TECHBRIEF

Leveraging Pocket Lidar for Construction Inspection and Digital As-Builts—Phase 1

FHWA Publication No.: FHWA-HRT-25-017

FHWA Contact: Matthew Corrigan (ORCID: 0000-0002-1230-8462), HRDI-20, (202) 493-3365, matthew.corrigan@dot.gov

This document is a technical summary of a case study for the Federal Highway Administration report *Leveraging Pocket Lidar for Construction Inspection and Digital As-Builts—Phase 1* (Forthcoming).

INTRODUCTION

The construction industry has traditionally been slow to adopt digital technology for various reasons, such as the one-off nature of each construction project and the difficulties with bringing digital hardware into a challenging field environment. Some industry professionals would argue that many technologies have also been unable to demonstrate the needed return on investment (ROI) or produce disillusionment after the hype. Over the past decade, three-dimensional (3D) laser scanning has gained traction within the construction industry as a means of documenting construction progress and, perhaps more importantly, identifying

Key Takeaway:

Lidar technology has become very important for many purposes in construction. PL is a potential game changer given that it has made the technology accessible to the masses.

Figure 1. Screenshot. Example point cloud of a drive approach, sidewalks, and catch basin captured in approximately 15 s with a pocket lidar (PL) device.

Source: Federal Highway Administration (FHWA). Created using data from 3D Scanner App visualized in CloudCompare version 2.13.[1,2]

U.S. Department of Transportation
Federal Highway Administration

Turner-Fairbank Highway Research Center

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

https://highways.dot.gov/research

constructed elements that do not match the design models. Early identification of these construction errors can significantly reduce the cost of future major repairs and waste of materials and energy. As a remote-sensing technology, lidar also provides significant safety and efficiency benefits compared with traditional surveying and mapping practices.(3)

Current methods of capturing 3D as-found or as-built condition data include using a laser scanner mounted on a fixed platform such as a tripod, or more recently, mobile scanners that can be mounted on a vehicle, unmanned aerial system, cart, robot, or that can be handheld or worn on a backpack or frame. The Federal Highway Administration (FHWA) has published TechBriefs on a variety of these systems and their applications.(4) Cost, accuracy, and site accessibility are major constraints that can limit the utility and effectiveness of these systems, particularly on complicated construction sites.

Since 2020, Apple® has equipped a consumer-grade, miniaturized lidar sensor system to their iPad Pro® tablet and iPhone® Pro smartphone.(5) The development of pocket lidar (PL) systems has the potential to bring lidar technology to all users, thereby breaking down the cost barrier and enabling routine inspection use. This level of expansion is similar to the wide-scale adoption of the Global Positioning System from its initial use of a select few to its broad use in navigation systems for cars.

A recent applied research effort commissioned by FHWA (*Leveraging Pocket Lidar for Construction Inspection and Digital As-Builts—Phase 1*) evaluated whether a small, handheld, consumer-grade lidar system (PL) can be an efficient and effective tool for routine use in construction project monitoring, delivery, acceptance, oversight, inspection, e construction, supporting Building Information Modeling initiatives, and creating digital as-builts for highway construction projects.(6,7) Given the high-return ROI already being produced by routine utilization of consumer tablets in these activities, as well as the low barrier to entry, integrating a lidar sensor can increase efficiencies, enhance the information collected, and increase ROI.

The following questions arose from the PL research results:

1. How does PL work?
2. Who can use PL?
3. What can PL be used for?
4. What benefits does PL provide?
5. How good is PL?
6. What should PL not be used for?
7. How is the best data obtained?
8. How can PL be implemented effectively?

HOW DOES PL WORK?

While many aspects of the lidar system are proprietary, some basic information has become available to help researchers understand more how the sensor works. The lidar sensor is a flash lidar sensor, which essentially captures a video stream of low-resolution depth maps (each pixel represents a distance to an object). These data are then blended with the video streams from the cameras through an artificial intelligence (AI), deep-learning process to produce a depth map in a higher resolution. Using timestamp information, these depth maps are related to the inertial measurement unit providing positional and orientation information necessary to construct the full point cloud. Some apps also utilize the Global Navigation Satellite System (GNSS) sensor within the device to reference the data.

