Utilization of Lidar Technology — When to Use It and Why

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Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

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Utilization of Lidar Technology — When to Use It and Why

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16. Abstract

Lidar technologies can assist transportation agencies during the design, construction, and maintenance phases of transportation projects. While Lidar has numerous applications, successfully deploying Lidar technologies is only possible if agencies have a solid understanding of their use cases and potential limitations. This report offers guidance the Kentucky Transportation Cabinet (KYTC) can use when making decisions on how to employ Lidar technologies in highway contexts. In addition to reviewing Lidar platforms and comparing Lidar-driven surveying to traditional surveying methods, the report examines challenges related to processing and storing Lidar data and the safety benefits Lidar technologies confer in the field. Brief case studies are presented which describe how Kentucky Transportation Center researchers have used Lidar to improve KYTC operations and asset management. Examples include measuring structure clearances, analyzing problematic road geometrics and monitoring slides. While Lidar technologies are beneficial, they are not appropriate for every project. As project size and complexity increases, the benefits of using Lidar technologies multiply.

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Section 1 Introduction

Over the last decade, transportation applications of Lidar have grown quickly, with agencies moving to deploy Lidar technologies in many contexts. Successfully implementing Lidar technologies demands choosing the right tool for the job while being aware of potential limitations. This report offers guidance the Kentucky Transportation Cabinet (KYTC) which can be used when making decisions on how to employ Lidar technologies in highway contexts. It reviews Lidar operations, hardware, and platforms; discusses accuracy expectations and guidelines; reviews data storage and software considerations; evaluates previous research on cost analysis; and looks at several projects that illustrate the challenges, benefits, and limitations of Lidar.

This report refers frequently to a National Cooperative Highway Research Program (NCHRP) study from 2013 — *Guidelines for the Use of Mobile LIDAR in Transportation Applications* — which was published through cooperation of professional researchers and includes studies sponsored by the American Association of State Highway and Transportation Officials (AASHTO).[a]

[a] The report can be found online at:
https://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP15-44_FinalGuidelines.pdf

Section 2 Previous Research

Chang et al. found the use of mobile Lidar systems has increased at transportation agencies throughout the United States. [1] Surveyors, engineers, and technicians are more informed about and open to Lidar, seeing it as a potential cost-effective alternative to traditional surveying methods. Using Lidar carries many benefits: higher levels of safety, productivity, applicability, and detail acquisition. Mobile Lidar excels over traditional methods as its ability to collect data from a distance at highway speeds reduces or eliminates the need for lane closures and exposure to hazardous environments. Mobile Lidar improves the safety of field personnel as well as the traveling public during data collection. However, widespread acceptance of using laser scanning to replace traditional methods has not occurred. Several reasons explain this reluctance — laser scanning systems are still expensive, workflows are complicated, and the size of datasets tend to overwhelm many computer systems. The data also requires trained staff and technicians to post-process and extract accurate deliverables. Chang et al. concluded that more evidence is needed to determine when a specific Lidar platform should be applied in lieu of traditional methods for various applications.

In 2013 NCHRP surveyed state departments of transportation (DOT) agencies to identify existing and emerging transportation applications of Lidar. Applications they had the most experience with included engineering surveys, mapping, and digital terrain modeling. Survey respondents reported they expected their agencies to adopt Lidar in all applications over the next five years (Figure 2.1).

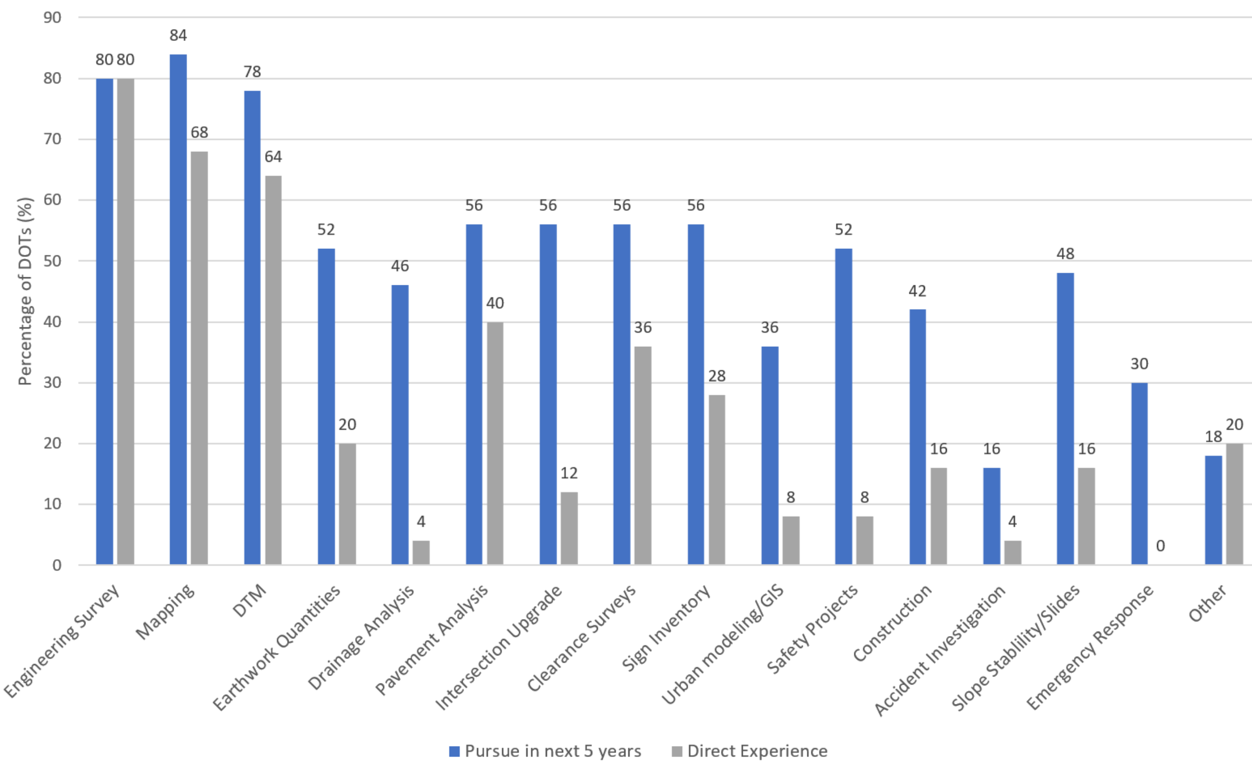

Figure 2.1 DOT Experience and Future Lidar Applications

Respondents rated the importance of Lidar technologies to future agency operations using a a 10-point scale (1= unimportant, 10 = very important). The mean score was 7.8, indicating DOTs regarded these technologies as very important to future operations.[2]

Since 2013, additional research has shown continued interest in and use of Lidar for transportation applications. As such, if the survey were conducted again the results would look much different, reflecting the continued growth of Lidar in all areas and the emergence of new applications.

2.1 Lidar vs. Traditional Methods

When surveying with a total station or GNSS, field crews collect data on a single point at a time, but Lidar systems can capture millions of points per second, significantly reducing how long it takes to complete data collection. Traditional surveying methods often require spending a significant amount of time in the field with a survey crew, followed by an equivalent or lesser amount of time in the office post-processing data.

Using LIDAR alters the traditional survey workflow from one where decisions are made in the field to one in which decisions are made in the office.[2] When using Lidar, fieldwork may only account for about 10% of the time needed to produce a deliverable. However, depending on the project scope, it can be more expensive to use Lidar than to survey using traditional methods. Post-processing Lidar data takes longer than traditional surveying methods.

2.2 Lidar Platforms

The three common Lidar system platforms are: (a) fixed terrestrial systems (FTS), where the scanner is mounted to a stationary surveying tripod; (b) aerial systems, which are mounted to aircraft or unmanned aerial systems (UAS); and (c) mobile Lidar systems (MLS), which are affixed to ground- or water-based vehicles (Figure 2.1).

Figure 2.2 Lidar Platforms

Fixed Terrestrial

Most FTS use a laser and rotating mirror to rapidly scan and image targeted objects and surfaces. Commonly mounted on a tripod, their static location allows operation without georeferencing. However, targets can be established on known coordinates for additional geodetic control and data registration. Due to their static location, FTS typically achieve the highest level of accuracy and point density of the three platforms.[3] Scanning operations on roadways may require traffic control because equipment and operators must work in close proximity to the targeted object. Depending on the project, additional post-processing may be needed to remove noise in the scan data created by vehicles.

Aerial

Aerial Lidar systems use scanners mounted on rotary or fixed wing aircraft to scan objects and surfaces. Global navigation satellite system (GNSS) receivers, an inertial measurement unit (IMU), and other onboard sensors establish the aircraft's position, orientation, and direction. Aerial systems collect data remotely and do not interfere with traffic. Depending on altitude, aerial systems may lack the scanning densities of FTS and MLS. [3] Lower density limits its utility to large-scale applications (e.g., topographic mapping); however, when deployed at lower altitudes, densities may be improved.

MLS

MLS are installed on ground-based vehicles. Mobile scanners are very effective for investigating highway corridors or large areas accessible by car, train, or boat. GNSS and IMU devices providing location and orientation data are critical for the absolute accuracy of MLS. Most MLS can collect data at highway speeds within the flow of traffic. In addition to increased efficiency of data collection, benefits of MLS include the minimization or elimination of traffic control, traffic disruptions, and safety hazards[3].

