Considerations for Effective LiDAR Deployment by Transportation Agencies

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ABSTRACT

Light Detection and Ranging (LiDAR) is becoming increasingly popular across the United States, and state transportation agencies are adopting practical use of the technology for transportation related applications. This is quite evident by the growing number of agencies acquiring LiDAR scanners and contracting LiDAR services. The primary factors behind this trend are that (1) surveyors, engineers, and technicians are becoming more educated and increasingly open to LiDAR and its applications, and (2) LiDAR is potentially more cost-effective than traditional surveying technologies. LiDAR can provide transportation agencies with the benefits of safety, data collection productivity, cost effectiveness, applicability, high levels of detail, and technologic advancement.

Many of the more practical uses and benefits of LiDAR have come to fruition in recent years, and transportation agencies have been more open to its utilization. However, there is little more than anecdotal evidence to support when a specific LiDAR platform should be applied over a traditional surveying method for various applications. Decision makers within geomatic and surveying departments who use LiDAR must regularly weigh the options of which surveying method to utilize for specific projects and base decisions on performance tradeoffs. The methodology presented in this paper aims to provide guidance on how agencies may determine whether or not LiDAR can be practically utilized within their organizations. It is recommended that interested parties systematically consider the aspects and performance measures outlined for effective deployment of LiDAR equipment or contracted services.

INTRODUCTION

Light Detection and Ranging (LiDAR) is becoming increasingly popular across the United States, and state transportation agencies are adopting practical use of the technology for transportation related applications. This is quite evident by the growing number of agencies acquiring LiDAR scanners and contracting LiDAR services. The primary factors behind this trend are that (1) surveyors, engineers, and technicians are becoming more educated and increasingly open to LiDAR and its applications, and (2) LiDAR is often more cost-effective than traditional surveying technologies. LiDAR can provide transportation agencies with the benefits of safety, data collection productivity, cost effectiveness, applicability, high levels of detail, and technologic advancement.

A key benefit of using LiDAR is its appeal to safety. By reducing lane closures and exposure to potentially hazardous environments, LiDAR improves the safety of field personnel as well as the traveling public during data collection efforts. As a remote sensing technology, LiDAR can collect data at a safe distance. Ground-based systems can accurately scan from distances of at least 150 feet, which is sufficient for many transportation applications. Airborne LiDAR completely removes data collection from the vicinity of the highway, thereby shifting the higher risks of traffic exposure to the lower risks of flight.

Due to LiDAR's rapid scanning ability, data collection can be completed in a fraction of the time required by traditional surveying and manual measurements. After initially establishing control points and setting up a system, LiDAR automatically collects and records measurements without user interaction. The data-rich point cloud created during a scan also has the ability to be re-mined for additional data elements beyond the initial intended purpose. For future reference or use, a single scan of a roadway can provide information on multiple roadway aspects, and thereby minimize redundancy in data collection. Another benefit is that LiDAR can be very cost effective when compared with traditional surveying and photogrammetry. Although the initial investment of acquiring LiDAR equipment is relatively expensive, the shared benefits across various business areas can help mitigate the high capital costs. The options of rental and fractional ownership can further reduce the burden of expenses. The technology can be utilized for most areas of surveying that require measurements of visible surfaces and unimpeded distances. Although a non-penetrating technology, LiDAR possesses the ability to scan potentially unreachable areas and complex infrastructure (e.g. tunnels and transmission lines) that would otherwise be difficult to obtain with traditional methods.

High-resolution point clouds and the sheer density of points collected are attractive features of LiDAR. The richness of data for the relative timeliness of field collection far exceeds that of many traditional surveying methods. Additionally, the digital images that are taken simultaneously with scans can be draped over point clouds for supplemental detail. Finally, as an emerging tool, LiDAR profits from the integration of remote sensors and geomatic instruments, and will continue to improve with technologic advancement. Unlike the more quantitative benefits previously mentioned, innovations in technology and trends toward data-driven decision making are essential. Technology elicits better and smarter engineering decisions; consideration and application of tools such as LiDAR can be instrumental in the constant improvement of transportation agencies and infrastructure serving the traveling public.

LiDAR has been commercially available since the 1990s, and the technology is continually undergoing rapid development in surface and object sensing as well as data processing. The total system cost has remained about the same, and purchasers or users can expect higher performance with lower costs as time progresses and the technology improves. Therefore, rather than focusing on the capabilities of current systems, this paper aims to define the principals pertaining to useful, high quality LiDAR implementation and provide a systematic method for considering its acquisition and deployment.