In some cases, this fusing can result in higher quality data from multiple sensors. However, in other cases, the AI can misinterpret the scene from photographs and create artificial depth maps. Fortunately, a confidence map can be created with each depth map to screen out lower confidence points.

Because the 3D reconstruction is achieved by fusing data sources from multiple sensors, the specifications of the cameras and sensors are essential and will affect the data quality of the 3D point clouds. The iPhone 13 Pro Max™ has three 12-megapixel (MP) cameras covering a wide range of focal length and aperture for the rear cameras. In comparison, the iPads only have two cameras, including a wide 12-MP and an ultrawide 10-MP camera.(8,9) All devices are equipped with the same lidar sensor. The front camera and depth sensor were not in the scope of the research as the depth sensor is limited by its short maximum range, which is not suitable for construction applications. In addition to the cameras, lidar, and depth sensors, all the devices are equipped with GNSS, an accelerometer, and gyros that can be used to estimate the location and orientation of the devices at a given moment during a data acquisition session. The iPhone 13 Pro Max also has an internal compass that can potentially improve positioning results.

Apple provides development kits that allow access to composite depth maps and other sensor information to capture and manipulate 3D point clouds and meshes as developers build custom apps.(10) Lidar-based apps are prolific. Current apps are undergoing regular development with frequent updates, and new apps are continuing to become available. Researchers evaluated many apps during the research process, and several of the apps were found to be suitable for construction applications.

WHO CAN USE PL?

The simplicity of the apps and the intuitive operation of the device enables a diverse workforce to utilize the PL with minimal training and support. Several editing and analysis tasks can be completed directly in the app so users do not need to learn complex desktop software for many purposes. Given the prolific nature of smart devices and that the apps use gestures similar to other apps on smart devices for tasks, the apps are generally intuitive and straightforward to operate. However, for effective operation, testing is necessary to develop clear workflows field personnel can follow for consistent results.

The device's flexibility allows it to be used by many personnel, such as the following:

- Quantity surveyors obtaining measurements.
- Inspectors performing quality control.
- Field crews performing as-built documentation.
- Maintenance crews recording work done or capturing geometry to communicate an issue with a section of roadway or other assets.
- Survey field crews filling in gaps from more robust terrestrial laser scans or capturing maintenance hole or trench information.
- And many more!

WHAT CAN PL BE USED FOR?

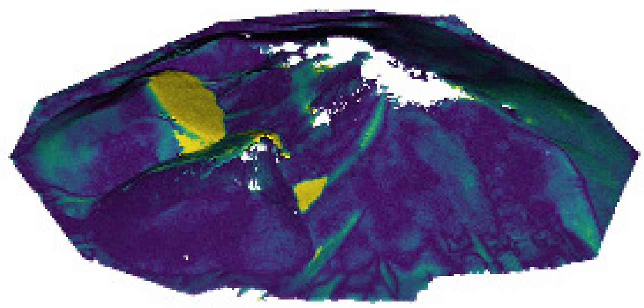
PL can be used with many applications (figure 2) to provide both quantitative and qualitative data. The PL fills a niche for capturing reasonable (cm-level) geometric information on objects and localized areas that are too time consuming for terrestrial laser scans but cannot be adequately captured with photographs. The small size of the device allows it to be operated in tight spaces (e.g., trenches, maintenance holes, construction sites with constricted access in some locations) that are challenging or unsafe to capture with other methods. PL is an inexpensive device that can quickly scan and store constructed elements to monitor progress.

The device can also complement data collected from other survey devices. Because techniques such as lidar and structure from motion and multiview stereopsis photogrammetry are line-of-sight techniques, those techniques will inherently contain data gaps that are not cost-effective to fill in with additional scans. PL, in contrast, can quickly capture those areas to be fused with the reference scan data. Some apps have the functionality to link these built-in scans.