2.2 Components and Operation

Fixed Terrestrial

FTS scanners and operations are the least complex. Given their static position, there is no need to account for changes in location or vehicle trajectory when scanning. Most FTS models are tripod mounted and comprised of the Lidar components, a built-in operating system, control interface, and an optional GNSS and/or RGB camera. Scan times vary based on user-defined accuracy, density, and targeted regions. FTS often require numerous scans and setups to provide adequate coverage. After scanning is complete, post-processing software uses targets or like features in the dataset to align or register individual scans to their respective locations. Multiple scans and setups can introduce errors and prolong post-processing efforts during registration.

MLS and Aerial

MLS and aerial systems share many of the same components and consist of two sub-systems: geopositioning and Lidar components. The geopositioning system includes the GNSS receiver(s), a Digital Measurement Indicator (DMI), and an Inertial Measurement Unit (IMU). The three components of the geopositioning sub-system work together to synchronize sensor(s) outputs. GNSS antenna(s) collect satellite positioning data, the IMU records inertial measurements and orientation (e.g., pitch, roll, yaw), while the DMI (mobile only) collects speed and linear distance information. Data post-processing yields an accurate representation of the vehicle's trajectory and orientation parameters along the traveled route.

The Lidar system is made up of laser scanner(s), a control unit, a logging computer for data synchronization, and a laptop PC used to control system functions. Laser scanners measure surroundings using light pulses to obtain range and angle measurements. Measurements are calculated using time of flight (TOF), where the scanner sends a laser pulse to the target and the time difference between the emitted and received pulses is used to determine the range from the scanner. The range (*R*) is calculated using the following equation:

$$R = \frac{1}{2} c\Delta t$$

Where c = the speed of light and Δt = the pulse's TOF.[4] Figure 2.3 illustrates common components of an MLS.

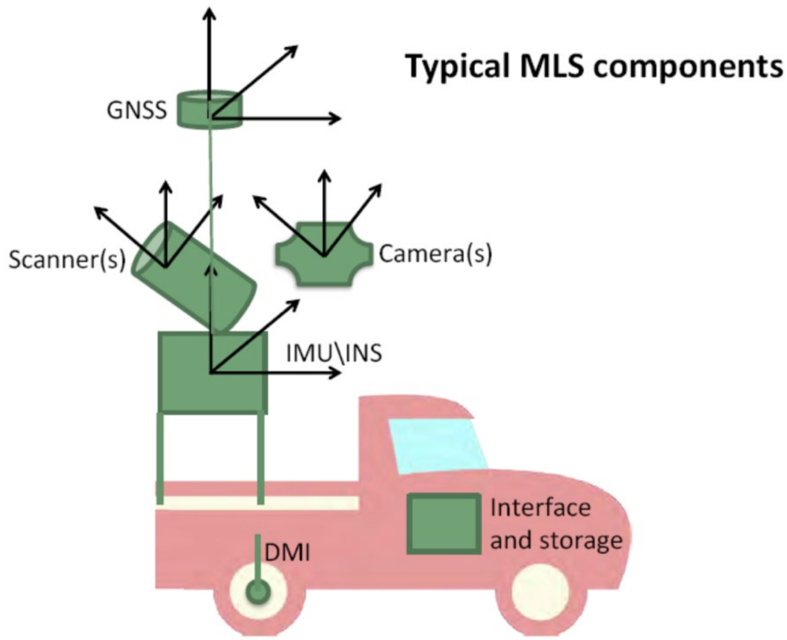

Figure 2.3 Typical Lidar Components

Post-processing geopositioning data produces a trajectory depicting a three-dimensional (3D) representation of the traveled route. This trajectory is synchronized to Lidar scanner outputs, correlating with the time of incidence.[4] The resulting data are an accurate 3D collection of surface measurements — referred to as a point cloud.

Lidar scanners can also extract surface reflectance properties. Each scanned point can be assigned an intensity value based on the pulse's return strength. Surface properties affect the amplitude of return pulses. Individual amplitude values are assigned within a defined numeric range which can be displayed over graduated color tables. Based on intensity properties, visualization software can differentiate between low-reflectance surfaces (e.g., pavement, structures) and highly reflective surfaces (e.g., lane striping, signage). Figure 2.4 shows differences in point cloud data with and without intensity values.

Figure 2.4 I-264 Tunnel with (Left) and without Intensity Values (Right)

Accuracy

An important consideration when determining if Lidar is viable for a specific project is achievable accuracy. There are two types of accuracies — network and relative. Network accuracy is determined by the position of the dataset relative to known geospatial locations, while relative accuracy refers to the accuracy of collected features or point-to-point distances. The same level of accuracy is not recommended for all applications. In some cases the relative accuracy of the point cloud is more important than the geospatial accuracy (e.g., Lidar data on bridge clearances). Here, the relative accuracy is essential, but the network or geospatial accuracy of the point cloud is less critical. The NCHRP report defines suggested network accuracy and density requirements based on application (Table 2.1). Network accuracies may be relaxed for applications identified in red italics and can change based on project needs or DOT requirements.[2]

Table 2.1 Matrix of Suggested Accuracy and Densities by Application

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

Achievable accuracies vary by platform. Table 2.2 provides known vertical accuracies for different geospatial data acquisition tools. Values vary between manufacturers and can potentially be affected by numerous factors limiting accuracy. Additionally, different collection methods produce different post-processed data sets: photogrammetry (images), Lidar (point cloud), and GNSS (coordinates). Methods should be chosen to align with project deliverables. Not all methods produce the same result.

Table 2.2 Achievable Accuracy by Data Collection Method

Data Collection Method	Optimal Achievable Network Accuracy (RMS)
Aerial Photogrammetry — sUAS	0.03m (3D)
Aerial Photogrammetry — Fixed wing	0.05m (3D)
Aerial Lidar — Fixed wing	0.05m (Vertical)
Aerial Lidar — Low-altitude helicopter	0.04m (Vertical)
Mobile Lidar	0.03m (3D)
Terrestrial Lidar	< 0.01m (3D)
GNSS — RTK	0.01m (Hz), 0.02m (Vt)

* Values represent the best results achievable on hard, well-defined surfaces. Lower accuracy is expected in more complex terrain and areas with dense vegetation.[11]

Most commercial providers of Lidar equipment apply geometric corrections during post-processing using differential GNSS (DGNSS). A statewide continuously operating reference system (CORS) network, base station, or a combination of the two is used to improve overall data accuracy and mitigate issues with the computed vehicle trajectory, usually caused by GNSS coverage outages or multipath due to obstructions (e.g., vegetation, overpasses, buildings). Depending on the application, additional adjustments may be required to align data with known coordinates. Accuracy guidelines often refer to network accuracy, where Lidar data is tested against known control points. In these scenarios, targets surveyed using a total station or GNSS are placed along the collection route. These targets or control points are identified in the laser data, and the point cloud is adjusted or tied down to the control points.

Mapping vs. Survey Grade Systems

Two grades of MLS accuracy are available: mapping and survey. A lower-grade laser and IMU are often used in mapping-grade systems, whereas a high-end laser and IMU are used in survey-grade systems. According to Olsen et al.,[2] mapping- and survey-grade systems are defined based on level of achievable accuracy. Mapping-grade systems can produce 3D point accuracy of 5 – 20 cm, whereas point accuracies for a survey-grade system are < 5 cm.

Hauser et al.[5] compared point cloud accuracies generated from a survey-grade Reigl VZ-400 FTS scanner to those from a mapping-grade Velodyne HDL-32E MLS scanner. The study used a point-to-plane comparison to evaluate each dataset. Twenty-five corresponding planar surfaces of 1 – 2m were selected from each dataset; a least-squares fit approach was used to determine the best fit equation for each surface. Point-to-plane distances were calculated for MLS and FTS planes, with distances considered the residuals of points from their true location. Additional evaluations were performed on the dataset, however, all methods agreed to within a few centimeters. This study found that the mapping-grade MLS system could collect point clouds with a 3D accuracy > 10cm, but could not collect data at the survey-grade level (< 5cm). Objects were much more defined in the survey-grade dataset, which is critical as the difference in level of detail and accuracy may determine to what extent the system can effectively be used (Figure 2.5)

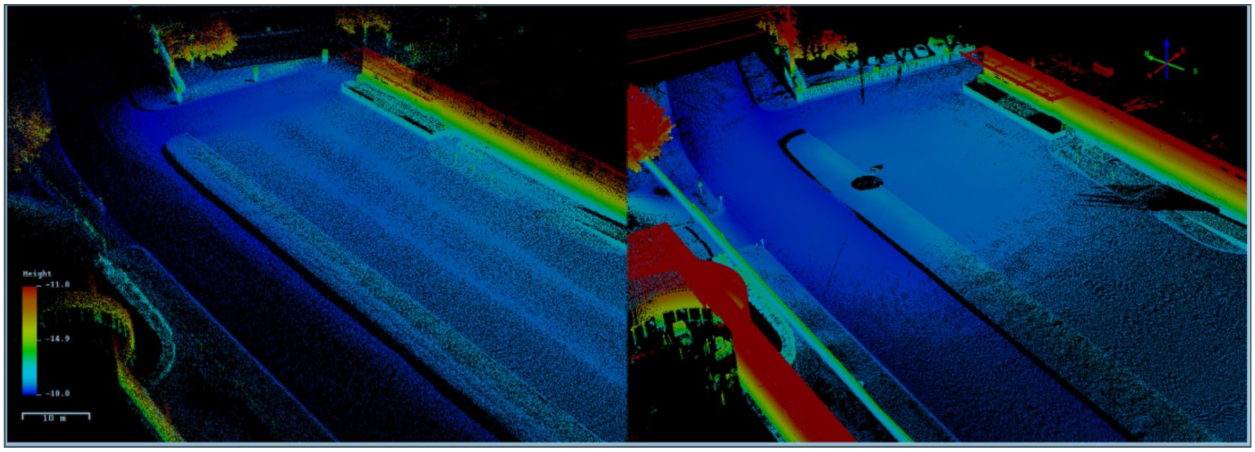

Figure 2.5 Mapping (Left) and Survey Grade (Right) Point Clouds

Deciding whether to use a mapping- or survey-grade system hinges on the needed accuracy and/or detail. Survey-grade systems are more accurate but come at a higher cost, while mapping-grade systems are less accurate but provide a cost-effective option depending on project requirements.

