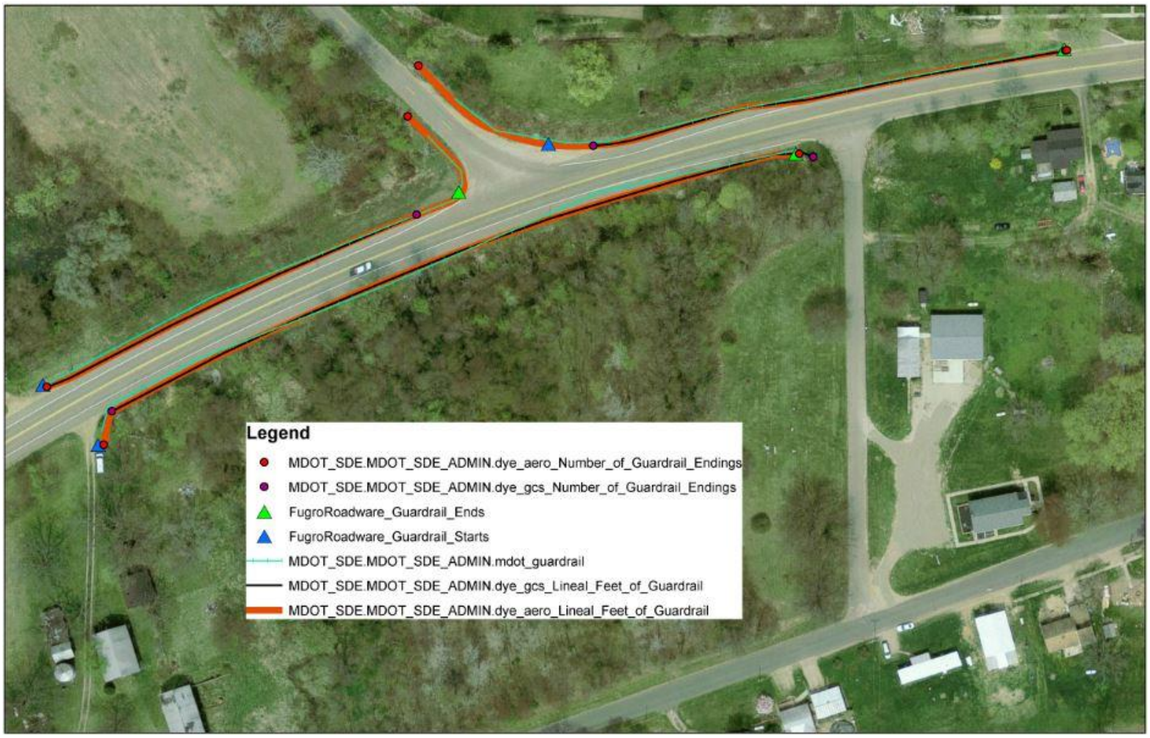


Figure 13: Guardrail Endings Located by Multiple Technologies



2. Method of Analysis

First, DMG manually collected and recorded data along the technology overlap section. DMG then analyzed and compared the results of each data collection process in order to identify discrepancies and reasons for the variance.

3. Presentation of Results

The results of the pilot route inventory data collection are shown in Table 19. These results are broken out by technology. Also, these results represent inventory gathered from the exact same roadway segment. Variances in data results were discussed in the "Summary of Data" portion of this section of the report and in the "Data Comparison" section below

Table 19: Technology Overlap Summary Results

Asset	DMG (Manual)	Fugro (Mobile Imaging)	AeroMetric (Mobile Imaging)	AeroMetric (Aerial LiDAR)	Existing MDOT Inventory
Attenuators	0	0	2	4	
Bituminous lanes (miles)	10.38	10.07	9.9	10.23	
Concrete lanes (miles)	0	0	0	0	
Total lanes (miles)	10.38	10.07	9.9	10.23	10.33
Catch basins	22	13	33	15	18
Culverts (each)	88	N/A	N/A	N/A	80
Curbs (miles)	0.68	0.61	0.65	0.67	
Delineators (each)	7	36	6	26	
Ditches (miles)	7.82	7.64	7.02	0.61	
Guardrails (linear feet)	2,496.56	2,581.47	2,472.85	3,051.18	2864.93
Guardrail endings (each)	5	N/A	10	10	
Mowable acres (acres)	7.53	14.07	12.29	14.73	
Gravel shoulders (miles)	1.35	1.12	2.05	2.64	
Paved shoulders (miles)	7.83	6.32	6.66	7.77	
Total shoulders (miles)	9.18	7.44	8.71	10.41	
ROW fencing (linear feet)	0	3,514.77	3,897.89	0	
Signs (each)	88	100	92	63	
Sweepable approaches (each)	20	9	132	9	
Traffic signals (each)	8	4	2	2	

4. Data Comparison

The project team chose the Kalamazoo region of MDOT to host the pilot project, primarily due to the quality of its preexisting inventory. This section compares the assets collected in the pilot with those present in the existing MDOT inventory.

The first example is “total lane miles”. The numbers across the four data collection methods and the existing MDOT inventory are roughly the same. The discrepancies between data are related to how total lane miles were defined rather than the collection method. For example, manual data collection included turning lanes and arrived at 10.38 total lane miles.

Catch basins are the second example for this data comparison. The data across the four data collection methods showed a range of 13 to 33 catch basins. MDOT’s inventory registered 18 catch basins.

Culverts are the third example. At the outset of this project, the project team understood that the remote sensing technologies would not be able to capture certain assets such as culverts, which explains why Fugro’s mobile imaging and Aerometric’s mobile imaging and LiDAR methods were not able to capture culvert data. DMG located 88 culverts through its manual data collection method, which is in line with MDOT’s existing inventory of 80 culverts.

Guardrails (linear feet) are the last asset example in this data comparison. The four data collection methods and the existing MDOT inventory are within a reasonable range: from 2472.85 to 3051.18 linear feet. The differences in values can be attributed to different data collection methodologies and are not a function of the specific technology. For example, manual data collection team measured guardrail until it met an intersection, while other vendors measured guardrail as it extended to adjacent roads at intersections.