BACKGROUND

LiDAR integrates lasers, sensors, Global Positioning Systems (GPS), and Inertial Navigation Systems (INS) as a range-based imaging tool. A LiDAR scanner measures the distance to an object or surface similar to radar or sonar technology (Fekete 2010). A system emits a number of laser signals and calculates the time-of-flight of individual pulses to identify the surrounding environment relative to its own position. Each laser pulse that contacts a surface and returns to the scanner has a corresponding Cartesian coordinate recorded in a database and subsequently registered into a digital three-dimensional space. The conglomeration of points within a digital space makes up what is known as a point cloud. A point cloud consists of a multitude of points that is dependent on the density of laser emissions and the range setting of a scan.

LiDAR Platforms

Generally, there are three LiDAR system types that include (1) the fixed-terrestrial system in which the scanner is mounted on a stationary surveying tripod, (2) the mobile-terrestrial system that mounts onto ground vehicles, trains, and watercrafts, and (3) the airborne system which scans from aircraft.

Fixed-terrestrial LiDAR, a static form of high density scanning, uses a laser and rotating mirror to rapidly scan and image surfaces. This type of system takes tripod-based measurements, and therefore does not require a global positioning system (GPS) or inertial navigation system (INS) for direct georeferencing. As a stationary system, fixed-terrestrial LiDAR typically achieves the highest accuracy of the three platforms. Generally, fixed-terrestrial LiDAR relies on control points. Therefore, to increase accuracy, targets can be established on known benchmarks for additional geodetic control and point cloud registration. When modeling an individual object, the relative orientation between multiple scans is sufficient for a high level of precision. If the object needs to be placed in a superior coordinate system, then an absolute orientation by georeferencing is necessary (Pfeifer and Briese 2007). Types of fixed-terrestrial LiDAR include (1) panoramic scanners, which rotate 360 degrees horizontally and 270 degrees vertically; (2) single axis scanners, which rotate 360 degrees horizontally and have fixed 50-60 degrees field of view vertically; and (3) camera scanners, which scan at set fields of view and have limited angular ranges (Shuckman 2011). Static systems can also be classified by operational range; generally, the closer the range, the more accurate the data. At the time of this publication, typical LiDAR systems used for survey grade measurements operate at distances of 150 to 250 yards; the range and accuracy capabilities are expected to improve over time.

Mobile-terrestrial LiDAR systems are installed on ground vehicles. Mobile scanners are very effective for larger areas and highway corridors accessible by car, train, or boat. The combination of on-board GPS and INS devices provide georeferencing, and are especially important for the absolute accuracy of a mobile system. Additional control points must be established along the data collection route for survey grade accuracy. Generally, mobile-terrestrial LiDAR can collect data at highway speeds within the flow of traffic. In addition to the increased efficiency of data collection, benefits also include minimization or elimination of lane closures, traffic disruptions, and safety hazards. Consequently, accuracy diminishes as additional devices are required to compensate for kinematic scanning.

For *airborne LiDAR*, the scanner is mounted on an aircraft and emits infrared laser signals at high frequencies to scan the earth's surface from aerial elevations. Scanners can be mounted on fixed-wing or rotary-wing aircrafts, including remotely piloted vehicles (RPVs). Airborne LiDAR uses longer wavelengths than terrestrial systems, which are less affected by atmospheric conditions. Airborne systems scan laterally to the aircraft's flight direction in an oscillating or swathing motion to capture features of the ground and built environment below. As for any mobile system, the position and orientation of the aircraft is then determined by GPS and INS devices. Although generally used for larger scale areas and asset grade data collection, airborne LiDAR can feasibly be flown at lower altitudes and over smaller sites for higher degrees of accuracy.

Transportation Applications

LiDAR data and services have been used successfully by a number of transportation agencies for bridges, construction, geotechnical engineering, highway design and corridor mapping, hydraulics and hydrology, pavement, photogrammetry, traffic safety and mobility, and other transportation applications. Examples of applications by business areas are provided in the following paragraphs.

Bridges

LiDAR has been the choice of many transportation agencies to gather data on bridges for its ability to reach inaccessible areas and obtain detailed information on intricate members and supports. LiDAR collects data remotely, providing safety to drivers and work crews by allowing normal traffic flow and avoiding lane closures in many instances. For these reasons, LiDAR has been proven useful for determining geometric clearances and monitoring bridge health. While stationary LiDAR systems are excellent for detailing individual bridges, statewide data collection by means of mobile-terrestrial LiDAR provides agencies with a viable, cost-effective option for federally-mandated biennial bridge inspections.

Construction

Due to the ability to collect large amounts of surface data quickly, LiDAR has been used to produce three-dimensional models of highway infrastructure. Scans can be routinely taken and used to monitor the stages of construction or create as-built models following completion of construction. For preconstruction design and project estimation, LiDAR is effective in calculating quantities accurately and quickly. This enables transportation agencies to save time and money while improving the accuracy of bids submitted.