Figure 2. Screenshots. Example point clouds for PL applications.

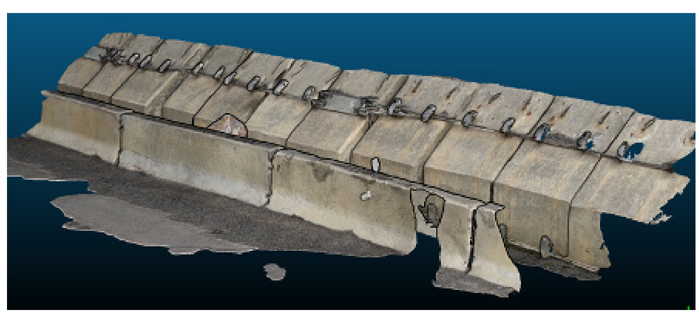
Source: FHWA.

A. Data acquisition of a stockpile.



Source: FHWA. Created using data from 3D Scanner App visualized in Cloud Compare version 2.13.[1,2]

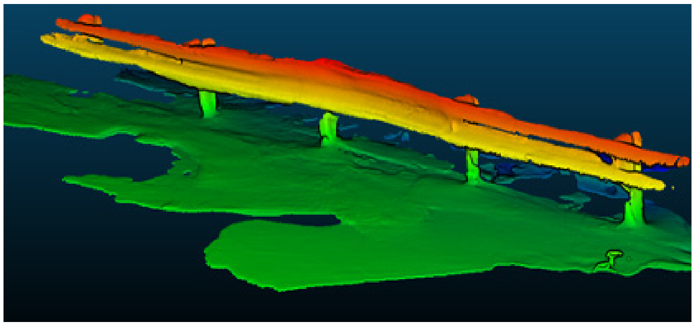
B. Change detection analysis of a stockpile.



Source: FHWA. Created using data from 3D Scanner App visualized in Cloud Compare version 2.13.[1,2]

C. Displacements of a concrete rock barrier wall and jersey barriers.

Figure 2. Screenshots. Example point clouds for PL applications. (Continued)



Source: FHWA. Created using data from 3D Scanner App visualized in Cloud Compare version 2.13.[1,2]

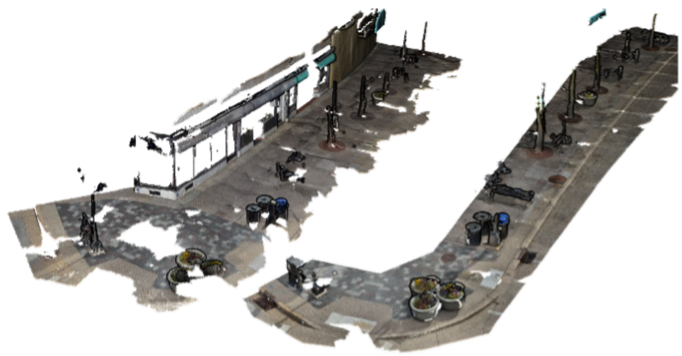
D. Damage to a section of guardrail.

Source: FHWA. Created using data from 3D Scanner App visualized in Cloud Compare version 2.13.[1,2]

E. Settling of pavement near a maintenance hole causing drainage and safety issues.

Source: FHWA. Created using data from 3D Scanner App visualized in Cloud Compare version 2.13.[1,2]

F. Scans of the interior of a maintenance hole and photograph of data acquisition process.



Source: FHWA. Created using data from Scaniverse and 3D Scanner App visualized in Cloud Compare version 2.13.[1,2,8]

G. Sidewalk, curb, and other assets on a streetscape.

Source: FHWA. Created using data from 3D Scanner App visualized in Cloud Compare version 2.13.[1,2]

H. Pipes in an open trench.

WHAT BENEFITS DOES PL PROVIDE?

Given PL's flexibility, ease of use, and efficiency, the PL sensor identified many capabilities related to construction projects (table 1). Beyond data collection, many apps enable some basic processing and analysis directly in the app, which is a significant time savings and substantially reduces the learning curve for operation.