Guidelines for LiDAR Survey Control (HD-301)

The excerpt below summarizes KYTC's guidelines for survey control of Lidar applications.[b] Due to the evolving software and mapping techniques for Lidar technologies, the procedures listed may be altered with approval from KYTC's state survey coordinator.

> *KYTC surveying standards for highway projects utilizing LiDAR state that data must be tested to meet a 95% confidence interval root-mean-square error (RMSE) for the type of data collected by either airborne, mobile or stationary scanners. In order to validate the data, control points must be established within the project. These control points are defined as supplemental control and require a 2 cm network accuracy, 95% confidence, and be tied to project control monuments. Guidelines for control point layout and local positional accuracies differ between methods as discussed below.*

Fixed Terrestrial Scanner (FTS)

An FTS acquires data at a specific range. Since ranges differ between manufacturers, vendor-specific targets tuned for the laser frequency and distance interval of the instrument are recommended. Control and validation targets should be placed at the recommended distance from the scanner and scanned at high density. Additional scans should be spaced so that 5 – 15% overlap can be obtained from the adjacent scan. Best results are typically seen when targeted control stations are evenly spaced throughout the project. Variation in target elevations is desirable to aid scan-to-scan registration. Hard surface topographic TLS surveys require control and validation point and surveyed local position accuracies of Hz ≤ 15mm and Z ≤ 15mm. Figure 2.6 is an example of an FTS project layout.

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[b] The complete document can be found at: https://transportation.ky.gov/Highway-Design/Survey%20Documents/KYTC%20Survey%20Manual-Chapter%20300.pdf

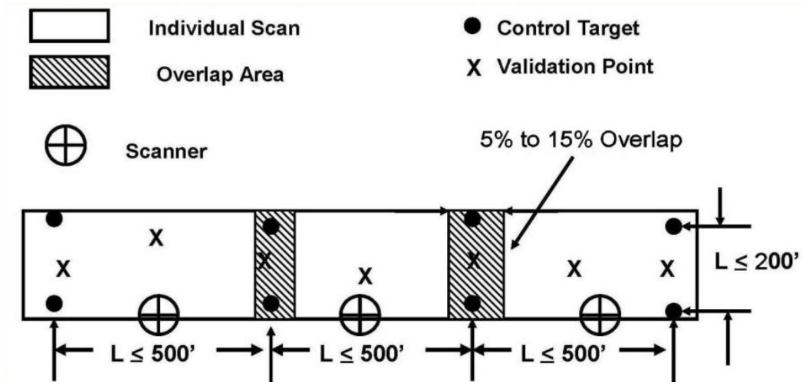

Figure 2.6 Example of FTS Control Layout

MLS
Mobile mapping control points falls into two categories *Transformation* or *Validation*. Transformation points serve as the control for processing point clouds. Validation points are used to check the geospatial data adjustment to the transformation points and allow for quality assurance/quality control (QA/QC) checks of adjusted scan data. Both point types should be spaced evenly throughout the project.

The scanned area should have control on both sides of the road. Validation points should be spaced at a maximum of 500’ intervals and transformation points at 1,500’ intervals (Figure 2.7). MLS surveys require local points to have surveyed local positional accuracies of Hz ≤ 15mm and Z ≤ 15mm or better. Differential digital leveling is the preferred method of establishing transformation and validation of point elevations.

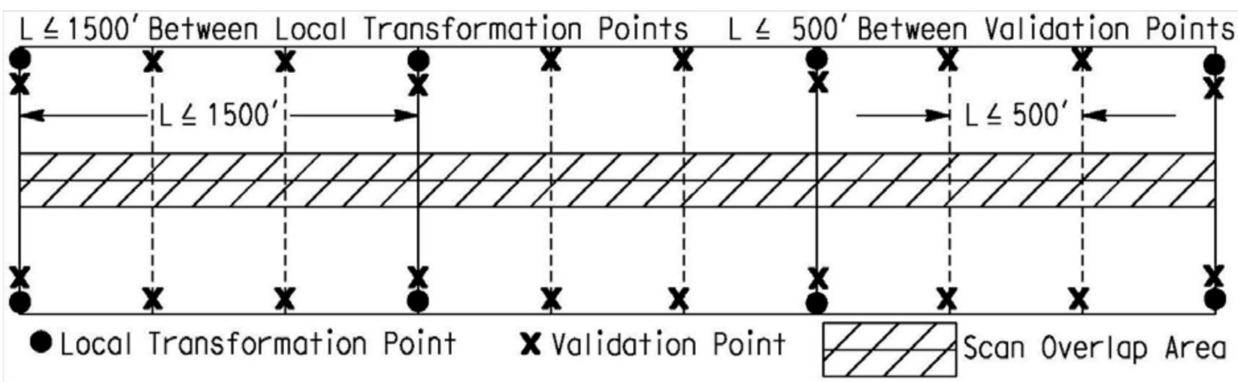

Figure 2.7 Example of MLS Control Layout

Aerial Mapping Control
All controls set for KYTC aerial mapping should be tied to a primary control and spaced as required by project conditions. Project control may be used if no primary control is available. Control points may be placed after Lidar acquisition is complete, assuming ground conditions are unchanged. Preference should be given to points associated with permanent, recoverable structures so they may be used in future survey work (e.g., manholes, curbs, utility structures).

Network vs. Relative Accuracy
Establishing control points allows point cloud data to be adjusted and tested for accuracy against known coordinates. But control points are not always necessary.

Clancy[6] found that in many instances Lidar data used to determine clearances for bridges, overpasses, power lines, and signage do not benefit from absolute, or network-grade accuracy provided by established control. In many applications relative point-to-point accuracy provided by the scanner is more important than the absolute georeferenced accuracy. Projects using relative accuracy are not limited to clearances. Crash investigations, pavement analysis, hydraulic analysis, asset identification and other applications can be analyzed without establishing control. Omitting the control component saves time and expense, especially on large-scale projects. However, if Lidar data are to be used as inputs into other technologies or operations reliant on geospatial location, accurate absolute accuracy is imperative.

2.3 Processing and Software

With traditional surveying methods, most of the project is spent collecting data in the field. Conversely, when Lidar is used, most project workflows occur in the office. Most Lidar workflows include some or all of these processing tasks:

(1) Apply corrections to the data from boresight (if applicable)
(2) Georeferencing/coordinate system transformation
(3) Mapping color/intensity information
(4) Point cloud creation
(5) Filtering/removal of noise/unneeded points
(6) Feature extraction
(7) Analysis or model generation[3]

Figure 2.8 presents a typical workflow for MLS surveys. Modifications may be needed depending on the scope and deliverables.

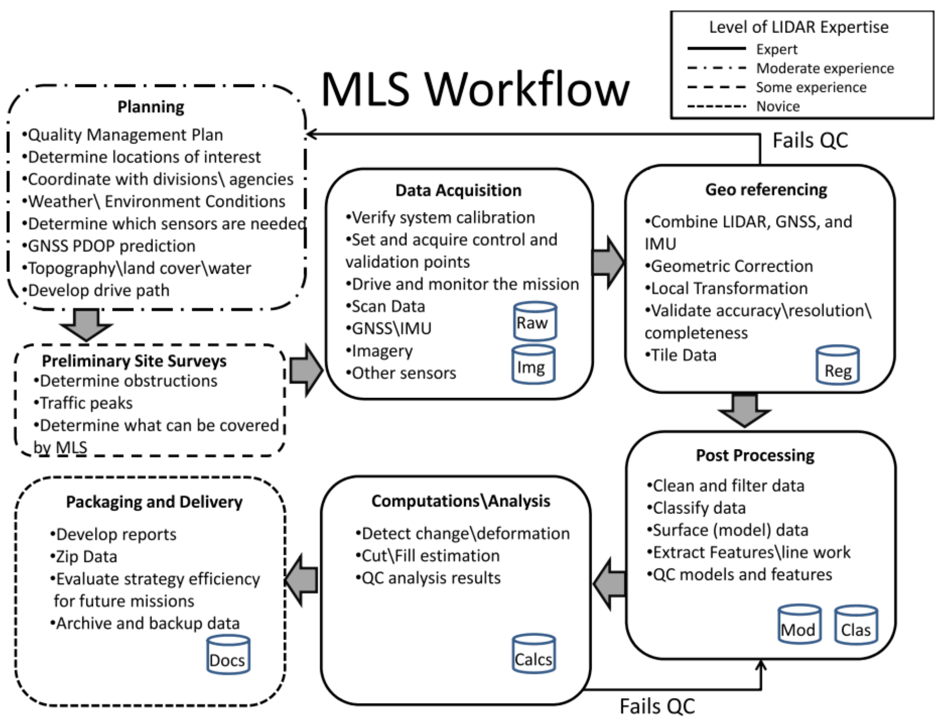

Figure 2.8 Typical MLS Workflow

Once data have been acquired and downloaded, they must be georeferenced and validated. During this phase trajectory information collected from the GNSS, IMU, and DMI is post-processed with vendor-specific software packages. Using data from external GPS and/or CORS base stations to compute corrections for the vehicle's receiver, software exports an accurate overall position and orientation solution, resulting in a smoothed best estimate of trajectory (SBET) file. Further processing aligns the SBET file with Lidar outputs from the scanner(s) through the correlation of GPS timestamps. Additional corrections and coordinate system transformations are applied if needed.