Geotechnical Engineering

LiDAR has been used in the geotechnical field for its ability to provide accurate data on complex geologic formations, earth retaining walls, and structural foundations. Due to LiDAR's high-speed, long-range scanning capabilities, surveyors are able to collect data safely without physical exposure to potentially dangerous or difficult terrain. Rock mass characterization, rockfall and landslide mapping, tunnel construction and maintenance, slope stability, earthwork quantification, and structural health monitoring are useful LiDAR applications for geotechnical engineering.

Highway Design and Corridor Mapping

Fixed-terrestrial LiDAR could be useful for individual, high-profile highway design projects, while mobile and airborne LiDAR systems can be utilized for entire corridors. Scans provide detailed information and representation of existing transportation infrastructure and surrounding conditions. Applications include three-dimensional design, elevation and cross-section measurements, asset inventory, and topographic surveying.

Hydraulics and Hydrology

The ability of LiDAR to gather bare-earth information is used by agencies to create flood and inundation maps. Post-processing software has the ability to remove trees and other ground impedances from LiDAR point clouds. LiDAR can be deployed for digital elevation modeling, geographic information system integration, coastal change monitoring, flood and inundation mapping, and risk assessment of hazardous dams.

Pavement

LiDAR has been used to assess pavement attributes, such as road grade and cross-slope estimations. As LiDAR technology continues to advance, so too does its ability to collect with higher degrees of accuracy. Mobile LiDAR can quickly and easily be used to collect cross-slope information and characterize pavement distresses. Three-dimensional models derived from LiDAR point clouds can be utilized to generate detailed pavement resurfacing plans. Laser imaging systems are also effective under ambient lighting and low intensity contrast conditions that video-based monitoring and photo collection generally have issues with.

Photogrammetry

Terrestrial and airborne LiDAR have been used to supplement photogrammetric operations and aerial photography. Ground-based point clouds can provide much more accurate geometric measurements for estimating earthwork and vegetation quantities typically taken by plane. Point clouds created from airborne scans provide exceptional data for deriving elevation products and producing base maps. Other uses include airport obstruction mapping, digital elevation modeling, geographic information system integration, and transmission line surveying.

Safety and Mobility

LiDAR has been implemented in the transportation field for safety and mobility analyses by locating intersection sight obstructions and assessing traffic operations. While airborne LiDAR point clouds can be cleansed to derive bare-earth ground elevations, raw data points can alternatively be utilized to determine the presence of vehicles in the vicinity of the roadway and identify objects that may pose visual obstruction issues. As the technology becomes more affordable and improves, the feasibility of automatically detecting vehicles and objects in real-time for safety and mobility applications may be further realized.

Other Applications

LiDAR can aid transportation agencies committed to context sensitive solutions (CSS) or responsible for historic, natural, and cultural preservation. LiDAR has recently been used as a tool for documentation and preservation of sensitive transportation facilities and right-of-ways. As a non-intrusive tool, LiDAR creates detailed three-dimensional images without any destruction to a site or evidence. Thus, it has also been utilized for forensic science and scene reconstruction for criminal and crash-related incidences.

Acquisition Options

In terms of acquiring LiDAR scanners or data, the options include (1) contracting data collection/post-processing/feature extraction services, (2) renting and operating equipment, (3) purchasing and operating, or (4) purchasing fractional ownership (Yen et al. 2011). In addition to the deployment options, the accuracy requirement will dictate whether to use asset or survey grade systems. In deciding on which option to pursue, the amount and frequency of LiDAR use for transportation improvement projects and asset management programs should be reviewed to determine the optimal decision. The advantages and limitations of each option are outlined below:

Contracting Services – The primary advantage of this option is that a contractor will provide and produce the equipment, personnel, and final deliverables of an awarded project. Therefore, the transportation agency is not hampered with significant capital investment, personnel training, data processing, risk of technological obsolescence, and equipment maintenance/depreciation. Although third party contracts may lower the costs for individual projects, the hiring agency may not gain the greatest benefit if LiDAR is needed for long-term or frequent use. Another challenge is related to the variability of data and vendor capabilities. Consequently, the agency contracting services must establish data collection standards and a system for quality control (QC).

Renting and Operating – In addition to reduced equipment obsolescence risks and maintenance costs, the agency benefits from equipment availability and project schedule flexibility as long as reliable suppliers can procure the platform required. To get the most utilization from renting and operating LiDAR equipment, the agency must already have personnel trained in data collection and post-processing, sufficient information technology infrastructure, and a full understanding of the technology. This option could be of value to agencies interested in potentially purchasing LiDAR equipment in the future.

Purchasing and Operating – Considering the high initial costs of investing in a LiDAR system and the risks of obsolescence, the benefits may not be immediate or even tangible. The obvious advantage is that frequent and long-term utilization will reduce the overall lifecycle costs of employing LiDAR. Intangible benefits to an agency include overall improvements in data-driven decision making processes, reduction in redundant data collection, and advancement in technologic proficiency.