Comparing the collected data to MDOT’s existing inventory is one more way to verify the accuracy of the collection methods. This comparison produced satisfactory results, in which the only significant discrepancies resulted as artifacts of the pilot process. These variations wouldn’t be expected in a large-scale implementation.

V. Discussion

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A. Manual Data Collection

1. Testing Validity of Hypothesis

The hypothesis for our research was that utilizing a combination of remote sensing technologies would allow MDOT to locate and measure highway assets in a manner that would decrease worker exposure, speed data collection, increase data accuracy and quality, and reduce overall costs. With this in mind, we looked at each asset to test the hypothesis against our observations during the pilot study.

The pilot study results indicate that manual data collection is an effective way to accurately gather asset inventory data at relatively low costs. Manual collection enables workers to pick and target specific sections of the roadway with on-foot mobility that is not possible with a vehicle or stationary equipment. Assuming that the necessary safety equipment is available, a person on the ground can be closer to an asset than can any type of technology. Closer proximity to the asset allows one to conduct a more definitive visual assessment, which in turn can sometimes provide a more accurate evaluation of the asset's condition. Close proximity to assets also provides crews with the opportunity to report high priority work and safety issues as soon as they encounter these in the field. For example, a crew member may encounter a guardrail that is so damaged that it may no longer function as a safety device and therefore needs immediate repair.

However, manual data collection exposes workers to potential danger, as they need to be on foot in many instances.

Additionally, individuals performing manual data collection can sometimes provide specific insight if a question or issue about the data on a certain section of roadway arises during post-collection processing. However, unlike mobile imaging and LiDAR processes, manual data collection does not capture visual evidence that can be revisited; an inspector would have to go back into the field to verify any questionable data.

Lastly, when applied statewide, the remote technologies gain significant economies of scale over manual data collection. On a statewide scale, remote technologies spread mobilization and startup costs over the entire state-maintained system to increase data collection speeds and reduced costs.

Table 20 shows the hours spent collecting data in the field and processing that data in the office. MDOT provided fully-loaded cost rate of $45 per hour for employees performing manual data collection. This rate includes hourly pay rate, overhead, and fringe benefits for an experienced maintenance worker. In addition, the field work required one vehicle, at a rate of $8.32 per hour. The field work also required a hand-held GPS unit. Based on depreciating the units over their useful life, DMG and MDOT agreed on an estimated cost of $1/hour for each unit. The average cost rates for the full 31.2 mile manual data collection portion of the pilot are shown in Table 20 below. We estimate that the cost to MDOT to collect data for this section of the roadway would have been $13,378. MDOT has 9,653 miles of state-maintained trunkline.

(see http://www.michigan.gov/mdot/0,4616,7-151-9620_11154-129683--,00.html)

If we extrapolate the data collection costs to cover the entire MDOT-maintained system, we project that the cost would be $4.14 million and would require approximately 87,500 worker hours to complete collection and processing.

Table 20: Manual Data Collection Cost Summary

Crew Size	Field Data Collection (Hours)	Office Data Processing (Hours)
1	0	110
2	42	0
3	29	0
Total	**171**	**110**
Cost Summary		
Hours per mile		9.01
Salary cost per mile		$405.29
Equipment cost per mile		$23.48
Total cost per mile		$428.77

2. Factors Affecting the Results

There are several factors that can impact the results of manual data collection. As DMG experienced firsthand, weather can cause delays, and in some cases, make asset data collection impossible. Additionally, the competence of the data collection crews and the functionality of their tools can also affect results. For instance, DMG used basic GPS devices during the manual data collection process, which made data entry a slow and laborious process Currently, MDOT has handheld GPS devices that allow for more efficient data entry. Investing in more advanced hardware would enable crews to more quickly and accurately record asset data information.

3. Implications

Manual data collection is comparable, and in specific cases (e.g., culverts), the preferred method of asset inventory collection. This is especially true of the relatively short pilot route. However, when applied statewide, the advantages become less pronounced or disappear altogether. Remote technologies offer opportunities to realize economies of scale, and spread mobilization and startup costs across the entire 9,653 mile state-maintained system. Also, remote technologies offer an opportunity to reduce worker exposure, speed data collection, and revisit asset data at any time.

B. Mobile Imaging (Fugro)

1. Testing Validity of Hypothesis

Pilot results indicate that Fugro's mobile imaging process validates three components of our hypothesis. Mobile imaging can reduce worker exposure, speed data collection, and improve data accuracy and quality. The ability to review any frame of the mobile image data enables users to perform quality control as desired. As discussed in the literature review, there are limitations to the technology, specifically in regard to assets not readily visible from the roadway (e.g., culverts). However, collected asset data can be reviewed in order to ensure data accuracy and quality; this is not possible with manual data collection.

Pilot results also indicate that Fugro's mobile imaging technology will not validate the fourth component of our hypothesis: that remote asset data collection is cheaper than manual data collection. However, a statewide asset data collection effort will reduce the effect of startup and mobilization costs. This cost reduction will in turn decrease the cost per mile estimate to approximately $89 per mile, which is much lower than the statewide estimates of $429 per mile for manual data collection.

2. Factors Affecting the Results

DMG contracted Fugro's data collection and processing services for $19,361. As noted previously, Fugro collected data along 52.5 centerline (trunkline) miles of MDOT roadway, or for a $368.78 cost per trunkline mile. This average cost estimate did not take into account any economies of scale. We assumed a percentage of Fugro's cost per mile of data collection was a result of preparation and startup costs. The effect of these mobilization costs is reduced if it is spread over the entire state-maintained network. Also, there are assets that, once inventoried, will only require periodic updates to the inventory. For example, large assets, such as bridges, rest areas, and weigh stations would not require frequent updates. It is also important to note that vendor availability should be considered when procuring data collection services. Contractors will need advance notice to prepare and mobilize their staff.

