TECHBRIEF

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

Enhancing Vulnerable Road User Detection and Volumetric Data Quality With Lidar Sensors

FHWA Publication No.: FHWA-HRT-25-007

FHWA Contact: Jesse Eisert (ORCID: 0000-0003-0116-5141), HRSO-30, 202-493-3377, jesse.eisert@dot.gov

This TechBrief is part 2 of a two-part series (part 1 is FHWA-HRT-24-135). The TechBrief is a technical summary of the Federal Highway Administration (FHWA) report *Enhancing Vulnerable Road User Detection and Volumetric Data Through Advanced Infrastructure Detection Technologies* (FHWA-HRT-24-175).

INTRODUCTION

According to the National Highway Traffic Safety Administration (NHTSA), 7,522 pedestrian deaths and 1,105 pedalcyclist deaths occurred in 2022, and nonoccupants of vehicles accounted for 21 percent of all traffic fatalities (National Center for Statistics and Analysis (NCSA) 2024a, 2024b; U.S. Department of Transportation (USDOT) n.d.) These data are available on the NHTSA File Downloads web page (USDOT n.d.). Vulnerable road users are at greater risk of serious injury or death if they are involved in a traffic crash (Organization for Economic Co-operation and Development 1998). According to Walker (2022), FHWA defines a vulnerable road user as follows:

> A vulnerable road user is a nonmotorist with a fatality analysis reporting system (FARS) person attribute code of pedestrian, bicyclist, other cyclist, person on personal conveyance, or injured person who is or is equivalent to a pedestrian or pedalcyclist as defined in the ANSI [American National Standards Institute] D16.1-2007 (ANSI 2007). See U.S. Code (U.S.C.) 23 §148(a)(15) and Code of Federal Regulations (CFR) 23 924.3 §490.205 [GPO 2024a, 2024b]. A vulnerable road user may include people walking, biking, or rolling. Please note that a vulnerable road user:
>
> - Includes a highway worker on foot in a work zone, given they are considered a pedestrian.
> - Does not include a motorcyclist.

The challenges associated with collecting nonmotorized data are documented in FHWA's *Traffic Monitoring Guide* and the National Cooperative Highway Research Program's (NCHRP) *NCHRP Report 797: Guidebook on Pedestrian and Bicycle Volume Data Collection* (FHWA 2016; Ryus et al. 2014). Researchers have discussed measuring pedestrian exposure to crash risk for more than three decades, but an effective method has remained elusive—partially due to the challenges associated with collecting pedestrian data. For example, vulnerable road users traverse paths that are less confined than fixed lanes, take shortcuts off sidewalks in unmarked crossing locations, and often travel in closely spaced groups. These tendencies make differentiating among individuals within a group challenging for sensors (FHWA 2016). Additionally, vulnerable road users are harder to detect at night. In 2020, 77 percent of fatal pedestrian crashes occurred in the dark, with 75 percent occurring from 6 p.m. to 3 a.m. and 23 percent occurring from 6 to 8 p.m. (NCSA 2022).

Light Detection and Ranging (LiDAR) sensor technology is one way to improve detection of vulnerable road users in dimly lit situations, such as at night, or in brightly lit situations (Williams 2017). Advanced detection systems must be able to make detections in the dark and to detect different types of vulnerable road users, including scooter users and wheelchair users. The number of electronic scooter systems implemented in North American cities from 2020 to 2021 increased by 30 percent (North American Bikeshare and Scootershare Association 2022). As scooter user activity increases, transportation agencies must be able to accurately detect these types of vulnerable road users. When considering exposure to crash risk, including all individuals is crucial. If LiDAR sensors cannot identify specific users, the calculation of exposure will be misrepresented, based on missing entire populations.

In calculations of exposure to crash risk, pedestrians of all ages must be considered. Studies have shown that child pedestrians (<18 yr old) are at higher risk of collision with motor vehicles compared with adults, especially at midblock crossings (Rothman et al. 2012). In 2021, 16 percent of children involved in traffic fatalities were pedestrians (NCSA 2022). Even though crash data on child pedestrians are available, few studies to date have examined the ability of advanced detection systems to detect children and adults with equal accuracy.