Fractional Ownership – Fractional ownership is common when asset investment costs are economically impractical. The benefits of these plans are reduced cost of entry and risk of obsolescence. Initial equipment costs depend on the percentage of ownership and incremental fees to cover maintenance and insurance. Generally, this option is applied to airborne LiDAR acquisition as the concept was originally pioneered to allow businesses share costs of co-owning an aircraft. To the same effect, fractional ownership may be feasible amongst interdisciplinary agencies within a state, such as the Department of Transportation, State Highway Patrol, and Department of Environment and Natural Resources.

METHODOLOGY

The benefits and wide variety of transportation applications of LiDAR make the technology a promising and attractive tool for transportation agencies. Yet, high upfront costs, technologic challenges, obsolescence, and investment risks deter many transportation agencies from utilizing LiDAR and limit widespread use. System-wide implementation and project specific deployment of LiDAR can both be financially feasible and practically effective if an agency evaluates the aspects most pertinent to three-dimensional scanning. Therefore, the considerations and performance measures outlined in this section may serve as a methodology to assist agencies in developing a framework for LiDAR use in their organizations.

When considering the acquisition of LiDAR systems and/or contracted services, a transportation agency should take into account the type of system best suited for the agency's needs; the agency's capital and funding availability; its human resources and organizational structure; its information technology framework; and the inherent limitations and risks of technological investments. In deciding which system best suits a particular transportation agency, the business areas (or departmental units) within the agency and their roles and responsibilities should be reviewed. LiDAR has limitations as a non-penetrating technology. As a result, there are many guidelines prescribed for system operations depending on the application. An illustrative example comes from the publication *Ground-Based LiDAR: Rock Slope Mapping and Assessment* (FHWA 2008). The publication outlines best practices for geotechnical application such as: (1) the offset distance from the scanner to the target slope should be at least the height of the slope; (2) the horizontal view of the scanner should be 50 degrees; (3) scanning at various angles is not necessary unless conditions are complex, if the case is such, 20 percent overlap between scans is sufficient. Similarly, to provide ample coverage of surveyed surfaces, scanning by mobile-terrestrial LiDAR often requires two passes, one in each roadway direction. Likewise, airborne LiDAR is limited by line of sight. Therefore, LiDAR data is often used to supplement alternative imaging techniques, rather than serving as the primary dataset. A fixed, mobile, and airborne LiDAR platform should be utilized when appropriate; the multitude of applications discussed in the literature review can provide guidance in platform selection. Furthermore, the system chosen must be assessed to ensure that the data and products derived from LiDAR will meet specifications defined by the governing standards and regulations that a particular agency adheres to.

Each platform varies in costs, accuracy, and data collection time, and may be implemented for a variety of different applications. In Figure 1, a radar chart compares the three platforms for their applicability, cost effectiveness, data collection productivity, ease of use, level of detail, post-processing efficiency, and safety. A 5-point rating scale has been applied for the platforms' performance in each aspect; a value of 5 represents the highest rating and a value of 1 the lowest. The value of 2.5 represents the baseline average as compared with other traditional surveying and mapping techniques. Therefore, values of 2 and 3 can be taken as below average and above average assessments, respectively. The center point of the chart serves as the graphical origin and is denoted with a value of 0. This comparison chart is based on the general utilization of LiDAR for all transportation and traffic related applications and would vary for specific circumstances. The performance categories and relative platform ratings are defined and discussed in further detail. When addressing specific applications, each platform's ratings may change for a given project's scope of work. This chart or modifications of it may be used to aid decision-making processes of deploying LiDAR.