3. Implications

In order to refine the statewide cost estimates, DMG requested an updated quote to gather asset data across the entire state. As we assumed, Fugro's cost per mile for statewide data collection is much lower than that of the pilot. Fugro has quoted approximately $861,000 for statewide asset inventory collection. This cost assumes that Fugro would recollect ROW data prior to asset extraction. Fugro also provided a quote of approximately $460,000 for statewide asset feature extraction without recollecting data. Table 21 and Table 22 detail the Fugro cost estimates.

Table 21: Cost Summary for MDOT Feature Asset Extraction with Data Collection

Description	Price per Unit	Quantity	Extended Price
Mobilization	$36,127.00	1	$36,127.00
Project setup and administration	$3,000.00	1	$3,000.00
Data collection	$325,144.35	1	$325,144.35
Asset extraction	$47.00	9,716	$456,652.00
Data processing and quality review	$39,701.00	1	$39,701.00
		TOTAL	**$860,624.35**
NOTE: Based on recollection of the ROW data to conduct the asset feature extraction.			

Table 22: Cost Summary for MDOT Feature Asset Extraction without Data Collection

Description	Price per Unit	Quantity	Extended Price
Project setup and administration	$3,000.00	1	$3,000.00
Asset extraction	$47.00	9,716	$456,652.00
		TOTAL	**$459,652.00**

C. Mobile Imaging with LiDAR and Aerial Imaging with LiDAR (AeroMetric)

1. Testing Validity of Hypothesis

Pilot results indicate that AeroMetric's mobile LiDAR, ROW imaging, and aerial LiDAR processes validate three components of our hypothesis. The technologies can reduce worker exposure, speed data collection, and improve data accuracy and quality. The ability to review any frame of the data enables users to perform quality control as desired. Pilot results indicate that AeroMetric's technologies will not validate the fourth component of our hypothesis: that remote asset data collection is cheaper than manual data collection. AeroMetric initially provided several quotes at various pilot lengths with an assumption that they accounted for economies of scale.

Data collection lasted two days, and data extraction was conducted in-office over a period of approximately two weeks. AeroMetric spent a total of 351 man hours on mobile imaging preparation, data collection, and extraction, which translates to approximately 6.8 hours per mile. For aerial LiDAR data collection, AeroMetric spent a total of 170 man hours in the field. Data extraction and processing required an additional 390 man hours. In total, AeroMetric spent a total of 560 man hours on aerial LiDAR inventory collection and processing, which translates to 11.2 hours per mile.

2. Factors Affecting the Results

The incorporation of LiDAR technology increased the price per mile for AeroMetric's data collection services. It is important to note that the capabilities of this technology are outside of the scope of this project, which was to gather basic asset inventories. As noted previously, contractor availability can impact the ability to procure asset data collection services.

3. Implications

DMG contracted AeroMetric's mobile LiDAR and ROW imaging data collection and processing services for a maximum of $49,000. AeroMetric collected data along 52.5 centerline (trunkline) miles, or for a $933.33 cost per trunkline mile. Currently, MDOT maintains 9,653 miles of trunkline. When we extrapolate AeroMetric's data collection costs to the entire MDOT-maintained system, we estimate the cost to be $9.01 million.

DMG contracted AeroMetric's aerial LiDAR data collection and processing services for a maximum of $45,000. AeroMetric collected data along fifty-five centerline (trunkline) miles, or for a cost of $818 per trunkline mile. Currently, MDOT maintains 9,653 miles of trunkline. When we extrapolate AeroMetric's data collection costs to the entire MDOT-maintained system, we estimate the cost to be $7.90 million.

D. Mobile Imaging with LiDAR (Mandli Communications)

Mandli Communications was unable to bid on and participate in the pilot, due to internal restructuring. However, it did offer a quote prior to the completion of the study. Mandli offered to use ROW imaging and mobile LiDAR technology to perform highway asset data collection. These technologies are proven to effectively gather accurate asset inventory counts.

1. Testing Validity of Hypotheses

The price quoted from Mandli validates three components of our hypothesis. The technologies can reduce worker exposure, improve data accuracy and quality, and be cheaper than manual data collection. Based on the pilot results that used similar technologies and collection methods, we assume Mandli's services would validate the fourth component of our hypothesis as well: that remote technology will speed data collection.

2. Factors Affecting the Results

Mandli included mobile LiDAR technology services in its quote. It is important to note that the capabilities of this technology are outside the scope of this project, which was to gather basic asset inventories. As noted previously, contractor availability can impact the ability to procure asset data collection services. This is particularly true in this case, as Mandli was unable to bid on the pilot project, due to corporate restructuring.

3. Implications

Mandli provided a quote of between $170 and $210 per lane mile to use ROW imaging and mobile LiDAR technology to perform highway asset data collection, which translates to approximately $542 per trunkline mile, or $5.23 million for a complete statewide asset inventory collection effort. This is cheaper than manual data collection, but more expensive than the services that Fugro offers. Again, the Mandli quote included LiDAR technology, which increased the price per lane mile.

E. Cost by Region

To supplement our analysis, MDOT requested that we provide estimated costs to perform the data collection in each of the seven state regions. To develop these estimates, we utilized 2010 MDOT highway performance monitoring system (HPMS) trunkline inventory data and applied the cost per mile rates for each technology to develop a cost per trunkline mile. This is shown in Table 23. It is expected that the economies of scale associated with a statewide collection could lower the total cost below what is shown below; this statewide cost can be considered an upper limit.