Table 1. Summary of capabilities, benefits, and opportunities for effective usage of the PL system.

Attribute	Capabilities
Mobile	• The flexibility of PL affords the ability to quickly move around and collect data in small, tight spaces (e.g., maintenance holes, trenches). • PL can be available onsite at all times given its portability and the overall usefulness of smart devices for many different purposes. • When combined with appropriate screen protectors and rugged cases, PL is suitable for the demands of the dusty construction environment.
Supportive	• PL could fill in gaps from terrestrial laser scans, reducing the overall time of field surveys. • Some apps have functionality to register and link PL scans with survey-grade lidar scans directly in the app. These scans can be important for efficiently creating as-built models.
Easy to Use	• Intuitive, easy to use yet powerful applications are also available with enhanced functionality. • Some apps provide detailed training resources and videos, such as tutorials on how to register multiple small scans together to reduce drifting. • Most processing can be done directly in the app, enabling inspectors to take advantage of information in the field. • The Applied Programming Interface and several apps provide or utilize the confidence scores provided with the depth map to improve or communicate the accuracy of the resulting models, depending on the application. • Most apps provide real-time feedback on areas that have been or have not been scanned, helping ensure that the model is more complete. Some apps even warn if the data collection is happening too rapidly. • Many apps provide data simplification functions.
Evolving	• Apps change rapidly with bug fixes and improvements. • Apps are supported by an innovative, vibrant development community. Substantial development and opportunities for improvement can occur through collaboration with the transportation and construction sectors.
Efficient	• The ease and rapid speed of data collection allows frequent surveys throughout the construction project to provide digital records at various stages. • As an example, trenches can be scanned to document the location and layout of piping and other utilities below ground before backfilling occurs so that the data can be recalled in the future when work is happening in the area to minimize damages to utilities and slowdowns in construction.

HOW GOOD IS PL?

Researchers conducted rigorous lab testing to evaluate data quality based on a variety of apps, configurations, objects, and conditions. The testing results showed many factors that influence accuracy of the data as follows:

- Data quality between the different devices (iPhone or iPad) varies in terms of noise, even when using the same app and configuration. Some apps rely more heavily on photogrammetric reconstruction and, as a result, struggle with symmetric objects.
- The resolution and precision of the scans are greatly affected by distance.
- Some apps perform downsampling to reduce the number of points and data size when exporting the point cloud.
- In repeatability tests, root-mean-squared (RMS) deviations between the repeated data collection were between 0.019 and 0.133 m, demonstrating that the data quality can vary even when scanning the same scene with the same app and path.
- Drift tends to increase with increasing travel time. Some apps were only able to collect data for a shorter time due to limited processing capabilities, but these durations and the allowable size of data depend on the app settings and configuration.
- Higher RMS errors were observed for smaller objects, particularly those less than 0.1 m. Some apps provide the settings optimized for small object scanning to improve the scan quality but are generally focused on photogrammetric solutions for the data capture method.
- No trends were observed in the data quality under different lighting and speed conditions even through many apps rely on photogrammetric solutions.
- The data quality is greatly affected by distance and angle of incidence. The distortion greatly increases with increasing angle of incidence, while the number of missing points increases with increasing distance. There is significant data dropout just at the 5 m maximum range.
- The data quality is not particularly sensitive to material texture, color, and moisture conditions, given its level of noise. However, because the system uses photogrammetry in addition to lidar, it can create false surfaces at the water surface, leading to incorrect elevation readings for the base of an object (e.g., incorrect invert elevation due to water at the bottom of a maintenance hole).