The end result is a file containing a list of spatially accurate points, which are in turned used to create the point cloud.

A point cloud is a text file that contains X, Y, and Z values for each measurement. Additional data (e.g., intensities, RGB values) are added to the text string if used. Point clouds can be exported in multiple file formats, however, the log ASCII standard (.las) file extension is one of the most universal and compatible with most software.

In raw form, a point cloud provides a comprehensive 3D representation of the scanned area. Although this can be useful for some forms of visualization, most project deliverables (e.g., lane lines, signage, clearances, surface models) are obtained from analyzing and/or extracting features from the point cloud. Vendor-specific software often lacks the tools required to evaluate or extract data, which has resulted in the growth of third-party software. Although Bentley Microstation and Autodesk AutoCAD have incorporated point cloud processing tools into certain software suites, third-party providers specializing in Lidar data extraction have increased in popularity.

To gather information on software experience and use, the California Department of Transportation (Caltrans) administered a survey on software platforms and feature extraction via the American Association of State Highway and Transportation Officials (AASHTO) Research Advisory Committee. Six private consultants and 19 states responded. The survey found the most common software packages for point cloud feature extraction were Topodot (13), Survey Control Centre (2), Trimble Business Center (2), Cardinal Systems VR (1), Mandli Roadview (1), Terrascan (1), Terrasolid (1), Polyworks (1), and Unspecified (1). Survey respondents were split on the question of whether different software packages were used to extract specific features (Yes (14), No (9)). Some respondents provided reasons for using multiple software packages, with most explaining that some software outperforms others in certain tasks. For example, one consultant uses Topodot exclusively, except for point cloud classifications, where ArcGIS Pro is preferred.[7]

Software should be selected based on project requirements. In many cases, multiple software suites are used to build a final product. Compatibility with an organization's existing software should also be considered because exchanging data between different platforms can be problematic.

2.4 Data Storage

Organizations realize the greatest value from Lidar data when they are shared across departments and integrated into relevant workflows. Many challenges are associated with managing extremely large Lidar data sets, but a centralized data model that enables collaboration between departments is critical to eliminating single purpose data applications.

Storing large Lidar datasets in an organization's system can be costly and resource-intensive. While storage costs have decreased, the cost of accessing and managing data has not. Furthermore, manufacturers are always improving technology, resulting in systems with new capabilities that operate faster and collect more data. The cost of efficiently storing and distributing data rises as the number of employees who require access increases.[2]

Choosing an effective network and/or storage configuration can be difficult. Factors that warrant consideration generally fall into one of three categories as described in the NCHRP study:

Local — The simplest approach. Files are stored locally on the host workstation. The primary advantage of this configuration is optimization of file read/write/transfer speeds. The speed of processing and analysis also increase when data reside on the host workstation. The main disadvantages of this strategy are poor access to data across the organization and hardware failures resulting in data loss.

Local area network (LAN) — Files are stored on a local file server connected to multiple workstations through a local network. Server throughput and network speeds may limit access. As a result, a high-speed connection and servers designed to manage large amounts of attached storage are suggested.

Wide area network (WAN) — No local storage of files. WANs (i.e., cloud storage) are a popular and economical alternative that use a third-party storage provider. Offsite data storage reduces local storage requirements. Files can be downloaded and shared from any location with a network connection. Key disadvantages of WANs include security concerns, long upload/download times for large datasets, and cost. [2] Additionally, WAN storage for Lidar data may evolve in the future. For light users of Lidar data, vendors are developing a Software as a Service (SaaS) option, which uses a lightweight third-party application accessible via internet which can be used to upload and view point clouds, giving users with less powerful workstations the ability to work with large datasets. However, the SaaS option is mostly used for visualization or simple measurements — analysis and extraction tasks are limited.

A combination all three solutions could be the most effective. A workstation connected to a local network, for example, could be dedicated to data transfer and post-processing. Data can then be uploaded to the cloud or LAN, where multiple users can access them.[2]

Table 2.3 lists file sizes of data collected using a mapping-grade MLS for an eight-mile stretch of I-5 in Oregon. In addition to the main corridor, ramps and frontage roads required additional passes to obtain adequate coverage, resulting in 65 total scanned lane miles. Raw and post-processed data files totaled 313 GB (4.8 GB per mile). Upon completion, the project had generated 481 GB of data, an average of 7.4 GB per mile — not including archives or backups.[9] File sizes differ greatly depending on the system used and data collected. For instance, Leica's Pegasus 2 mobile mapping system estimates 1.6 GB per mile for post-processed imagery and point cloud data.[13]

Table 2.3 File Sizes for Oregon DOT Project

	Length (Miles)	Raw Files (GB)	Processed Files (GB)	Deliverable Files (GB)	Totals (GB)
Mainline	23	40	96	53	189
Ramps and Frontage Roads	42	69	108	115	292
Totals	65	109	204	168	481

Lidar data obtained through either in-house or contracted services should be archived at the highest level of processing. Collected data may be valuable for future projects or assessments. Data storage configurations should be selected to allow easy access and collaboration between departments.

2.5 Cost Analysis

Lidar has many applications, however, it is not the best tool for all projects. It should not be treated as a one size fits all solution. In some circumstances, agencies may be more concerned with the final product and not the data acquisition technique. Cost-benefit analysis can help agencies determine if Lidar is a viable solution.[2]

Table 2.4 lists tasks and estimated cost increments for an MLS survey; static and aerial surveys are also applicable in certain categories. Data acquisition, georeferencing, extraction, and modeling tasks carry the highest expenses, likely due to equipment mobilization and time allocation. Workflows and expenses vary depending on application, project scope, and other considerations.

Table 2.4 Estimated Cost Increments by Task

Workflow/Deliverable Stage	Cost Increment	Consideration
Planning and Acquisition	$-$$$$	Acquisition could be a small part of the project for limited area or a large part acquiring for statewide collection. Planning, in most cases will be a small part of the project.
Geo-reference point cloud	$-$$$$	Geometric corrections and/or local transformation. Higher accuracy requirements will result in significantly more expense due to additional field procedures and advanced processing
QA/QC evaluation	$	Depends on requirements. High accuracy work requires significantly more QA/QC evaluation.
Tile/Organize Data	$	A variety of software is available to complete this task.
Sanitize Point Cloud	$$	Removal of unwanted features and outliers. Depends heavily on traffic conditions at time of collection.
Classify Point Cloud	$$	Depends on classification features. Ground vs. non ground is relatively inexpensive. Additional features require sophisticated algorithms and manual techniques.
Data Extraction	$$-$$$$	Point extraction and line work to develop DTM's, maps, or other deliverables.
Model 3D Objects	$$$-$$$$	Depends on the type of objects modeled. Some semi-automatic workflows exist. Others require manual processes.
Analyze	$-$$$	Depends heavily on the type of analysis needed.

Estimating project costs can be difficult. Generally, the largest influence on the cost of a Lidar project is accuracy requirements.[2] Projects requiring high accuracy may need extensive control established in the field (see HD-301). Additional control may be required in areas with complex environments where GPS solutions are hindered (e.g., tunnels, tall buildings, overhead vegetation).

The Missouri DOT (MODOT) conducted a study that compared the cost of Lidar to traditional survey and aerial mapping methods for a project on a seven-mile highway segment. The study tracked costs for planning, data acquisition, and post-processing deliverables (surface model, volumetric evaluation, and feature extraction). The study found conventional aerial mapping and aerial Lidar were the most cost-effective, followed by mobile Lidar, traditional surveying, and terrestrial Lidar (Table 2.5).

Table 2.5 Missouri DOT Cost Comparison Table

Data Collection Method	Hours	Person Days	Labor Cost ($)	Cost Per Mile ($)
Airborne Lidar	444	55.5	58,250	8,321
Conventional Aerial Mapping	548	68.5	55,234	7,891
Mobile Lidar	726	90.8	81,688	9.933
Traditional Survey Design	1,281	160.1	131,585	18,798
Static Terrestrial Lidar	1,700	212.5	205,805	29,258

Costs vary based on final scope of work, level of detail, approach, application, and other market factors[9]. When extracting deliverables, the study found that not all methods provided a comparable result. Terrestrial and mobile Lidar generated dense datasets of the roadway but failed to capture steep ditches or areas blocked by buildings. Aerial Lidar data were sparse in areas and lacked sufficient density to extract small features. Photogrammetry did not have enough detail to distinguish the roadway crown and small elevation differences.