Table 23: Costs per Trunkline Miles by Region

Technology/Vendor					
Region	**Manual**	**Fugro**	**AeroMetric Mobile**	**AeroMetric Aerial**	**Mandli**
Bay	$648,964	$134,067	$1,412,647	$1,238,359	$819,587
Grand	$401,864	$83,020	$874,767	$766,841	$507,521
Metro	$371,307	$76,707	$808,250	$708,531	$468,929
North	$839,265	$173,381	$1,826,888	$1,601,493	$1,059,921
Southwest	$780,382	$161,216	$1,698,713	$1,489,132	$985,557
Superior	$571,554	$118,075	$1,244,143	$1,090,645	$721,825
University	$525,654	$108,593	$1,144,229	$1,003,058	$663,857
Total	**$4,138,994**	**$855,060**	**$9,009,637**	**$7,898,058**	**$5,227,198**

VI. Conclusions

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A. General

In order to gain an understanding of the cost, accuracy, precision, and speed of each technology, DMG divided pilot project into five segments. Each of the four technologies was employed exclusively in its own segment and the fifth segment leveraged all four technologies. This section is called the technology overlap section.[3]

Collecting data on the technology overlap section was necessary in order to compare the results for each technology to one another. While there were many consistent asset inventory counts, there were also some discrepancies. Most of these discrepancies were not the result of faulty data collection or technology. Rather, these were the result of varying interpretations of how to measure assets. These instances highlight the need to develop and agree upon clear asset definitions prior to inventory collection. MDOT should consider developing a manual, complete with photographs, of state highway assets to minimize misinterpretations in future data collection efforts.

Each technology is unique, and as such, has inherent strengths and weaknesses when compared to other technologies. Manual data collection can be used to collect data on all assets. However, it in many cases requires inspectors to walk in or alongside live traffic when collecting data. One of the goals of the research was to reduce MDOT employee exposure, and a fully manual data collection plan would not accomplish that goal.

Not all collection methods require inspectors to be adjacent to traffic. Aerial photography puts the inspector in the air, thus reducing exposure to traffic. However, assets with small footprints (area when being viewed from above) are not easily discerned with aerial imaging. Right-of-way fence, small signs, delineators, small traffic signals, and culverts are difficult to accurately measure with aerial imaging.

Both technologies that used mobile imaging were very functional, allowing the inspector to avoid walking along the roadway while still collecting almost every asset.

There were a few assets that presented difficulties for each remote technology. Culvert locations can prevent observation with remote technologies, as they are frequently obstructed from the roadway. In addition, mowable area was difficult to accurately measure using a ground-based vantage point.

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[3] We summed the technology costs and collection rates for the entire length of each technology's collection area and divided it by the number of miles collected for each technology to calculate a per-mile cost and a per-mile rate of collection. Utilizing each technology over a large distance decreased the impact of small variances in collection rates and costs, which increased the reliability of our results.

B. Strengths and Weaknesses of Manual Data Collection

The manual collection process allows MDOT some key advantages over other data collection technologies. The first advantage of manual collection is the ability it provides the inspector to easily scale the collection area. Personnel complete the data collection process for mobile imaging and aerial photography on a large scale that covers an extensive area. Manual collection, however, enables workers to pick and target specific sections of the roadway. For example, if an employee is unable to measure a small section during data collection (possibly due to safety concerns or a traffic accident) or if the section requires an additional assessment, manual collection is quicker and cheaper than other collection technologies. There are virtually no mobilization costs, and the only equipment required for collection is a handheld GPS device, which the inspector would likely have immediately available. Other technologies would require much more effort to mobilize, and the necessary equipment is generally less readily available than handheld GPS devices.

An additional advantage of manual collection is that it affords the inspector the ability to observe the asset more closely than other collection methods. Closer proximity to the asset allows the inspector to conduct a more definitive visual assessment, which in turn provides a better evaluation of the asset's condition. Other technologies lack the ability to allow one to view assets up close or at all angles, but manual collection enables all these different points of view.

Manual collection also allows an individual to immediately account for specific sections of roadway, if such accounts are needed during assessment. This ability allows an inspector on the ground to report high priority work and safety issues as soon as he or she encounters them in the field. Barrier walls, impact attenuators, guardrails, and fences that are so damaged that they may no longer function as safety devices should be repaired as quickly as possible. Fallen trees or obstructive objects that could endanger the roadway should also be addressed as soon as possible. A manual data collection process allows the inspector to immediately report and attend to these hazards.

Another advantage of manual collection is that allows an individual who works on site the ability to reassess particular areas. If a question or issue about the data on a certain section of roadway arises during the post-collection phase, the individual that collected the data can provide specific insight, based on their experiences.

In addition to the general benefits, manual data collection also has asset-specific benefits. For example, culverts are best inventoried and assessed when personnel use manual collection because the positions and locations of these assets are often not clearly seen from the road or the air. If the view from the road or shoulder is unclear, a person on foot can examine a possible area where a culvert might be located. An individual on the ground can also position him or herself adjacent to a culvert, which better allows the inspector to determine the condition of the culvert and provide more thorough data.

Manual collection also has several disadvantages when compared to other data collection technologies. The first disadvantage is the amount of time it takes to complete the data collection process. Daily travel time to the start of each survey section, as well as the time it takes to set up equipment and safety devices, creates a considerably longer collection process than that of the use of mobile imaging or aerial photography. Daily mobilization and travel time further delays the start of the data management and valuation phase, which makes manual collection as a whole a potentially longer process than it is with the other data collection technologies.

The second disadvantage is the increased likelihood for potential human error. The consistency of the data provided is dependent on those individuals that collect it. Any errors in inventory or recording assessment in the field cannot be recounted or reviewed because this data is based on the crewmembers' visual accounts. Technologies that use cameras or LiDAR allow personnel to review the data as much as needed, after the data is collected in the field.

The third disadvantage of manual collection is the decreased safety of the crew members who perform the data collection; during this process, crew members work in a potentially hazardous traffic environment. Remote technology reduces that danger and ensures that collection is more safely completed. Aerial photography and mobile imaging create minimal risk for crew members compared to that of manual collection.

A major lesson learned from our manual collection phase was the impact that weather can have on the overall process. We initially began the data collection process early in the year. There was several inches of snow on the ground and snow piles exceeded one foot in depth on many shoulders and curbs, which limited our ability to assess some assets. Also, we initially planned to complete our collection process in a one week period; however, the snow so greatly impacted our timeline that we had to divide the process into two separate collection periods. Snow in the roadway obstructed our view of and ability to collect data for culverts, catch basins, ditch miles, motorized trail, mowable acres, paved shoulder miles, and gravel shoulder miles.