To research viable methods for improving vulnerable road user safety, FHWA designed and developed a vulnerable road user technology test bed at Turner-Fairbank Highway Research Center (TFHRC) (FHWA n.d.). The test bed examines technologies and sensors that can support pedestrian and bicyclist system concepts, standards, and applications and related product innovations (Jannat et al. 2021). As part of the test bed, FHWA installed and calibrated two LiDAR sensors based on original equipment manufacturer (OEM) specifications; the OEM stated the sensors can detect vehicles, pedestrians, and bicyclists.

The OEM specifications also indicated the LiDAR sensors did not need light to detect various road users. Instead, the sensors used laser reflection from road users, which enabled sensors to detect vehicles and vulnerable road users at night, over long distances, or in adverse weather conditions, such as fog, rain, and snow. Understanding the ability and applicability of these sensors under various conditions may potentially help State and local departments of transportation determine whether to suggest implementing the sensors as part of safety initiatives and whether the count data from LiDAR sensors can calculate pedestrian exposure.

OBJECTIVES

The purpose of this research is to evaluate the appropriateness and applicability of LiDAR sensors for collecting vulnerable road user count data under variable conditions that can provide information for measuring exposure to crash risk.

The research team tested the LiDAR sensor's ability to detect the following types of vulnerable road users under different conditions, including crossing time of day (day or night), speed (slow or fast) and location (intersection or midblock):

- Single pedestrian (two types):
  - Adult.
  - Child (represented by an articulating pedestrian dummy).
- Multiple adult pedestrians.
- Bicyclists.
- Scooter users.
- Wheelchair users.

METHOD

Apparatus

This study used several technologies to conduct testing on the TFHRC vulnerable road user technology test bed. The test bed contained two marked, signalized intersections with pedestrian crosswalks, signal heads and call buttons and one marked midblock crossing along a two-lane, two-way, 22-ft-wide road.

LiDAR Sensor

The research team selected one 32-channel LiDAR sensor located on the TFHRC test bed intersection. The LiDAR sensor has a measurement range of 650 ft, a range accuracy of ±3 cm, a horizontal field of view of 360 degrees, a vertical field of view of 40 degrees, and a frame rate of 5–20 hertz. The sensor has capabilities to detect pedestrians and vehicles, count vehicles and pedestrians, collect traffic data, monitor traffic flow, and detect out-of-crosswalk occurrences. The sensor was set to detect and track the movements of pedestrians within the sensor's field of view.

The research team used proprietary software from the LiDAR sensor manufacturer to process and save the LiDAR sensor data and determine successful detection and counts. The software allowed for multimodal count data per a customizable counting zone definition. The research team visualized count data from specific locations and detection zones during designated time periods using this software and then used these count data to verify detection of vulnerable road users and count data accuracy.

The research team placed the LiDAR sensor along Innovation Drive on the TFHRC campus. The research team set the sensor to observe the intersection crosswalk and the midblock crosswalk within the TFHRC test bed. Each crosswalk was located within the field of view and detection distance of the sensor, as determined by the OEM specifications. The research team selected crosswalks A and B as the primary crosswalks to test the sensor. Crosswalk A (midblock crossing) was on a vertical curve.

For data collection, the team initially chose two LiDAR sensors located on the TFHRC campus but excluded one sensor from the results due to technical issues. The sensor used was labeled C234. Figure 1 shows the general locations of each sensor.

CCTVs

The research team used two closed-circuit television (CCTV) digital video recorders (DVRs) to record a live, high-resolution video feed in color during data collection. The CCTV DVRs were located 133 ft and 136 ft from the intersection and midblock crossing, respectively. The DVRs were zoomed in to see vulnerable road user activity on the testing site. The video feed kept a record of the ground-truth motion of vulnerable road users during testing. The video recording was then compared with the aggregate count output of the LiDAR sensor to verify the quality of the LiDAR sensor recording.

LiDAR Sensor Roadside Data Processing Unit and Data Analytics Software

The LiDAR sensor input was condensed into a single data stream and processed through a roadside data processing unit. The unit, which was housed in milled aluminum, was installed at the intersection near the sensor and consisted of a 512-core graphics processing unit with 64 tensor cores; an 8-core, 64-bit central processing unit; and 32 gigabytes of 256-bit random access memory.