This study demonstrates that data collection methods should be selected based on project requirements. In some situations, a combination of methods may be necessary to produce required deliverables. Since Lidar is an efficient form of data collection, MLS and aerial datasets for large projects can be acquired quickly. On small or mid-sized projects other technologies may be a more practical option. The value of Lidar increases exponentially as project size and complexity increase.

2.6 Work Zone Safety

Several studies have highlighted Lidar's safety benefits.[1,2,3,4,11] A key advantage of mobile and aerial Lidar is their ability to collect data remotely or within prevailing traffic flows, resulting in minimal traffic impacts and reducing the need for lane closures. Additionally, Lidar systems can be operated in dark environments during off-peak traffic flows. Data collection can proceed without exposing workers and the public to traffic hazards. Terrestrial Lidar systems, total stations, and physical measurements all need personnel on the ground, requiring the support of work zones where areas are often established to provide a safety buffer between traffic and employees. A recent Federal Highway Administration (FHWA) report found that 842 work zone fatalities occurred in 2019 (cf. 757 in 2018). The 11.2% increase was the largest since 2016.[14] Williams et al.[2] found that drivers may become distracted by highway operations, diverting their focus through the work zone. Often, surveyors have no option but to endure high-risk situations, whereas aerial and mobile Lidar mostly eliminates surveyor-vehicle interactions during data collection. Deployment of mobile or aerial Lidar systems will likely reduce or eliminate the need for establishing work zones on data collection projects. Although traffic disruption is minimal, traffic congestion and obstacles like vegetation can obstruct a Lidar sensor's field of view (FOV). In certain situations, a rolling roadblock can be used to provide a buffer for the scanning vehicle.

2.7 Limitations

Lidar has many benefits but also some limitations:

- Geospatial accuracy is highly dependent on GNSS. Buildings, vegetation, and other obstructions can affect satellite reception and significantly degrade data quality. GNSS planning and forecasting tools are available and can be used to identify the best window for data collection.
- Fog, rain, dust, snow, and other airborne particles can prevent scanners from reaching the targeted surface or create noise in the data.
- Vehicles travelling in the sensor's FOV can hinder data collection. Rolling roadblocks can be used as a buffer for the scanning vehicle.
- Wet pavement provides poor scanning results as conventional Lidar systems do not penetrate water.
- Lidar sensors scan the environment within the line of sight. Steep slopes, ditches, or other features out a scanner's FOV are not captured. Additional methods and/or scans may be needed to acquire these data.
- The range of data acquisition for Lidar sensors varies by manufacturer. Data resolution and density degrade as distance from the scanner increases. Additional scans may be needed to obtain adequate coverage. Data alignment issues can be problematic if the GNSS solution has changed between scans.
- Systems, software, and training can be relatively expensive.
- Data processing workflows are complicated and require experienced staff.
- The large volume of data collected from Lidar systems can be difficult and expensive manage and store.

Section 3 Lidar Use Cases

This section discusses examples of Lidar transportation applications. KTC has performed MLS surveys using a survey-grade Lynx V100 mobile mapping system manufactured by Teledyne Optech. The system collects up to 200,000 points per second using dual lasers. Geospatial and trajectory data are collected using an Applanix positional orientation system (POS) consisting of two survey-grade antennas, an IMU, and DMI. Manufacturer accuracy specifications for the system are ± 5cm at 1σ.

3.1 Clearances

While design guidelines for collecting minimum vertical clearances have been established, extraction methods have not been specified. State DOTs have been left to decide on the best method to obtain measurements. Although many tools and techniques exist for acquiring minimum vertical clearances, a defined approach has not been determined. Traditionally, collection methods have used a total station, laser tape, or other means to obtain measurements. While these methods can be accurate, they present challenges. One major issue is field personnel safety. Field data collection exposes workers to dangerous conditions, especially along high-speed or congested highways. Additionally, these operations often require the establishment of work zones to create a safety buffer between employees and the public. Establishing work zones for individual or small groups of structures consumes time and resources and may disrupt traffic flow, presenting additional safety concerns for employees, pedestrians, and drivers.

Accuracy can also be a concern with traditional techniques. When acquiring measurements, a person must stand directly beneath the targeted surface. Human error may be amplified when working next to traffic when a person is attempting to monitor the surrounding environment while carefully trueing a leveling rod or operating a laser tape. If the instrument is not perpendicular to the vertical axis and/or centered below the targeted surface, errors may be present in the data. Workers must also locate the lowest point on the structure, which may be difficult to determine due to changes in roadway elevation and variable overhead clearances.

To alleviate some existing constraints associated with traditional methods, KTC in a joint venture with KYTC, began extracting clearances from overpasses along Kentucky’s interstates and parkways using mobile Lidar. To date, 582 bridges have been scanned along nine routes. Data collected via MLS were post-processed and classified to remove vehicles or obstructions from point clouds. Microstation and Topodot were used to extract minimum overhead clearances from bridge structures with respect to lane striping. Point cloud and minimum clearance data were combined and drafted into individual PDF template files (Figure 3.1).

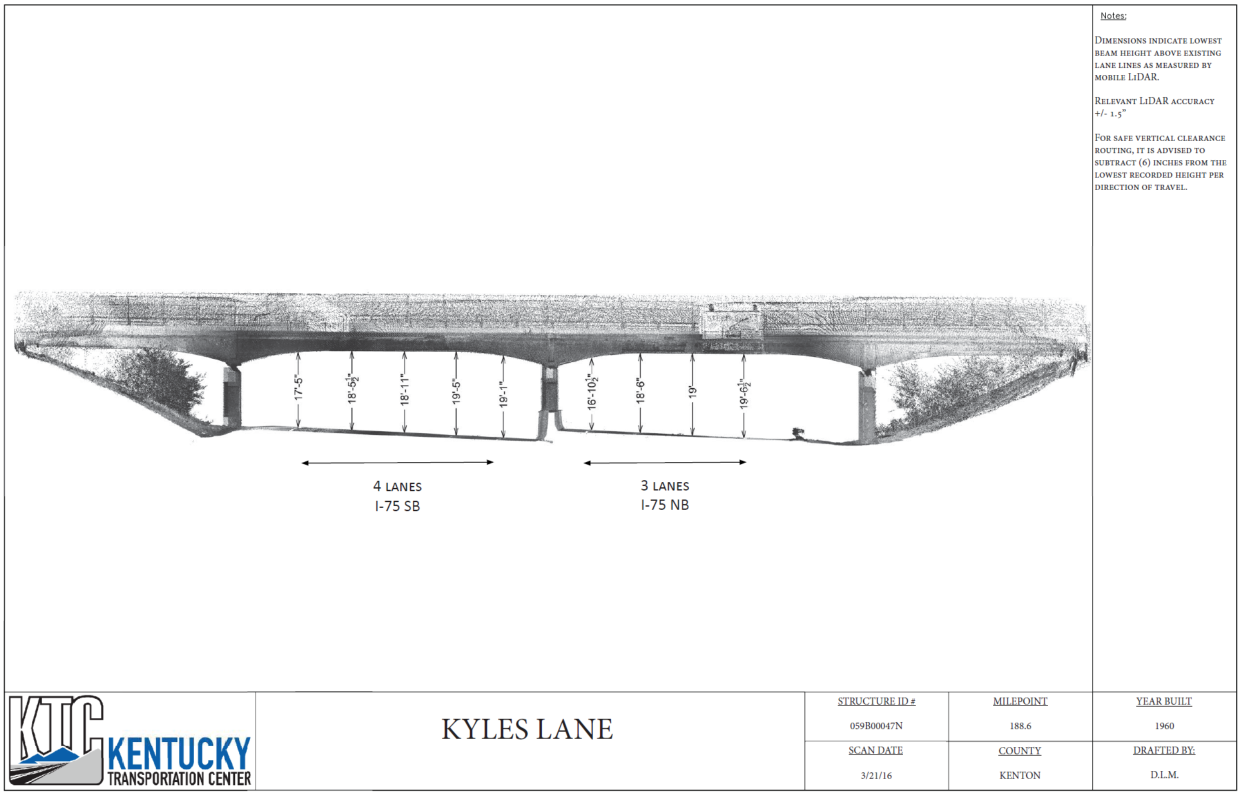

Figure 3.1 Bridge Clearance Template

KTC stores bridge clearance data in a user-friendly ArcGIS database that hosts an interactive map. Minimum clearance information can be viewed by selecting a bridge on the map and reviewing its PDF clearance template. The accompanying .las point cloud file can also be downloaded and analyzed. Users can apply filters to identify structures based on the lowest minimum vertical clearance per direction and route. For example, a filter using a safe routing height of 15’ on the Western Kentucky Parkway (WB) yields records for four structures with minimum clearances < 15’. These data can facilitate routing for KYTC’s over-dimensional permitting process and provide important clearance information to District Offices.

To confirm MLS data, measurements were taken from a subset of structures on each route using a laser tape mounted to a level-rod and compared to those derived from point clouds. In total, 123 individual bridges were compared. The mean difference was .0634’ (~3/4”) (Figure 3.2), which is within the manufacturer’s specifications.