As previously mentioned, a web-based mapping tool was a very effective data validation and quality assurance tool during our data collection process. The ability to upload and transfer data from a GPS device and Excel file into a web-based mapping tool gave us a reliable data management method and allowed us to validate the accuracy of the GPS points we collected in the field. Another technology available for consideration include Desk Top GIS software, utilizing MDOT owned imagery.

During our daily collection process, we uploaded all data points to Excel, which allowed us to manage and organize waypoints by assets and transfer them to a web-based mapping tool. The ability to change each individual asset to a specific visual icon on the web-based mapping tool presented a detailed view of every individual asset type's location on the roadway, which enabled us to track and manage all data points collected and to confirm the accuracy of the GPS. We were also able to use the tool to validate the measurement of the assets' lengths and distances. When provided with a stop and start point, one can use the program's tools to measure an asset's distance. In addition, the majority of the web-based images were clear enough that we could remotely identify and measure linear assets, without the need to enter the field.

C. Strengths and Weaknesses of Mobile Imaging (Fugro)

Fugro collected asset inventory data by capturing high-resolution mobile images while traveling at highway speeds. The images will allow MDOT to revisit its data as necessary. As shown, the cost to perform Fugro's statewide mobile image data collection is significantly cheaper than that of manual data collection. MDOT must also consider the amount of time required to conduct manual data collection (weather considerations) along the entire state-maintained system.

Fugro spent approximately 7.4 hours per mile along its data collection route, compared to 9.01 hours per mile for manual data collection. MDOT maintains 9,653 miles of trunkline, which translates to a savings of approximately 15,541 labor hours by using mobile imaging instead of manual data collection. More importantly, if a vendor conducts the work, MDOT personnel wouldn't spend time collecting data in the field.

In addition to reduced costs and labor hours, there are other advantages that MDOT should consider when it chooses an inventory collection technology. First and foremost, Fugro's mobile imaging technology allows personnel to collect all data from a vehicle, which greatly reduces worker exposure and increases safety. In addition, the images are stored and can be re-examined, as necessary. The high resolution images allow for virtually any detail that is visible from the driving surface to be clearly evaluated without incurring additional costs. The manual data collection cost rate we provided does not include any recollection trips. If data is missed or inaccurately identified, the personnel would have to visit the site again, which increases the cost. DMG believes that these added benefits could sufficiently offset the additional cost of mobile image inventory data collection.

D. Strengths and Weaknesses of Mobile Imaging with LiDAR and Aerial Imaging with LiDAR (AeroMetric)

The data that AeroMetric delivered is of acceptable quality for MDOT's asset inventory needs. However, the data collection services costs are significantly higher than those of both manual data collection and Fugro's mobile image system. AeroMetric estimates mobile LiDAR and ROW imaging costs for the entire state-maintained road network ($9.01million) at more than double the cost of manual data collection ($4.17 million) and ten times the cost projection of Fugro's mobile imaging ($861,000). AeroMetric's cost estimate to deliver aerial LiDAR data collection services is $7.9 million. This cost projection is more than three times the cost for manual data collection and nine times Fugro's cost estimate for mobile imaging.

This projected cost increase is primarily due to the use of LiDAR in the data collection process. LiDAR is an effective and useful technology when it is used to determine the nearly exact location of a physical asset. For the purposes of this research study such a high level of accuracy was not necessary. The increased benefit of higher accuracy is not commensurate with the increased cost to use this technology.

E. Strengths and Weaknesses of Mobile imaging with LiDAR (Mandli Communications)

Mandli was not available to participate in the pilot data portion of the research. However, Mandli was again contacted after the pilot was complete, and they provided an estimated cost to use ROW imaging and mobile LiDAR technology to collect highway asset data. These technologies are proven to effectively gather accurate asset inventory counts. Mandli provided a quote at an average of $190 per lane mile to use ROW imaging and mobile LiDAR technology to gather highway asset data collection, which translates to approximately $542 per trunkline mile.

When we extrapolate this cost to the statewide mileage totals, we estimate that Mandli could deliver asset data collection services for approximately $5.23 million. This method is more expensive than both manual data collection and Fugro's services, but cheaper than the services that AeroMetric offers. Although Mandli was unable to participate in the pilot, it has worked successfully throughout the country on similar asset collection contracts, with great success.

F. Culvert Collection

As previously stated, culverts are unique, compared to the other assets included in this research. Because they are underground, they are only visible at their ends, which may or may not be visible from the roadway. Manual data collection was the only technology that could reliably identify culverts. While walking the route is costly and time intensive, we discovered no other methods no other methods of culvert identification with which other agencies have been successful.

If a reliable culvert inventory will be established, the most accurate way to build this inventory is to manually collect each culvert across the entire system. However, the cost of such an effort would be almost as high as the cost to collect all assets with manual data collection. DMG recommends that MDOT use a sampling approach to reasonably estimate the system-wide inventory at a fraction of the cost of a full collection. The miles to be collected and associated costs to sample the system are shown in Table 24. The values are shown in order to achieve the corresponding margin of error at the regional level.

In addition, we can assume that the costs would be slightly lower than the provided values, due to the slightly decreased field effort needed to only collect culvert data. The cost estimates are based on our experience collecting, processing, and delivering all assets simultaneously. DMG recommends that MDOT collect the miles of culverts necessary to achieve a 10 percent margin of error for each region. If this effort is applied throughout the system, the result would be a statewide culvert inventory with a margin of error of less than 4 percent.