The research also explored the accuracy of more detailed field tests. Note that when evaluating the suitability of PL for a particular application, the accuracy should be evaluated in context with the specific application, field methods, app (and version) used, and device used as the resulting accuracy can vary substantially. Several field tests were conducted and are described in the full report. Herein are a few representative examples of the field tests:

- Table 2 summarizes results from comparing parking stall dimensions extracted from two apps to a high-quality reference scan obtained with a Leica RTC360. Close agreement within a few percent was observed in the length and width dimensions and associated computed area.
- Table 3 provides a comparison of volumetric information obtained for a stockpile. Errors are much larger for dimensions in this case as longer scan times were required for complete coverage compared with the prior example. However, when compared to the reference scans, the volumes agreed within 2 percent compared for the large pile and 10 percent for the small pile.
- Table 4 summarizes the cloud-to-cloud surface matching between diverse objects captured in the research. The mean and standard deviation from the comparison were consistent and in line with the nominal accuracy of the sensors.

Table 2. Comparison of parking stall dimension measurements (length, width, and area) between the Leica RTC360 scanner (reference) and two apps.

	RTC360	3D Scanner App[1]			Scaniverse[11]		
Measurement	Dimension	Dim.	Diff.	Percent Diff.	Dim.	Diff.	Percent Diff.
Length (m)	5.387	5.450	0.063	1.17	5.329	−0.058	−1.08
Width (m)	2.356	2.301	−0.055	−2.33	2.299	−0.057	−2.42
Area (m^2)	12.692	12.540	−0.152	−1.20	12.251	−0.441	−3.47

Dim. = dimension, Diff. = difference.

Table 3. Comparison of distance and volumetric measurements for stockpile comparing measurements when the reference surface is unavailable and when the reference surface has been captured.

	RTC360	3D Scanner App[1]			Scaniverse[11]		
Measurement	Dimension	Dim.	Diff.	Percent Diff.	Dim.	Diff.	Percent Diff.
Horizontal distance between two targets (m)	10.880	10.801	−0.079	−0.73	10.872	−0.008	−0.07
Vertical distance between two targets (m)	3.031	2.863	−0.168	−5.54	2.325	−0.706	−23.29
Volume of original stockpile (m^3)	138.969	141.817	2.848	2.05	138.659	−0.310	−0.22
Added volume of the new pile (m^3)	13.496	14.681	1.185	8.78	14.397	0.901	6.68

Table 4. Cloud-to-cloud comparison.

	3D Scanner App[1]		Scaniverse[11]	
Dataset	Dim.	Diff.	Dim.	Diff.
Sidewalk	0.052	0.037	0.065	0.037
Curbs	0.046	0.036	0.054	0.036
Traffic light	0.020	0.018	0.014	0.012
Trenches	0.030	0.029	0.037	0.032
Pile 1	0.031	0.027	0.028	0.028
Pile 2	0.034	0.027	0.010	0.008
Maintenance hole 1	0.030	0.022	0.010	0.014
Maintenance hole 2	0.027	0.021	0.010	0.017

Note: Maximum distance threshold is 0.10 m; reference are RTC360 scans.

WHAT SHOULD PL NOT BE USED FOR?

Despite the promising features noted in the previous section, PL has limitations in its current implementation (table 5). Some of these limitations may be improved in future generations of the sensor and apps. A solid understanding of these limitations can help ensure effective field use and improve the quality assurance process. However, identifying the appropriate time to use PL will ensure the maximum ROI. For some applications, particularly high-accuracy applications, other technologies may be more efficient, even if initially more costly or complex. For sensitive projects requiring high accuracy, trusted technologies should be used. However, many applications do not require scrutiny (e.g., inventory, progress monitoring, and trench as-builts) and are not hindered by these limitations.

Table 5. Summary of limitations for effective usage of the PL system.