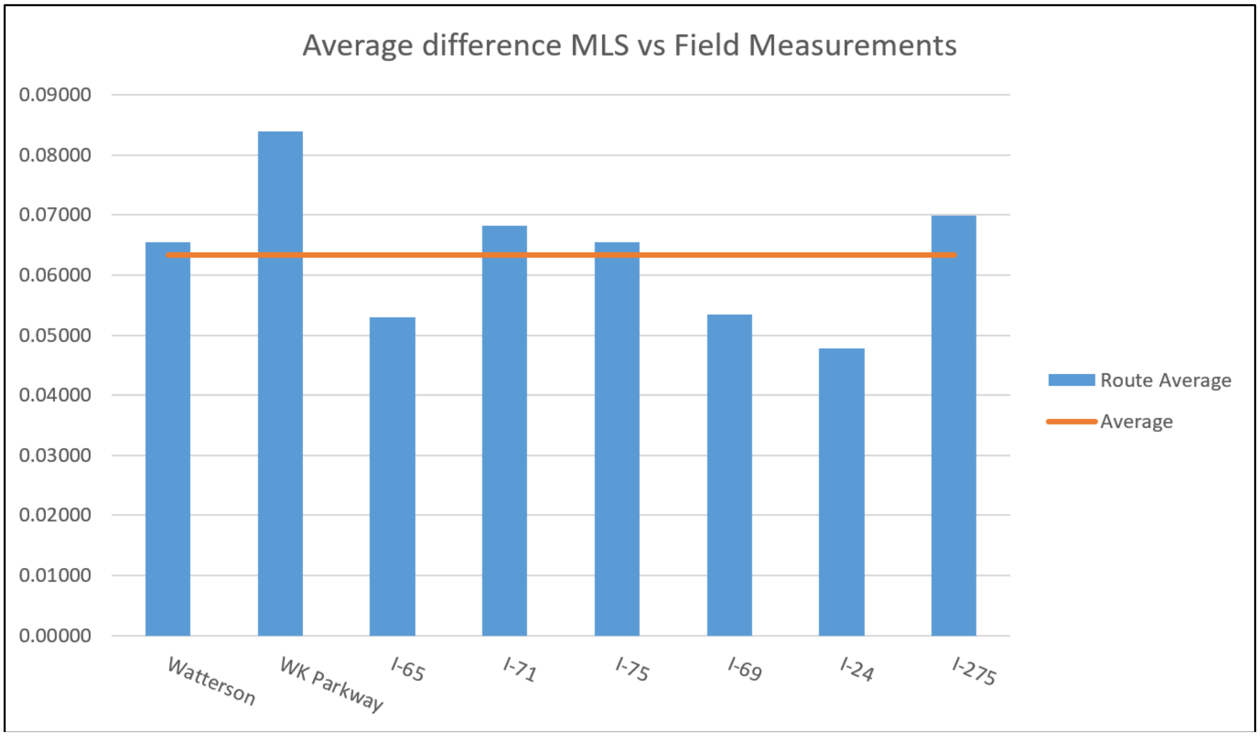

Figure 3.2 Average Differences in MLS and Field Measurements (feet)

Data collection on these routes were done to minimize traffic disruption and generate cleaner datasets. With the help of a safety vehicle, vehicle-mounted scanners passed under structures at 40 mph. Given that MLS collect about 200,000 points per second, at the minimum speed (40 mph) a system should be able to collect enough data for clearance extraction, eliminating the need for traffic control.

3.2 Accident Investigations

In 2014 KYTC officials expressed concern about the number of wet-weather crashes along a 1,000' stretch of I-471 in Kenton County that contained vertical and horizontal curves. Officials speculated that an issue with roadway geometry affected surface runoff patterns, increasing crashes during heavy rainfall events. To identify the problem, KTC used a mobile Lidar system to scan the area.

To identify inadequate surface geometry, the point cloud was used to extract cross-sectional surface points from the shoulders and all three lanes at 5' intervals. These points were triangulated to create an accurate digital terrain model (DTM) of the roadway surface. MicroStation's flow path tool was used to simulate water flow on the digital surface. Figure 3.3 shows the simulated water flow channeling downstream against the inside barrier wall. At approximately 625' downgrade, water drains back onto the roadway surface. Further investigation found a low spot and/or sag in the pavement crown-line on the high-side of the superelevated section, which promoted water flow into driving lanes. To confirm the flow path model, a 25-gallon water tank was emptied along the high-side shoulder (Figure 2.11). Field observations aligned with the flow path model.

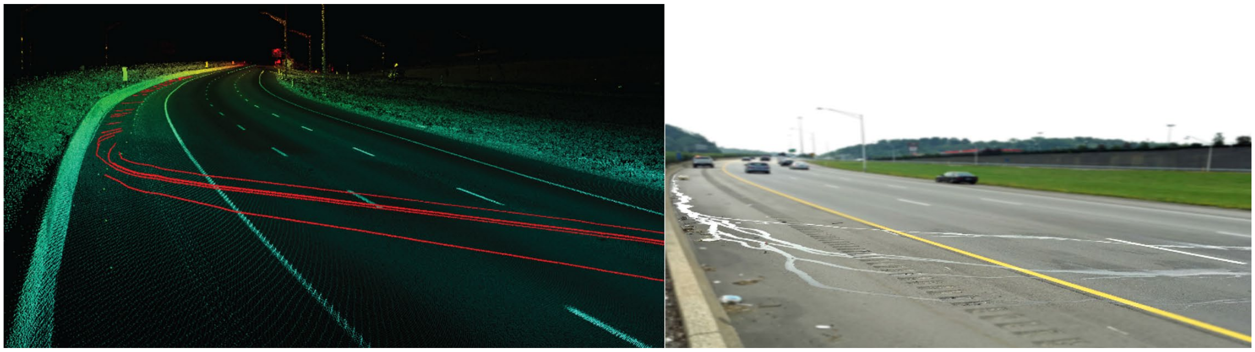

Figure 3.3 I-471 Flowpath Model (Left) and Field Observations (Right)

Once the problem area was identified, a highway grinder was used to reprofile the crown, lowering the roadway surface's elevation adjacent to the barrier wall. This let surface water remain in the channel between the crown and barrier wall until it reached a drainage inlet, effectively rerouting the accumulation of water away from driving lanes.

Since this project, mobile Lidar has been used on projects throughout the state to identify pavement geometry issues. The technology is well suited for these projects, especially compared to traditional methods. Typically, surveyors target defining features such as EOP, lane lines, pavement crown, and barrier walls. DTMs derived from traditional surveying can be highly accurate, however, it is unlikely they contain enough detail to detect small changes required for drainage analysis. Mobile Lidar systems can scan the entire environment, providing much better resolution of site geometry. Additionally, traffic disruptions and employee exposure to hazards are reduced since data are collected at highway speeds.

3.3 Highway Safety Improvement Program

KTC has used mobile Lidar to provide technical support for the state's Highway Safety Improvement Program (HSIP) since 2016. The Center has focused primarily on roadway sections experiencing a higher-than-expected frequencies of roadway departures that could be attributed to improper pavement geometrics. Using the state's crash database, officials analyze crash statistics to identify roadway segments and curves where high crash rates may correlate with improper roadway geometry. These sections are generally between 5 and 10 miles long and located in rural areas. To identify problematic geometric configurations, as-built surfaces must be analyzed. Previously, survey crews would obtain as-built data, however, this method is time-consuming and creates traffic disruptions on corridors known for high crash rates.

To aid the collection of as-built data, KTC utilized an MLS system to scan designated areas. Data collection is very efficient, requiring just a single pass at 40 mph. Depending on project locations, multiple routes can be scanned in a single day. After post-processing, the point cloud (Figure 3.4 top left) is analyzed. Using Microstation/Topodot software, lane lines and roadway surface points are extracted. Triangulation of the surface points results in a highly accurate DTM of the as-built surface (Figure 3.4, bottom left). To visualize cross-slope values, each triangle in the DTM is displayed based as slope percentages using a graduated color table ranging from 0% to 15% (Figure 3.4, right). The resulting dataset lets transportation officials quickly identify and isolate areas for further investigation. Slope maps for each project can be accessed via KTC's ArcGIS server.