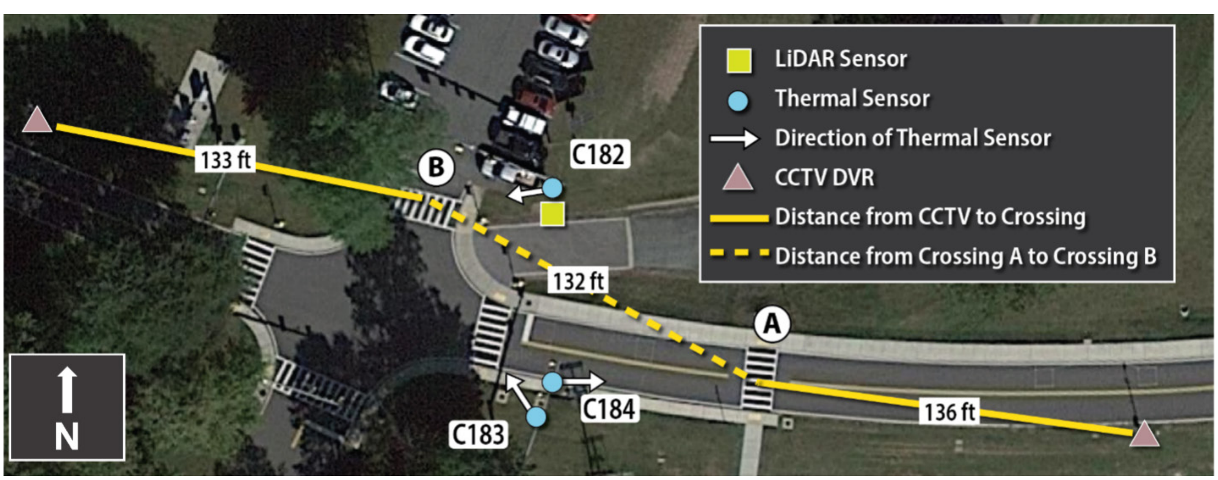
The unit allowed for edge-based computing, enabling real-time data processing with the vendor's proprietary software license, which included data analytics software with multiple functionalities. The software's system aggregated count data for roadway agent detections every 15 min. To get and count individual crossings, the research team set the out-of-crosswalk event detection to include the crosswalk. From these data, the team could record and manually aggregate crosswalk crossings in the regions of interest.

Note: From this point on in this document, all references to the LiDAR sensor being evaluated are referring to the ability of the sensor when paired with the roadside data processing unit and data analytics software.

Video Recording Software

The research team used open-source video recording software coded to record data during trial runs of the CCTV DVRs. The team manually coded detections from video data when count data failed to save properly,

Figure 1. Photo. TFHRC pedestrian technology test bed and LiDAR and thermal sensor locations.



CCTV = closed-circuit television; DVR = digital video recorder.

which happened in less than 3 percent of cases due to prematurely ending the saved count feed.

Electric Scooter

The team used a 350-watt electric scooter with a 36-volt, 15-ampere-hour battery. The scooter manufacturer lists the scooter's top speed at 20 miles per hour (mph) and its load capacity as 220 lb.

Wheelchair

The team used an electric wheelchair with a 12-volt battery. The wheelchair manufacturer lists the wheelchair's top speed at 4 mph and its load capacity as 700 lb. The wheelchair's leg rests were attached and used during testing.

Bicycle

A research team member rode a 26-inch manual cruiser bicycle to represent bicyclists.

Belt-Driven Articulating Pedestrian Dummy

The team used a programmable articulating pedestrian dummy to simulate a child-size vulnerable road user. The child-size pedestrian dummy is 45.5 inches tall and approximately the average height of a 6-year-old male child (Kuczmarski et al. 2000).

Vulnerable Road Users

The single adult pedestrian, three adult pedestrians, and operators of the wheelchair, scooter, and bicycle, were members of the research team. The agents acting as these vulnerable road user types were a mix of males and females of various age ranges and races.

Experimental Design

The research team worked with FHWA to identify factors needed to address the objectives for the LiDAR sensor. Several unknowns appeared to exist regarding these sensors, including capabilities for midblock detection, differentiation, identification of closely clustered groups of pedestrians, and performance levels in adverse weather conditions. The selected LiDAR sensor was within the detection range defined by the OEM specifications for either the designated intersection or midblock crossing.