Attribute	Limitations
Data quality	• The PL does not provide intensity information. • Lidar resolution within a frame is relatively low. • Slightly noisy point cloud data when multiple scans are combined. • Artifacts such as repeating offset surfaces can occur regularly in the data due to errors in the photogrammetric processes and SLAM (simultaneous localization and mapping).
Operation	• Limited field of view can be captured and viewed on the screen. • Potential safety hazards can arise during operation as the operators are focused on the screen during the scanning process. Some of these hazards can be alleviated with experience and using an extension rod to minimize the impact on the operator's field of view.
Size	• The sensor provides a very limited field of view; hence, lots of movement is required to capture the scene. • The range of the sensor is limited to 5 m. This small maximum range can limit its effectiveness in applications such as scanning rock slope faces, bridges, and other features. • Drifting occurs when attempting to scan large areas. Operators typically need to limit scans to small areas (10 m × 10 m). Some drifting can be mitigated by multiple scans, but that increases processing time and often requires postprocessing in the office. Often large areas will need survey control to maintain high accuracy. • The sensor is unable to resolve small features (<10 cm).
Inconsistency	• The level of documentation can be limited for some apps. • The apps change rapidly. While ordinarily these upgrades are positive, the changes can lead to inconsistencies in results between surveys and affect workflow processes. It is often unclear how app upgrades will directly affect results. Hence, use of the device on monitoring projects could be problematic when updating apps to later versions. • Results can vary substantially as app settings change. Workflows need to be established and validated with specific app settings for consistency. • While the AI engine blending the lidar and photogrammetric data can make results look visually compelling, the AI does not necessarily provide accurate data. Caution is necessary for higher accuracy applications as the operator is not fully aware of what modifications have been made to the data or what the AI has interpreted as reality compared with direct measurements.

HOW ARE THE BEST DATA OBTAINED?

The data collection process is similar to the process for structure from motion and multiview stereopsis photogrammetry, except the field of view is smaller, and the process uses continuous rather than discrete photos. For best results when scanning, users should consider the following recommendations:

- Limit scans to small, localized areas (10 m × 10 m) or objects.
- Collect short duration scans (<30 s) to avoid drift in the data. Scans can be merged later, if needed, in many apps.
- Use selfie sticks to shorten the distance from the objects and for hard-to-reach areas (e.g., undersides of pipes).
- Move around the scene in a smooth fashion to capture objects from multiple perspectives. Avoid panorama scanning approaches as those weaken the photogrammetric portion of the data.
- Avoid focusing on the screen too long for safety and watch for surroundings when walking around with the device.

Check out these YouTube Channels for Tips and Tricks!

- Pocket Lidar for Transportation[12]
- Surveying with the Apple iPhone Lidar[5]

- Avoid moving too fast and jerky as well as too slow. Experiment with the device until comfortable with the ideal acquisition speeds.
- Pay attention to the feedback on the screen as to where there are gaps in the data acquisition.
- Know when the tool is right and when a higher quality laser scanner should be used. Realize that this tool is complementary to, not a replacement for, a higher-grade scanner. For example, while TLS may be inexpensive initially, if very high data quality are needed or a large area needs to be surveyed, a lesser quality scanner will be more expensive in the long run compared with survey grade laser scanners.

Figure 3. Photograph. Example acquisition of data from a trench using a selfie stick to capture hard-to-reach features.

Source: FHWA.

HOW CAN PL BE IMPLEMENTED EFFECTIVELY?

Determine ROI and how widespread this technology usage should be in an organization. In some cases, the cost of a smart device with lidar capabilities ($1,200) to capture the relative locations of pipes before they are buried is insignificant compared to costs of litigation should an issue arise when excavating near existing pipes. However, costs will scale with the number of inspectors.

The following recommendations for implementations maximize quality, ease of use, and ROI with the lidar device:

- Develop rigorous workflow procedures and protocols to ensure systematic, trustworthy data collection within agencies.
- Conduct pilot tests within an agency to verify the protocols for operation.
- Calibrate by periodically testing with known objects to ensure the device is operating properly, especially when upgrading an app.
- Test different apps before establishing workflows. Some apps performed better in some situations or scans compared with others.
- Investigate updates regularly and keep apps up to date when possible. Be sure to test results after app updates.
- Perform additional research, testing PL for specific applications. (The aforementioned research project will continue to explore and document selected applications in more detail through case studies to serve as a starting point.)
- Investigate the augmented reality and virtual reality capabilities of applications that can be developed from the high quality lidar and photogrammetric sensors on PL devices.
- Share knowledge. Have a forum for inspectors to share tips and tricks they have learned.