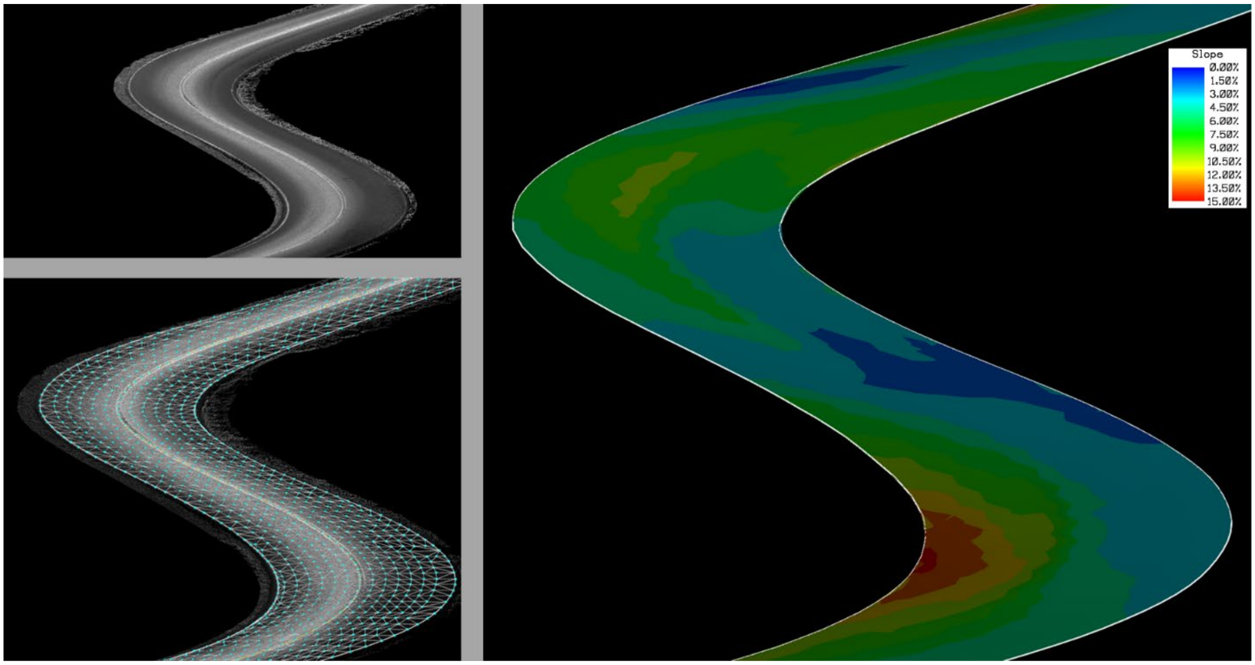

Figure 3.4 Jessamine Co. US-68 Point Cloud, DTM, and Slope Map

Data were collected for HSIP projects between late fall and early spring during leaf-off conditions. Lack of foliage makes it easier to retain a GPS signal. While not as desirable as clear open skies, leaf-off conditions allow for the best acquisition and retention of an accurate GPS solution, minimizing multi-path and signal disruption.

3.4 Slab Settlement and Roadway Distress Mapping

In March 2018, KYTC District 5 was dealing with slab settlement on a 25-mile stretch of I-65 spanning Jefferson and Bullitt counties. To identify corrective measures, the district needed a better understanding of the project. KYTC used mobile Lidar to detect, map, and quantify areas of longitudinal differential pavement settlement. A rolling roadblock was organized to secure two lanes for the scanning vehicle, leaving the third lane open to traffic. Two passes were made at 40 mph in the slow and fast lanes. About 75 lane miles of data were collected over four hours (Figure 3.5).

Figure 3.5 KTC MLS System and Rolling Roadblock

After initial processing, Microstation/TopoDOT software were used to isolate a 2’ swath of point cloud data on each side of the longitudinal joint. A horizontal plane was extracted from the data to create a reference for measurement. Adjacent slabs were analyzed based on vertical deviation from the reference plane, resulting in classified points colorized in ½” increments. Post-processed results included a classified dataset that mapped the location and severity of differential slab settlement. An example of the point cloud before and after classification is shown in (Figure 3.6) accompanied by a cross section (Figure 3.6). To aid in field location and prioritize areas for remediation KTC developed a spreadsheet that referenced station numbers to settlement magnitude, and length of distress. In total 4,364 linear feet of settlement were identified (Table 3.1).

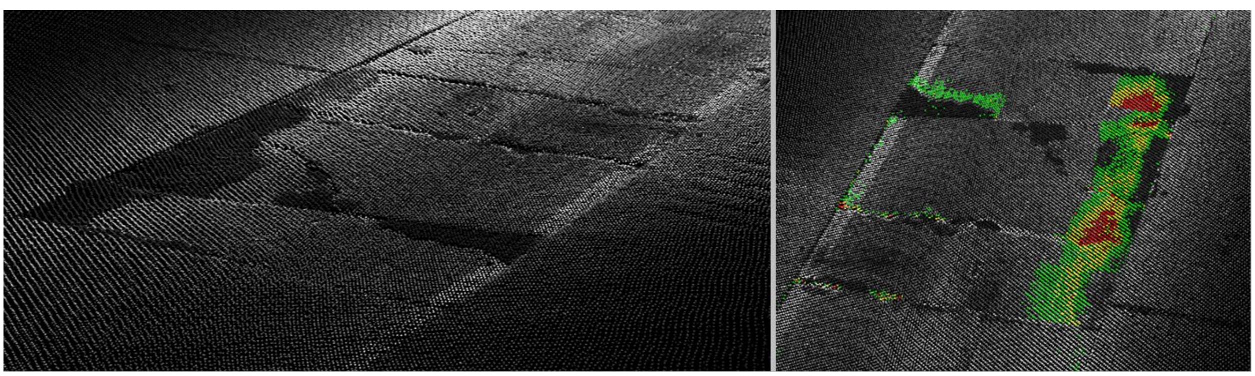

Figure 3.6 I-65 Settled Slab Point Cloud and Classification

Figure 3.7 Settled Slab Cross Section

Table 3.1 Summary of I-65 Slab Settlement

Joint Location	Magnitude of Slab Settlement		
	.5 – 1"	1 – 1.5"	1.5" +
Shoulder / Lane 1	10	0	0
Lane 1 / Lane 2	689	115	49
Lane 2 / Lane 3	679	183	44
Lane 3 / Shoulder	2233	284	78
All Joints	3611	582	171

3.5 Landslide Monitoring and Change Detection

In September 2020, KTC was asked to help monitor a slide on KY-2926 in Campbell county. KYTC District 6 indicated large cracks had been apparent since July, following the installation of an earthbag wall two years prior. The roadway surface dropped around 13" in areas along the initial cracking. Horizontal bulged deformation was observed in the bottom segment of the earthbag wall (Figure 3.8).

Figure 3.8 Roadway Failure (Left) Earthbag Barrier Wall (Right)

It was suggested multiple static Lidar scans would be the best approach to monitor slide movement. Using a Faro Focus *S* scanner, three scans were performed over seven months. To ensure future scans originated from the same position, three control points were established below the earthbag wall across the creek where no movement was suspected. Additional scans taken from the roadway surface were aligned with targets placed along the guardrail. On each date KTC performed seven scans. Figure 3.9 shows the registered point cloud from the 9/20 scan.

Figure 3.9 KY-2696 Point Cloud

Figure 3.10 compares cross-section scans from 9/20 (white) and 4/21 (red). Table 3.2 lists horizontal offsets of the earthbag wall measured from the point cloud. The roadway surface's elevation adjacent to the initial failure (top left corner) shows little change, indicating alignment between scans.

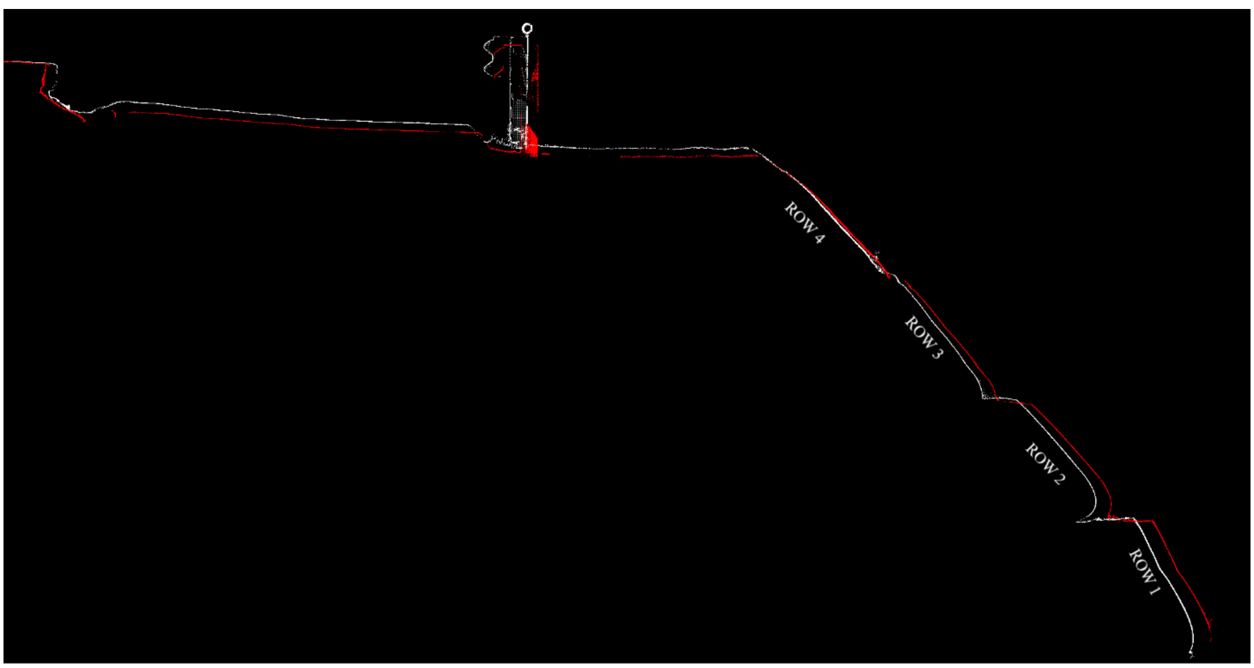

Figure 3.10 KY-2696 Cross Section Comparison

Table 3.2 KY-2696 Earthbag Wall Movement

ROW#	Scan 2 — 10/5/20	Scan 3 — 4/19/21
1	.052’	.527’
2	.052’	.442’
3	N/A	.372’
4	N/A	.172’

The guardrail post (Figure 3.11) provided an additional reference for measurement. Comparing point cloud data from 9/20 (white) and 4/21 (red) showed horizontal movement of .296’ and vertical movement of .226’.