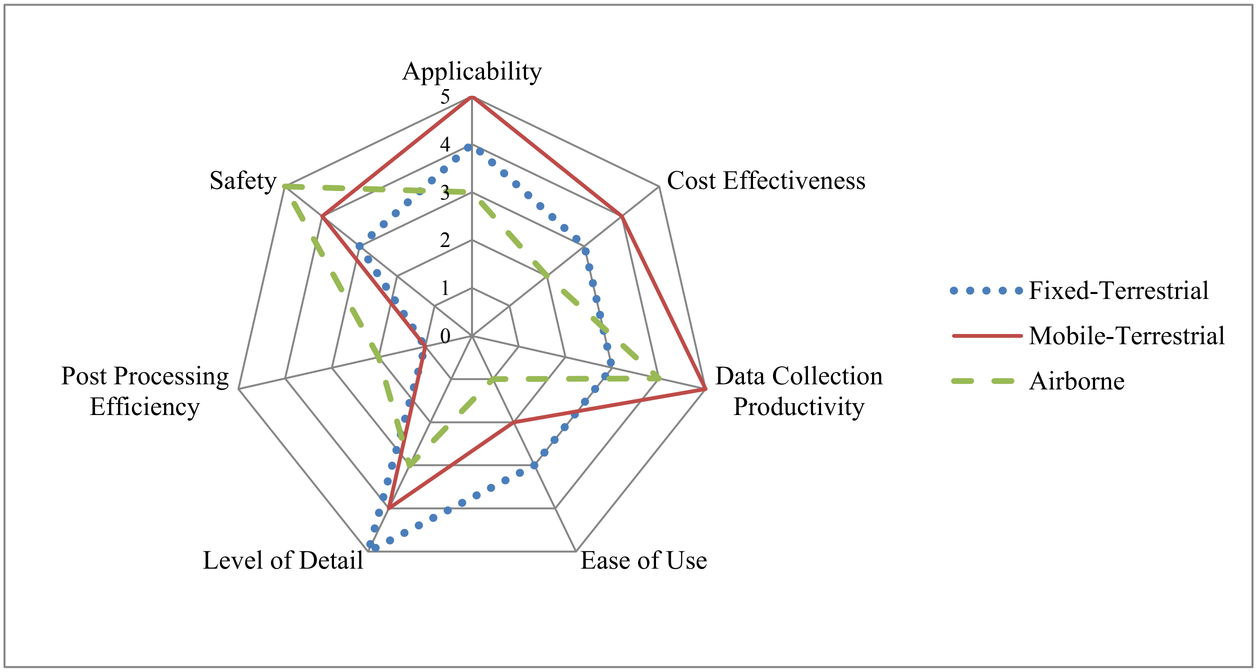

Figure 1 A radar chart comparing the aspects of the three LiDAR platforms

Applicability was determined by the number of useful applications each platform has in transportation related projects. While more accounts of LiDAR utilization for transportation applications present examples of fixed-terrestrial utilization, trends toward the implementation of mobile-terrestrial systems are rapidly emerging. These trends are primarily due to the advancements in scanner technology; mobile-terrestrial systems have benefited significantly in the ability to capture survey grade data while traveling at highway speeds. Therefore, mobile systems can produce highly accurate point clouds while covering large project sites that would otherwise be inefficient and costly of stationary setups. Although airborne LiDAR can be used in areas inaccessible by foot or ground vehicle, it has limited mapping capabilities and is less accurate. It does, however, receive an above average rating when compared with other aerial imaging techniques. Available LiDAR datasets are used to enhance photogrammetric operations, and data will be updated as the costs are driven down and the technology becomes readily accessible.

Cost effectiveness relates to the competitiveness of implementing one system over another. In term of implementing LiDAR across all transportation and traffic applications, fixed-terrestrial and airborne systems were given an above average and below average score, respectively. While fixed-terrestrial systems produce high detail, the scanner is limited to the effective range relative to its setup location. Much like traditional Total Station surveys, labor and cost increase proportionally with the required number of setups. However, rapid scanning and simultaneous measuring greatly reduce costly field work. Airborne systems tend to have the lowest frequency of deployment, thus the high costs of owning/renting, storing, maintaining, and operating fixed-wing or rotary-wing aircrafts reduce the overall cost effectiveness. These expenses could be marginalized by obtaining existing datasets or contracting services. Associated costs of a ground vehicle are relatively inexpensive when compared to the investment in scanner and sensor equipment. Although mobile-terrestrial LiDAR system acquisition costs may be significantly higher than that of fixed-terrestrial scanners, the long-term cost effectiveness and ability to survey from site to site without additional setups give it a higher rating.

Data collection productivity of mobile and airborne LiDAR is higher than that of fixed due to their capability of covering much more ground in a single scan. Mobile-terrestrial LiDAR received the highest rating for rapid rates of data collection and high degrees of accuracy; it collects data at highway speeds and produces detailed point clouds that can be used for both asset and survey grade applications. While mobile and airborne platforms integrate GPS and INS that simultaneously track the location and position of a moving scanner, fixed-terrestrial systems often require multiple set ups to produce a single point cloud of a site being scanned. Yet, the ability to simultaneously take multiple measurements gives stationary scanners the edge over traditional techniques.

Ease of use is based on the tasks of operating each type of LiDAR platform. Compared to other survey and geodetic tools, LiDAR is fairly complex as proper operation requires proficient understanding of the technology. Assuming that the operator is proficient, the operator only needs to activate the scan cycle after initially setting up the scanner. Therefore, fixed-terrestrial LiDAR is given an above average rating. In addition to scanner operation, mobile-terrestrial and airborne LiDAR require knowledge of GPS and INS devices. The multi-sensor systems must be calibrated to account for the relative locations of each sensor and the complexity of data received. Compared with other manual and/or video based techniques, operation of mobile-terrestrial scanners is highly specialized. Airborne LiDAR received the lowest rating due to an additional requirement of needing a professional pilot fly an aircraft or operator control a RPV.