The research team conducted pilot testing for the sensor and setup. During piloting, the team tested each condition level of each factor at least twice to ensure no major issues existed with the LiDAR sensor setup or study design. The research team identified four key factors for the study: vulnerable road user type, speed, time of day, and location. Table 1 shows the condition levels for each factor. The specific values of each level of each factor were established in a previous study that FHWA conducted to evaluate the ability of thermal imaging sensors (FHWA 2024). The only change in the current study was using an electric wheelchair instead of a manual wheelchair.

Table 1. Factors and condition levels.

Factor	Condition Level
Vulnerable road user type	Single adult pedestrian Child-size pedestrian dummy Wheelchair user Three adult pedestrians Bicyclist Scooter user
Speed	Slow Fast
Time of day	Day Night
Location	Intersection Midblock

Vulnerable Road User Type

The research team chose six vulnerable road user types to evaluate the LiDAR sensor's ability to detect different vulnerable road users (table 1). El-Urfali et al. (2019) used the single-adult-pedestrian condition to test advanced detection technologies, and this condition served as a comparison point in this study for the performance of the other vulnerable road user types.

The child pedestrian dummy simulated a child pedestrian, testing the LiDAR sensor's ability to detect vulnerable road users of different sizes. The LiDAR sensor was positioned so that the dummy could enter and leave the detection zone moving in one direction. The study used the condition with three adult pedestrians to determine the sensor's ability to detect multiple entities crossing in a group. In addition to those four pedestrian types, the three other levels included an adult-wheelchair-user, an adult bicyclist, and an adult scooter user. The adult-wheelchair-user condition used a motorized electric wheelchair.

Speed

The research team established two levels of speed—slow and fast—for each vulnerable road user type. Table 2 lists the speeds chosen for each vulnerable road user type. The principal investigator validated the speed from the live-tracking data during data collection.

Table 2. Fast and slow speeds for each vulnerable road user type.

Vulnerable Road User Type	Slow Speed (mph)	Fast Speed (mph)
Single adult pedestrian	2	5
Three adult pedestrians	2	5
Wheelchair user	2	5
Child-size pedestrian dummy	2	5
Bicyclist	5	10
Scooter user	5	10

Time of Day

The experiment used two levels—day and night—to test the sensor's ability to detect vulnerable road users under daylight conditions and at night, when ambient light is not present. The research team defined day as any time during the period from at least one hour after sunrise to one hour before sunset of each day. The team defined night as any time during the period from at least one hour after sunset to one hour before sunrise. These definitions meant that during the day level, the team conducted experiments in full daylight; during the night level, the team conducted experiments with no sunlight. Additionally, the team collected data about ambient weather conditions (i.e., sunny, partly sunny, cloudy) but did not collect data during very cloudy or adverse weather.

Location

The team chose the intersection crossing (B) and midblock crossing (A), as shown in figure 1, for data collection. Road closures at these locations helped to ensure the safety of team members.

System Performance Metrics

The research team tested each of the 48 conditions 8 times. The team made a total of 384 observations. When collapsing across all factors except for vulnerable road user types, which had the largest number of levels, the total observations for each level was 64—an acceptable number of observations to have a 95-percent confidence level (±5 percent). The total number of observations for the levels of the other factors was 192 observations—also an acceptable number of observations for a 95-percent confidence level (±5 percent).

This study's performance measures were true detection accuracy (recall), system accuracy (precision), and F1 score—a type of *F*-score that measures accuracy by using precision and recall. Because both the recall and the precision of advanced detection technologies are important, an F1 score can be used. An F1 score measures accuracy and incorporates the proportion of hits compared with all trials (including misses) and all detections (including false positives), weighing those two aspects of accuracy equally.

Table 3 lists the four potential outcomes for any single trial (i.e., detection or no detection) that occurred during data collection. Agencies use these potential outcomes to calculate the established performance metrics. True detection accuracy measures the LiDAR sensor's ability to detect vulnerable road users while also accounting for misses. For example, if the sensor makes 5 successful detections out of 10 possible correct detections, the true detection accuracy rate is 50 percent. System accuracy measures the LiDAR sensor's ability to detect only vulnerable road users and exclude nonvulnerable road users and false detections. For example, if the sensor makes a total of 10 detections but only 8 are accurate detections of actual vulnerable road users (i.e., 2 false detections), the system accuracy rate is 80 percent.

Table 3. Potential outcomes for a single trial of data collection.