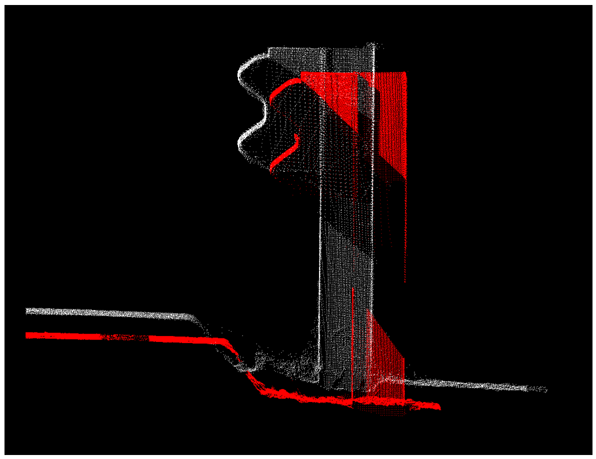

Figure 3.11 KY-2696 Guardrail Cross Section

Static terrestrial Lidar scanning proved to be a valuable tool for this project. While a total station could have obtained the same measurements, traversing the steep earthbag wall and identifying repeatable survey rod positions would have been difficult. Scanning the entire environment provides high-resolution data for a large area, whereas traditional survey methods can only target smaller areas; changes outside these areas may go unnoticed.

3.5 ADA Compliance

The Americans with Disabilities Act of 1990 (ADA) requires that all public and private organizations providing services to the public ensure their facilities and infrastructure comply with regulations. The ADA requires entities to develop transition plans that “[identify] physical obstacles in the public entities facilities that limit the accessibility of its programs or activities to individuals with disabilities.” In 2019 KYTC partnered with Michael Baker to develop a statewide inventory of KYTC-maintained pedestrian infrastructure and evaluate compliance of as-built facilities against ADA standards. Michael Baker collected over 4,000 miles of data throughout the state using mobile Lidar. Data were post-processed to locate and evaluate more than 34,000 curb ramps, 18,000 crosswalks and 1,600 miles of sidewalk. Post-processed data were uploaded to a GIS database that can be used to rank and prioritize deficiencies. Figure 2.20 shows a heat map indicating locations with the most deficiencies.

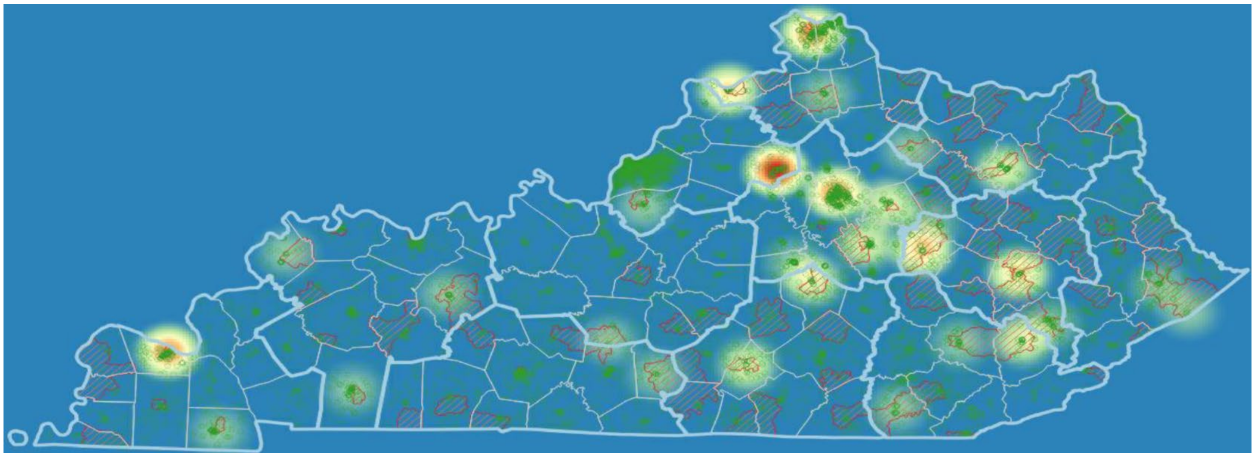

Figure 3.12 ADA Prioritization Heat Map

Mobile Lidar is an excellent choice for large-scale projects given its ability to map the environment quickly and efficiently. Curb ramps, crosswalks, intersections, and sidewalks can all be inventoried in a single dataset. Multiple locations can be scanned without disrupting traffic or deploying a survey crew.

3.6 Other Applications

NCHRP Report 748 and *Synthesis of Transportation Applications of Mobile LiDAR* review other transportation applications of Lidar as outlined below. Appendix A includes an organizational chart.

Project Planning

- Lidar data provides critical geometric information and can document spatial relationships, which can facilitate planning decisions.
- Planners can virtually explore project sites, reducing the need for field visits.
- DTMs derived from Lidar data let practitioners quickly view surface data for the roadway and surrounding areas. Analyzing DTMs provides insight planners can use to inform future project decisions.

Maintenance

- *Drainage* — Slopes and elevations can be extracted from Lidar data to support drainage analysis. Extracted surface models can be simulated using HEC-RAS or other software to estimate drainage accumulations and aid assessment or design.
- *Vegetation Management* — Datasets can be analyzed for line-of-sight limitations or to identify areas of encroachment near roadways or powerlines.

Construction

- *AMG (automated machine guidance)* — Lidar surveys can obtain data for use in AMG. Highly accurate DTMs from Lidar data can serve as inputs for machine control workflows. An accurate control network is necessary for machine control applications (see HD-302).
- *As-Built/As-Is* — Change detection and deviation software can identify differences in design/as-built surfaces for construction quality control.
- *Quantities* — Lidar data can be used to calculate area, volume, lengths, and other features used for quantities (e.g., guardrail, striping, areas of pavement patching). Earthwork quantities can be obtained using mobile Lidar data but may need to be supplemented by other methods if steep slopes or ditches are outside of the scanners line of sight.
- *Pavement Analysis* — Potholes, large cracks, joint separation, settlement, rutting and other features can be extracted from Lidar data. These datasets require high local accuracy and densities. Single-sensor datasets are recommended to mitigate potential alignment issues. Current resolution capabilities may not be sufficient to detect small cracks (mm-level widths).

- *Clearances* — Clearances for bridges, powerlines, signage, and other overhead structures can be assessed. This requires high local accuracy, but network accuracy is less critical. Datasets can be modeled for virtual clash detection. Minimum clearances can inform transportation information models (TIM) that support oversized permitting.
- *ADA Compliance* — Lidar data can be used to determine if ramp slopes comply with ADA regulations.

Safety

- *Forensics/Accident Investigation* — Lidar data can be used to extract geometric information (e.g., grade, slope, lane/road width, signage, sight distance, other safety analyses).
- Areas experiencing excess wet weather crashes can be analyzed for geometric design issues that contribute to hydroplaning.
- Analysis is performed virtually offsite.

Asset Management

- Many features can be extracted and inventoried from point cloud data (e.g., signs, utilities, lane striping, manholes, drainage infrastructure, barrier walls, guardrail, overpasses). Software developers are continuing to improve semi-automatic feature detection, which could further streamline workflows.

Geotech

- *Landslide/Retention Wall Monitoring* — Lidar data can be used to monitor unstable slopes or the movement of retention walls. Multiple scans are needed to generate comparisons. Static terrestrial scanners are best suited for these applications. Established control points on stable ground are imperative to achieve repeatable results.

3.7 Key Takeaways

- Lidar transportation applications have seen rapid growth in the last decade. As technologies evolve, agencies will need to understand their advantages and limitations to maximize potential benefits.

- Lidar technologies significantly reduce field collection time but increase time spent in the office processing data. Agencies may need additional hardware and software to effectively manage datasets.

- Lidar-capture platforms (fixed, aerial, mobile) and collection methods vary; each produces different types of datasets. The collection platform should be chosen to ensure project deliverables meet client expectations.

- Project control should be set before scanning operations based on applicable guidelines. Digital leveling is a preferred method for establishing elevation.

- Achievable accuracies should be aligned with project requirements and confirmed with the manufacturer's specifications. GPS signal forecasting may be needed to determine the best window for data collection.

- Data stored in an environment that can be shared between departments is critical to reduce single-purpose data acquisitions.

- A single Lidar dataset can be used in many applications. Data from all projects involving Lidar point clouds should be retained for future data mining.

- Cost-benefit analysis should be performed to determine if Lidar is a viable solution. Accuracy requirements and field control are generally the key drivers of costs. Small-scale projects may not benefit from Lidar. Lidar technologies become exponentially more valuable as project size and complexity increases.

- Because Lidar data are collected remotely, the safety of workers and the travelling public is improved by reducing or eliminating the need for work zones and boots on the ground.

Section 4 Conclusion

Lidar has numerous transportation applications, however, it is not always the most practical method. Integrating Lidar technologies into agency practices can be challenging because they represent a major departure from data collection and analysis methods that have been used traditionally. Organizations that understand Lidar's benefits and limitations can make informed decisions about its use on future projects. Continued investment, research, and experience increases efficiency, cost savings, and future value as Lidar technologies become further integrated into agency workflows.

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Appendix A Lidar Applications Flowchart