Level of detail varies for each of the platforms. Fixed-terrestrial LiDAR was the highest rated for its capability in producing data with the greatest absolute accuracy and relative precision. While mobile-terrestrial systems collect less accurate absolute accuracies, they still can be used for survey grade data collection. Airborne LiDAR is more commonly used for asset grade surveys to produce base maps and elevation/surface models. In comparison with other photogrammetry methods, aerial scanning provides higher density measurements for improved surface modeling thus received an above average rating.

Post processing efficiency is relatively low for scanners. Where LiDAR has a distinct advantage in data collection productivity, it loses in post-processing efficiency. The large amount of data and detail captured with LiDAR scanners makes analysis very time consuming. Less stringent accuracy requirements and limited applicability of airborne LiDAR reduce the complexity of processing useful data.

Safety relates to the reduction of potential hazards to field personnel and the traveling public during transportation-related data collection, and it is the key advantage of LiDAR over other surveying methods. Although fixed-terrestrial LiDAR requires field personnel to be exposed along the travel way, the speed and range of data collection reduce the overall exposure to dangerous traffic/environmental conditions. Mobile-terrestrial and airborne LiDAR allow operators to survey at highway speed or completely away from highway, thus, receiving higher and highest ratings, respectively.

If an agency finds that the system in consideration produces excessive amounts of detail and more than sufficient accuracy, it may decide that current methods suffice and that the cost of LiDAR acquisition exceeds the benefits. Consequently, it is most important to first consider traditional surveying methods. To compare LiDAR with traditional surveying methods, performance measures should first be established for various aspects. The aspects for evaluating advantages and disadvantages of utilizing one technology over another may include cost, delivery time, safety, and data quality. LiDAR may have many potential advantages over conventional methods, but often these benefits may not be fully realized or easily quantified. Thus, the previous performance analysis can be modified to address and determine the optimal tool to be deployed for a specific application. To illustrate, an example is provided. An evaluation of LiDAR for the Missouri Department of Transportation (MoDOT) was conducted to compare the three LiDAR platforms with traditional methods for roadway design utilization (Vincent and Ecker 2010). A mapping company was hired to collect data using all types of LiDAR on a seven-mile stretch of MoDOT highway. The project site had all ground control survey (via traditional survey design) and photogrammetric data (via conventional aerial mapping) collected prior to comparison.

The evaluation found that conventional aerial mapping along with airborne LiDAR provided the shortest potential schedule for collecting mapping data. Mobile-terrestrial LiDAR came in third; followed by traditional survey design and fixed-terrestrial LiDAR, respectively. The speed of mobile-terrestrial and airborne LiDAR could not be matched by traditional surveying. For cost, conventional aerial mapping and airborne LiDAR were the most effective followed by the aforementioned order. Conventional aerial mapping was most cost effective for the data collection of required features. A summary of labor and cost estimates adapted from the study is shown in Figure 2; the estimates were determined by pricing surveying/mapping tasks (excluding mobilization and other direct costs) and determining the staff requirements for the seven-mile project corridor.

Data Collection Method	Hours	Person Days	Labor Cost	Cost Per Mile
Airborne LiDAR	444	55.5	$58,250.00	$8,321.00
Conventional Aerial Mapping	548	68.5	$55,234.00	$7,891.00
Mobile-terrestrial LiDAR	726	90.8	$81,688.00	$9,933.00
Traditional Survey Design	1281	160.1	$131,585.00	$18,798.00
Static-terrestrial LiDAR	1700	212.5	$204,805.00	$29,258.00

Figure 2 Labor and cost table for MoDOT evaluation on survey/mapping techniques for roadway design

Furthermore, LiDAR benefited primarily from safety enhancements and data quality, but was at a disadvantage for data processing and management. Field crews, designers, and roadway users saw improvement in safety throughout the project corridor during data collection by the reduction of site visits and design field checks. The data provided via LiDAR scanning allowed for more accurate project profiles and precise earthwork quantities. Key findings showed that, although, mobile-terrestrial LiDAR took twice the collection time of aerial surveying, it produced six times the potential information content. The major issue with all three LiDAR platforms was the large amount of point cloud data collected. In terms of managing, manipulating, and extracting useful information, the software limitations hindered the ability to effectively process raw data, thus required significant back office work and IT upgrades. In Figure 3, a radar chart has been developed to visually illustrate the evaluation of the five methods used in the study. The rating scale has been adjusted to represent the ranks of each method for each performance aspect; 1 being the lowest and 5 the highest.