Table 24: Culvert Collection Cost and Effort
(Varying Region Level Margin of Error [MOE] at 95 Percent Confidence)

	20 Percent MOE		10 Percent MOE		5 Percent MOE		3 Percent MOE	
Region	Miles	Cost	Miles	Cost	Miles	Cost	Miles	Cost
Bay	24	$10,825	90	$40,595	307	$138,472	625	$281,906
Grand	23	$10,374	87	$39,241	273	$123,137	500	$225,525
Metro	23	$10,374	86	$38,790	266	$119,979	479	$216,053
North	24	$10,825	92	$41,497	321	$144,787	691	$311,676
Southwest	24	$10,825	89	$40,143	293	$132,158	570	$257,099
Superior	24	$10,825	91	$41,046	317	$142,983	672	$303,106
University	24	$10,825	90	$40,595	298	$134,413	594	$267,924
Total	166	$74,874	625	$281,906	2075	$935,929	4131	$1,863,288

G. Recommendations for Future Research

We recommend that MDOT continue to investigate new opportunities to utilize advancing technologies to collect asset inventory. We anticipate that firms will continue to develop hardware, software, and processes that will allow states to more accurately and efficiently collect highway asset data. Specifically, we recommend that MDOT investigate additional opportunities to incorporate LiDAR functionality (e.g., pavement condition assessments) into the highway asset data collection process, providing it becomes less cost-prohibitive.

We also expect that firms will continue to develop hardware and software to aid in manual data collection. Handheld devices, tablets, and new software programs may allow MDOT to realize additional efficiencies in the traditional manual data collection process.

H. Recommendations for Implementation

Throughout this project, DMG evaluated the asset data collection technologies for accuracy, precision, and for cost-effectiveness. In order for MDOT to implement the results of this study, it will need to move forward with advertising for vendors to provide data collection services using the recommended technology. The steps necessary to execute and implement this data collection effort are detailed below.

1. Estimated Costs, Software Requirements, and Anticipated Results

DMG recommends that MDOT outsource the data collection to a vendor that can suitably deliver a project of this magnitude. Based on the estimates we received, we anticipate a vendor utilizing mobile imaging technology, without LiDAR supplementation, would be able to collect and deliver inventory and location for the assets at a lower cost than that of manual collection and processing or the other technologies reviewed during the pilot.

In order to estimate equipment and software requirements, DMG conducted a best practices review of the functionality of GIS systems used in other states. In addition, DMG met with MDOT's GIS staff to review the current enterprise systems used to collect, store, display, and manage existing asset-related data. Lastly, DMG calculated file size requirements for the various technologies studied, as shown in Table 25. When MDOT estimates future data needs, it should consider the frequency of the data collection effort, as well as potential lane mile growth, and the resulting effect on data storage requirements.

Table 25: Asset Data File Size Estimates

Vendor	Data File Size per Mile	Image File Size per Mile	Current Statewide Estimate
AeroMetric Mobile	41.5 KB	625.5 MB	6,038 GB
AeroMetric Aerial	41.5 KB	9.05 MB	87.4 GB
Fugro	34 KB	164.2 MB	1,585 GB
DMG	33 KB	N/A	313.11 MB

2. Capturing Inventory Data

Currently, MDOT uses DOT personnel to collect inventory data. The inspectors use Trimble handheld GPS devices in the field to manually collect inventory data. The data is stored on the GPS device as a .SHP file (shapefile) that is then uploaded to the GIS database when the device is returned to the office. A data dictionary is loaded to the GPS device, which allows the inspector to save inventory data in a format that is easily uploaded to the statewide geodatabase.

The shapefile format is commonly used throughout the industry. As such, remote data collection technologies can provide output data files in the same format as MDOT's current handheld GPS devices. This consistent data format will allow MDOT to seamlessly incorporate the data remote technology collects into its current geodatabase.

3. Storing Inventory Data

MDOT uses SQL server as its database system, and manages the data through an ArcGIS server. Many other state DOTs use SQL server, as it contains the flexibility to cater to the unique needs of DOT data users. For example, the Mississippi Department of Transportation implemented a beta version of Microsoft ® SQL Server Spatial ® 2008 R2 Enterprise across the agency in 2010. Implementation of this system helped the agency achieve two main goals: the ability to access large files using an external storage feature and enhance agency reports through improved mapping capabilities.[4]

MDOT takes care to protect the integrity of its GIS data. When a user wishes to edit data in the geodatabase, that user must check out the data for the section of the roadway to be edited, which lets other users know that the data is being edited. The data correlating with that section of roadway is downloaded to the handheld GPS unit, which is then taken out in the field in order to add or edit the data. After the inspector is finished with that dataset, he or she will upload the data back to the master geodatabase. This new data must be approved before it can be used to overwrite the existing data in the geodatabase.

We recommend that MDOT continue these practices through any transition to another data collection methodology. Once the data is collected and stored, it should be subject to the same approval and validation process regardless of the collection method.

4. Sharing Inventory Data

MDOT uses ArcGIS from the ESRI platform as its interface to read and edit its geodatabase. ArcGIS allows users to map their data in order to make better decisions related to inventory. In addition, ArcGIS Explorer is a free viewer that allows the user to open and view a geodatabase. MDOT currently posts inventory data to the Michigan Department of Technology, Management, and Budget (DTMB) and Center for Shared Solutions and Technology Partnerships webpage[5]. Anyone with web access can download a variety of geographic data libraries in shapefile (.SHP) format including, but not limited to:

- Census data
- Geology
- Hydrology
- Land use
- Transportation

Currently available transportation shapefile data includes:

- Mile marker sign inventory
- All Roads
- Railroads
- State Roads

[4] http://www.microsoft.com/casestudies/Microsoft-SQL-Server-2008-R2-Enterprise/Mississippi-Department-of-Transportation/State-Transportation-Agency-Speeds-Access-to-Business-Intelligence-for-Better-Reporting/4000007057
[5] http://www.mcgi.state.mi.us/mgdl/?rel=ext&action=sext

By developing a more complete and accurate asset inventory, MDOT will be able to share data that is more useful to the data consumers, including research agencies, universities and colleges, and local governments and planning organizations.