FUTURE ACTIVITIES

In addition to assessing the capabilities and limitations of PL sensor system technology, the research team has performed case studies and demonstrations by engaging with transportation agencies and contractors well positioned to adopt and utilize the technology. Likely many more new and exciting opportunities exist to utilize this portable, flexible, easier-to-use technology on smart devices.

Key Takeaway:

While the research provides insights into the suitability of PL, specific workflows and calibration processes should be developed for the applications of interest to ensure the highest quality results.

Remember—PL is new, evolving technology developed for other purposes. So, while PL can be a useful, valuable tool, caution must be exercised in ensuring that tried and tested workflows with quality assurance checks are developed and implemented to produce the desired results before adopting the technology for use on projects.

REFERENCES

1. Laan Labs. 2024. *3D Scanner App* (software). https://3dscannerapp.com/, last accessed October 25, 2024.

2. CloudCompare. 2023. *GPL* (software). Version 2.13. http://www.cloudcompare.org/, last accessed December 2, 2024.

3. Olsen, M. J., G. V. Roe, C. Glennie, F. Persi, M. Reedy, D. Hurwitz, K. Williams, H. Tuss, A. Squellati, and M. Knodler. 2013. *Guidelines for the Use of Mobile LIDAR in Transportation Applications*. NCHRP Report No. 748. Washington, DC: Transportation Research Board.

4. FHWA. n.d. "Every Day Counts" (web page). https://www.fhwa.dot.gov/innovation/everydaycounts/, last accessed November 22, 2024.

5. @Rami Tamimi. n.d. Rami Tamimi. YouTube channel. https://www.youtube.com/@RamiTamimi/featured, last accessed November 22, 2024.

6. Olsen, M. J., E. Che, J. Jung, M. Thorsen, J. Caya, and G. Roe. (Forthcoming.) *Leveraging Pocket Lidar for Construction Inspection and Digital As-Builts—Phase 1*. Washington, DC: FHWA.

7. FHWA. 2022. "Building Information Modeling (BIM) for Infrastructure " (web page). https://www.fhwa.dot.gov/infrastructure/bim/, last accessed December 2, 2024.

8. Apple, Inc. 2021. "iPhone 13 Pro Max - Technical Specifications" (web page). https://support.apple.com/en-us/111870, last accessed November 22, 2024.

9. Apple, Inc. 2021. "iPad Pro" (web page). https://www.apple.com/ipad-pro/specs/, last accessed November 22, 2024.

10. Apple, Inc. 2021. "Augmented Reality" (web page). https://developer.apple.com/augmented-reality/arkit/, last accessed November 22, 2024.

11. Niantic, Inc. 2024. *Scaniverse* (software). https://scaniverse.com/, last accessed October 25, 2024.

12. @applelidarfortransportatio1925. n.d. Apple Lidar for Transportation. YouTube channel. https://www.youtube.com/channel/UC9WAoH6_qsH1yobqCviqDbg, last accessed November 22, 2024.

Source: Federal Highway Administration (FHWA). Created using data from 3D Scanner App visualized in CloudCompare version 2.13.[1,2]

Researchers—This study was conducted by EZDataMD LLC, 5C Strategy, and MPN Components. Michael Olsen (EZDataMD), Ezra Che (EZDataMD), Jaehoon Jung (EZDataMD), John Caya (5C Strategy), Mitch Thornsen (5C Strategy) and Gene Roe (MPN Components) contributed to this case study under order number 693JJ321P000047.

Distribution—This TechBrief is being distributed according to a standard distribution. Direct distribution is being made to the FHWA divisions and Resource Center.

Availability—This TechBrief may be obtained at https://highways.dot.gov/research.

Key Words—Pocket lidar, imaging, measurements, construction, stockpiles, trenches.

DECEMBER 2024

Recommended citation: Federal Highway Administration, *Leveraging Pocket Lidar for Construction Inspection and Digital As-Builts—Phase 1* (Washington, DC: 2024) https://doi.org/10.21949/1521533

FHWA-HRT-25-017
HRDI-20/12-24(WEB)E