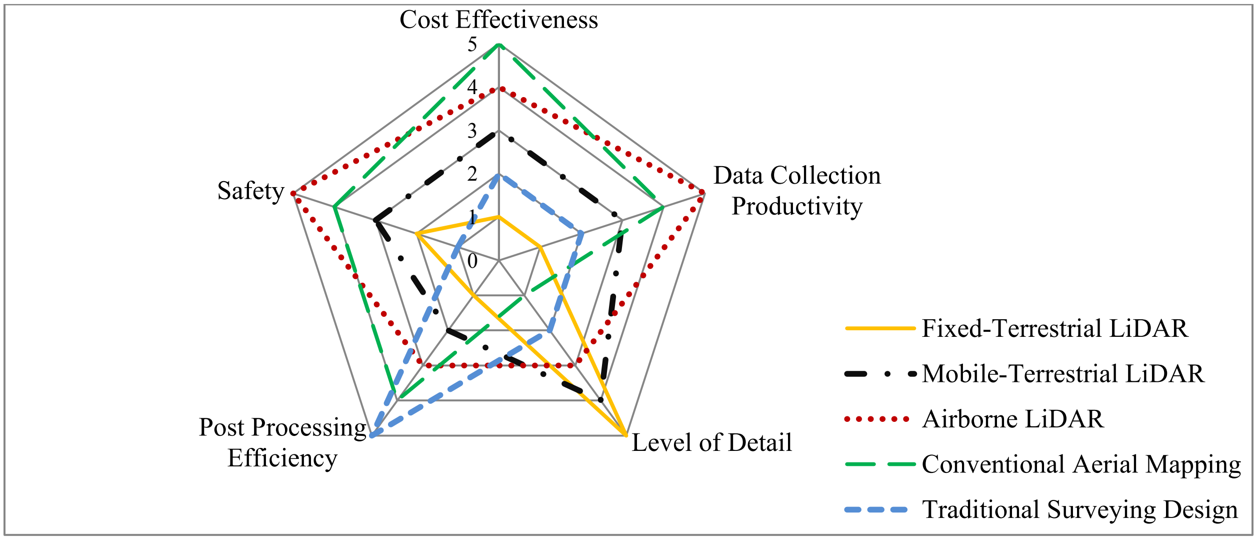

Figure 3 Evaluation of various data collection tools for roadway design applications

Airborne LiDAR and conventional aerial mapping appear to be the most promising tool for this specific roadway design application. These aerial techniques benefited significantly from ease of access to the project site, speed of data collection, and reduced risk of safety hazards. Subsequently, the assessment acknowledges the idea of potential data sharing opportunities, or the "Collect once, Use many" model. Alternative LiDAR platforms should still be considered for cost effectiveness and potential benefits across multiple projects. Static scanners collect data densities greater than mobile sensors but require more time and exposure to field conditions, adding to the cost and project schedule. Therefore, fixed-terrestrial LiDAR is better suited when high detail and accuracy is required for a limited project area. Mobile-terrestrial LiDAR would be effective for high traffic conditions, urban environments, and corridor improvement projects, and airborne LiDAR may be most appropriate for inundation mapping, utility and corridor mapping, and disaster response.

Although LiDAR costs continue to become more affordable as the technology matures, the initial purchase and setup of LiDAR systems can be a costly investment. Along with the expenses of scanners, sensors, and vehicle equipment, an interested agency also will be required to make investments on personnel training, workstation upgrades, software purchases, and technologic infrastructure. Therefore, when assessing the total budget for LiDAR acquisition, the interested party should evaluate their current capabilities and assets, taking into account any additional investments required for a fully functional LiDAR system. In terms of personnel, does the agency have technologically proficient personnel whom are readily available and willing to learn the processes of collecting and analyzing LiDAR data? If not, will funding be sufficient to hire dedicated staff or contract services? These are only a couple of basic questions the agency should understand with regards to the acquisition of LiDAR. Whether buying LiDAR equipment or contracting services, it is of upmost importance to establish guidelines, define the workflow process, and standardize a contract scoping method.

At the business specific level, the agency and its individual units must identify the applications most pertinent to their areas of expertise, and determine whether the work is to be conducted by a service providing group or a particular agency unit. While most end users of LiDAR data and derived products will never need to conduct point cloud analyses, other units requiring more complex analyses may be better suited for internally processing data. Although it would be most cost-effective to concentrate resources in an individual group, the complexity of various LiDAR applications may make it infeasible. Thus, optimizing resource allocation and staff utilization must be planned and understood, accordingly. Figure 4 displays a matrix of which platforms are most useful for specific transportation applications by business areas. The “Optimal LiDAR Platform” column was based primarily on case studies and literature review. It is not to say that a platform cannot be used for a specific application, but rather to suggest what platform may be most effectively and efficiently deployed for a given circumstance.