Use of Data and Sharing of Results

While MDOT's GIS office will own and maintain the inventory data, a complete and accurate highway asset inventory can benefit several agencies. For example, the Utah DOT recently collected a comprehensive asset inventory and several departments within the Utah DOT are utilizing this data, including:

- Asset management
- Structures
- Traffic and safety
- GIS
- Technology services
- Motor carriers

The Utah DOT utilized mobile LiDAR technology to collect the highway asset inventory. As a result, its planning department can utilize the information in the preconstruction and design phases of transportation projects.

To effectively share the data across agencies, MDOT should consider the following:

- Provide web-based access to MDOT asset data
- Provide read-only access to MDOT's asset database via a VPN
- Provide requested data via cloud service, Dropbox, or similar service
- Provide requested data on DVD or other portable media

Additionally, MDOT can make the asset inventory available to the general public. The following are general suggestions when sharing the data across agencies and to the public.

A complete asset inventory can also enable MDOT to develop an estimated valuation of state highway assets, a component of a comprehensive and federally mandated transportation asset management plan (TAMP).

Security of certain asset attributes is a valid concern that can be managed by restricting access to sensitive information.

To efficiently share information, MDOT will need to maintain an index or atlas so data requestors know what information is available. Additionally, the requestors should be able to retrieve or request information via a range of selection criteria (e.g., type of asset, route, mile point, and organizational units, such as region city, or county).

5. Implementation Plan

a. Develop RFP for statewide implementation

Based on the results of our research, DMG suggests that MDOT collect its inventory using one, or a combination, of the following technologies: mobile imaging, video logging, photo with LiDAR, video with LiDAR, manual data collection. MDOT should develop an RFP for statewide implementation requiring vendors to propose a data collection approach utilizing these technologies. Based on our findings, these options offer the best value for MDOT.

During this project, we found LiDAR to be comparatively expensive. If a vendor chooses to include LiDAR in its proposed solution, the vendor should price that service separate from the imaging or video service. Due to the increased cost, the vendor should also provide justification as to why the use of LiDAR would be justified and be able to clearly demonstrate that during a proof-of-concept or "spotlight" session.

In addition, MDOT will have to determine which of the twenty-seven assets need to be collected with the remote technology and which assets have already been collected using other means. DMG recommends that the following large assets be collected using alternative means, such as a web-based mapping tool or routine inspections: bridges, pump stations, tourist facilities/rest areas, and weigh stations. Once large assets are identified and recorded, they will only require periodic updates, which can be completed as new assets are constructed and old assets are retired.

Based on the findings of our manual and remote sensing data collection pilot, we have provided the suitability for collecting the remaining twenty-three asset types using each approach in Table 26. The suitability for each method of data collection, in terms of accuracy and precision of results, is rated as H (Highly suitable), A (Acceptable), and N (Not recommended).

Table 26: Suitability of Data Collection Approaches

Asset	Manual	Video	LiDAR	Frequency (years)
"A" miles (CL miles)	H	H	H	1-2
Attenuators (each)	H	H	H	1-2
Bituminous surface (lane miles)	H	H	H	1-2
Catch basin (each)	H	N	N	3-4
Concrete surface (lane miles)	H	H	H	1-2
Culvert (each)	H	N	N	3-4
Curb (miles)	H	H	H	1-2

Asset	Manual	Video	LiDAR	Frequency (years)
Delineator (each)	H	H	H	3-4
Designated snowmobile crossings (each)	H	N	N	3-4
Ditch (linear miles)	H	N	N	3-4
Freeway light (each)	H	H	A	3-4
Gravel shoulder (miles)	H	H	H	3-4
Guardrail (linear feet)	H	H	H	1-2
Guardrail ending (each)	H	H	H	1-2
Lineal feet of existing ROW fence (feet)	H	A	N	3-4
Lineal feet of soundwall (feet)	H	H	H	3-4
Mowable acres (acres)	H	N	N	3-4
Non-motorized trail (feet)	H	N	N	3-4
Paved shoulder miles (miles)	H	H	H	1-2
Sign (each)	H	H	H	1-2
Sweepable approach (each)	H	H	H	1-2
Total lane miles (miles)	H	H	H	1-2
Traffic signal (each)	H	H	H	1-2

H=Highly Suitable, A=Acceptable, N=Not Suitable

The necessary frequency of data collection for inventory purposes depends on how often the asset locations and quantities are likely to change, as well as any state or Federal reporting requirements that may apply. Bridges are inventoried and inspected at two-year intervals and a many pavement characteristics are reported annually (although the data may be collected on a two-year cycle). For other assets that are safety-related (namely signs, guardrails, crash attenuators, traffic signals, and freeway lights), a 1 to 2 year cycle should be sufficient. For other less-critical assets, an inventory update frequency of every 3 to 4 years is acceptable. The recommended data collection frequency for each asset is shown in Table 26.

After developing the initial asset inventory, the most efficient approach for keeping the inventory up-to-date is to establish a department-wide policy that no asset will be added, modified, moved, or removed without notifying the office(s) responsible for maintaining the inventory database(s) of the change. Maintaining the inventory could be done by using a modern asset or maintenance management system (MMS), many of which allow for reporting work and location data for specific assets. Additionally, MDOT can require the same asset inventory update information from contracted maintenance firms, as well as through the importing as-built construction plans into the asset inventory. By applying these practices, MDOT can increase the amount of time between asset inventory data collection cycles, or, in the case of some assets, eliminate the need for them altogether.

In order to fully realize the benefits of the economies of scale, we recommend that MDOT collect all assets statewide within a single RFP. However, if MDOT wishes to limit its asset collection in order to minimize costs, we have ranked assets based on relative importance. With most technologies, inventory collection costs will be the same no matter what number of assets are collected. The cost changes based on the number of assets extracted from the collected data. Based on the ranking of these assets, nine received the highest designation, which we would recommend as the most important assets to be collected. It is more useful for planning and budgeting for MDOT to obtain an accurate statewide inventory for these priority assets than it is to develop a complete inventory of all twenty-seven assets in a specific region. These high priority assets are listed in Table 26.