Applications	Optimal LiDAR Platform	Primary Business Areas: Structures Management/ Maintenance	Construction	Geotechnical Engineering	Highway Design	Hydraulics	Pavement Management/ Maintenance	Safety and Mobility
Airport Obstruction Survey	Airborne	X						
As-built/ CADD Modeling	Fixed-Terrestrial, Mobile-Terrestrial	X	X	X	X			
Asset Management	Mobile-Terrestrial, Airborne	X		X		X	X	X
Base Mapping	Mobile-Terrestrial, Airborne	X			X			
Clearance Measurement	Fixed-Terrestrial, Mobile-Terrestrial	X	X	X	X			X
Corridor Mapping/ Highway Planning	Mobile-Terrestrial, Airborne				X			
Coastal Change	Airborne					X		
Crash Reconstruction	Fixed-Terrestrial							X
Crime Scene Investigation	Fixed-Terrestrial							X
Digital Elevation/ Surface Modeling	Fixed-Terrestrial, Mobile-Terrestrial, Airborne			X	X			
Floodplain and Inundation Mapping	Airborne				X	X		
Foundation Assessment	Fixed-Terrestrial, Mobile-Terrestrial	X		X				
High-definition Hydraulic Modeling	Fixed-Terrestrial, Mobile-Terrestrial					X	X	X
Hydrologic Stream Modeling	Mobile-Terrestrial, Airborne					X		
Intersection Obstruction	Fixed-Terrestrial, Mobile-Terrestrial, Airborne				X			X
Pavement Grade and Cross-slope	Fixed-Terrestrial, Mobile-Terrestrial		X		X		X	X
Quantity Estimation	Fixed-Terrestrial, Mobile-Terrestrial, Airborne		X	X	X			
Rock and Slope Characterization	Fixed-Terrestrial, Mobile-Terrestrial			X				X
Site Preservation	Fixed-Terrestrial	X	X					
Structural Health Monitoring	Fixed-Terrestrial, Mobile-Terrestrial	X		X				
Survey Grade Geometric Measurement	Fixed-Terrestrial, Mobile-Terrestrial	X	X	X	X		X	
Traffic Operation	Mobile-Terrestrial, Airborne							X
Utility Survey	Fixed-Terrestrial, Mobile-Terrestrial, Airborne		X		X			
Volumetric Change Detection	Fixed-Terrestrial, Mobile-Terrestrial	X		X				

Legend: *Fixed-Terrestrial* *Mobile-Terrestrial* *Airborne*

Figure 4 LiDAR platform utilization by applications and business areas

Once LiDAR related tasks have been integrated into an agency's workflow process, workstation upgrades will most likely be required as the computer graphics and computing power are relatively demanding for LiDAR data processing. The three driving factors are the level of detail required, the type of computing tasks conducted, and the computing requirements of the software implemented. Generally, the final products derived from LiDAR have been simplified to be accessible and manageable by basic workstation machines. Therefore, the agency can minimize the costs of workstation upgrades and software purchases by contracting services or purchasing final products. If the agency decides to collect and process raw LiDAR data in-house, the cost of investing in workstations and software will be dependent on the types of applications utilized as well as the accuracy, precision, and size of the information required. Most LiDAR scanner manufacturers design software and provide supplementary support for their systems. Thus, selecting equipment and software that matches an agency's implementation goals will optimize the investment of LiDAR acquisition. Consequently, LiDAR investments come with the risk of obsolescence, as technology is constantly improved and replaced.

Remote sensing/surveying technology and equipment, as with the case of LiDAR, continually evolve over time and are replaced by other tools and instruments. Surveying has experienced significant innovations, from the early methods of triangulation stations, geodetic levels, transits, theodolites, steel measuring tapes, and Gunter's Chain to the development of Electronic Distance Measuring Instruments (EDMI), Total Stations, and automatic levels, and most recently, to GPS, INS, and three-dimensional LiDAR scanners. An agency acquiring LiDAR must accept the risk of the technology becoming obsolete, and in today's technologic world this could happen at a faster rate than in the past. Hence, LiDAR acquisition through derived products, contracted services, or equipment rental rather than a complete overhaul may leverage the benefits to costs. Any party interested in LiDAR investments should determine the feasibility of acquisition, the capability of integrating the technology into departmental practices, as well as the frequency and lifecycle duration of utilization. The aforementioned considerations and an understanding of LiDAR's limitations are crucial in deciding how and when to acquire LiDAR technology and/or data.

CONCLUSIONS AND RECOMMENDATIONS

The practical uses and benefits of LiDAR have come to fruition in recent years, and transportation agencies have been more open to its utilization. However, there is little more than anecdotal evidence to determine when a specific LiDAR platform should be applied over a traditional surveying method for various applications. Decision makers within geomatic and surveying departments who use LiDAR must regularly weigh the options of which surveying method to utilize for specific projects and base decisions on performance tradeoffs. The aforementioned methodology presented aims to provide guidance on how agencies can determine whether or not LiDAR can be practically utilized within their organizations. It is recommended that interested parties systematically consider the aspects and performance measures outlined in this paper for effective deployment of LiDAR equipment or contracted services.

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