Table 26: High Priority Assets

Lane miles	CL miles	Attenuators
Concrete lane miles	Guardrail	Bridges
Asphalt lane miles	Guardrail endings	Traffic signals

We recommend that MDOT include multiple divisions and regions within the department during the scope definition phase. This will provide an opportunity for a variety of stakeholders to establish their priorities for roadway asset categories. In addition, this approach would provide an opportunity for stakeholders to offer input and identify opportunities to maximize the utilization and effectiveness of the asset inventory data across the entire department.

Once highway assets are selected, they must be clearly defined. As discussed previously, there were several assets that were ambiguously described during the pilot. DMG recommends that MDOT host a pre-proposal conference to specifically define the assets that the vendor will collect. The meeting should, at a minimum, answer the following questions.

- How does MDOT distinguish between attenuators and guardrail endings?
- How does MDOT define a catch basin versus other surface drainage features?
- Where should the guardrail measurement start and stop when the guardrail continues around an intersection corner?
- What areas adjacent to the roadway should be counted as mowable—only state maintained routes or all routes?
- How much clear space adjacent to the roadway is required to constitute a shoulder?

- Where should measurement stop when a length of ditch runs perpendicular to the roadway?
- How should the inspector identify sweepable approaches in the field?
- Should traffic signal units be counted, or traffic lights, or both?

Additionally, DMG recommends that MDOT record the results of the pre-collection meeting in a formal procurement document that can be referenced as needed, both internally and by potential vendors. The document should include clear asset definitions, as well as supporting images, which should minimize the risk of asset misinterpretation during field collection.

Within the RFP, MDOT will clearly define several aspects of the desired project scope. These aspects are identified and described in Table 27 below.

Table 27: MDOT Responsibilities

MDOT Responsibility	Description
Assets to be inventoried and the attributes to be measured for each	This list and description will be further defined in the pre-proposal meeting.
Asset prioritization	If the scope does not include the entire system, the RFP should define how assets should be prioritized for collection.
Construction mitigation strategy	MDOT must describe how to proceed if a route is under construction
Technology to be used for collection, or a list of acceptable options	Based on the recommendations within this report, MDOT should specify what technology or technologies are acceptable for the vendors to use.
Data delivery requirements	MDOT should require the vendor to deliver the data in a format that is compatible with its current geodatabase.
Project completion date	This date will be determined based on the scope and RFP date.
Progress reporting requirements	MDOT should require the vendor to update it on collection and extraction progress throughout the project, as well as the development of additional deliverables as necessary.

In response to the RFP, the vendor's proposal should include, at a minimum, the content listed and defined in Table 28.

Table 28: Vendor Responsibilities

Vendor Responsibility	Description
Understanding of project	Vendor must show an understanding of the objectives and scope of the project, as well as a professional ability to communicate its understanding.
Project experience	Vendor must provide description and reference for at least one project of similar type, size and scope, successfully completed within the last five years.
Data collection methodology	Collection methodology must be proven, and the vendor must have experience with the proposed technology.
Process for data extracting, processing, and delivery.	Vendor must describe how data will be extracted, processed and delivered. Method and delivery must be compatible with current MDOT geodatabase.
Quality assurance/quality control methodology	Vendor must describe procedures that will be followed for quality assurance/quality control
Attend a mandatory pre-proposal meeting with MDOT staff to review project.	Review will include all topics referenced within this table, as well as safety requirements, contact information, and further clarification of assets, as referenced within this report.

b. Review proposals and create short list of vendors

Once they have been submitted, the MDOT selection committee will review the proposals and create a short list of potential vendors. Vendors on the short list should have experience collecting inventory data on projects similar in scale to what is defined in the RFP and be able to meet all requirements listed in the RFP. A general guide for creating the short list should include the considerations shown in Table 30.

Table 30: Vendor Short-list Considerations

Vendor Short-list Considerations	Description
Understanding of project	Did the vendor's proposal demonstrate a clear understanding of project objectives and requirements?
Adequate experience	Has the vendor successfully completed a project of similar type, size and scope within the last five years?
Requisite staff qualifications	Does the vendor's proposed staff have adequate qualifications to successfully complete the project?
Approach, work plan, and schedule meets MDOT requirements	Did the vendor propose an approach, work plan, and schedule that meets MDOT requirements?
Proposed technology within allowed options	Does the vendor propose to use data collection technology as specified, or allowed, in the RFP?
Proposal is compliant with all RFP requirements	Does the vendor's proposal comply with all requirements in the RFP?

c. Mandatory vendor demonstration

As part of the RFP process, MDOT should require each vendor to conduct a demonstration, or “proof-of-concept”, of its technology and data output. This demonstration should be over a relatively short section (approximately ten miles) to validate the vendor’s ability to deliver accurate and useful inventory data. The demonstration will also enable MDOT to identify opportunities for improvement to any of the project components. For instance, demonstration results may indicate that there is an issue with asset definitions, which leads to the misidentification of highway inventory. A vendor demonstration ensures that MDOT has fully vetted all aspects of remote asset inventory collection prior to statewide implementation.

The proof-of-concept will also provide the vendor with an opportunity to demonstrate the cost effectiveness of supplemental LiDAR data, if proposed.

d. Review vendor demonstration results

MDOT will receive the results of the demonstration and conduct QA on the results, including a DTMB geodatabase review, which includes the following:

- Accuracy of asset location compared to other vendors and within allowable tolerance of baseline data, if available
- Precision of defined assets (e.g., is guardrail identified as guardrail, not curb?)
- Completeness of the geodatabase against the requirements and ensure it can easily be integrated into the enterprise GIS

e. Select vendor

Based on the results of the vendor demonstration, MDOT will select a vendor. Assuming multiple vendors can successfully deliver inventory data sufficient for MDOT’s expectations, MDOT could select the vendor based on the list of selection criteria and scoring factors shown in Table 31.

Table 29: Vendor Selection Criteria

Selection Criteria	Value
Price	50%
Project Schedule	25%
QA/QC provisions	20%
Proximity to Michigan	5%