Vulnerable Road User Crossing	Sensor Output	Outcome
Crossing	Detection	Hit
Crossing	No detection	Miss
No crossing	Detection	False detection
No crossing	No detection	Correct rejection

The research team used true detection accuracy as a measure to determine the abilities of the sensor. The team used system accuracy in conjunction with true detection accuracy to calculate an F1 score, which was used to assess the applicability of the LiDAR sensor for detecting vulnerable road users. Applicability of the sensor is based on sensor ability to detect not only vulnerable road users but also to minimize false detections.

Following are equations for the chosen performance metrics:

- True detection accuracy:

$$\sum Hits/(\sum Hits + \sum Misses)$$

- System accuracy:

$$\sum Hits/(\sum Hits + \sum False\ Detections)$$

- F1-score:

$$2\frac{(True\ detection\ accuracy * System\ accuracy)}{(True\ detection\ accuracy + System\ accuracy)}$$

The higher the value of true detection accuracy, the more likely the sensor can detect vulnerable road users when a vulnerable road user is truly present. Based on El-Urfali et al. (2019), the research team set the minimum acceptable F1 score as 0.85 and the minimum acceptable true detection accuracy as 85 percent. Any scores below these thresholds resulted in unacceptable performance ratings (table 4).

Table 4. True detection accuracy thresholds.

F1 Score	True Detection Accuracy (%)	Rating
≥0.85	≥85	Acceptable performance
≤0.84	≤84	Unacceptable performance

DATA ANALYSIS AND RESULTS

The research team calculated true detection accuracy, system accuracy, and F1 scores from the count data collected for each combination of factors and compared the data across the levels of each factor. The team used data from sensor C284 to collect all the intersection and midblock conditions. Table 5 shows the total number of vulnerable road user crossings (total number of hits and misses), total detections (hits and false positives), total number of misses, and total number of hits for each combination of factors. Using the count data, the research team calculated true detection accuracy, system accuracy, and F1 scores for each condition for the LiDAR sensor. The team aggregated total crossings, detections, misses, and hits across all 56 conditions and calculated the total true detection accuracy, system accuracy, and F1 score for the LiDAR sensor. Some values under system accuracy and F1 score had no hits or false positives—thus resulting in zero being divided by zero, creating a nonapplicable value.

Table 5. LiDAR sensor outcomes and performance metrics by condition.

Vulnerable Road User Type	Location	Mode of Travel	Time of Day	Total Crossings (No.)	Total Detections (No.)	Total Misses (No.)	Total Hits (No.)	True Detection Accuracy (%)	System Accuracy (%)	F1 Score
Single adult pedestrian	Intersection	Fast	Day	8	8	0	8	100	100	1.00
Single adult pedestrian	Intersection	Fast	Night	8	8	0	8	100	100	1.00
Single adult pedestrian	Intersection	Slow	Day	8	8	0	8	100	100	1.00
Single adult pedestrian	Intersection	Slow	Night	8	8	0	8	100	100	1.00
Single adult pedestrian	Midblock	Fast	Day	8	8	0	8	100	100	1.00
Single adult pedestrian	Midblock	Fast	Night	8	8	0	8	100	100	1.00
Single adult pedestrian	Midblock	Slow	Day	8	8	0	8	100	100	1.00
Single adult pedestrian	Midblock	Slow	Night	8	8	0	8	100	100	1.00
Child pedestrian dummy	Intersection	Fast	Day	8	0	8	0	0	—	—

Table 5. LiDAR sensor outcomes and performance metrics by condition. (Continued)

Vulnerable Road User Type	Location	Mode of Travel	Time of Day	Total Crossings (No.)	Total Detections (No.)	Total Misses (No.)	Total Hits (No.)	True Detection Accuracy (%)	System Accuracy (%)	F1 Score
Child pedestrian dummy	Intersection	Fast	Night	8	0	8	0	0	—	—
Child pedestrian dummy	Intersection	Slow	Day	8	0	8	0	0	—	—
Child pedestrian dummy	Intersection	Slow	Night	8	0	8	0	0	—	—
Child pedestrian dummy	Midblock	Fast	Day	8	0	8	0	0	—	—
Child pedestrian dummy	Midblock	Fast	Night	8	0	8	0	0	—	—
Child pedestrian dummy	Midblock	Slow	Day	8	0	8	0	0	—	—
Child pedestrian dummy	Midblock	Slow	Night	8	0	8	0	0	—	—
Wheelchair user	Intersection	Fast	Day	8	5	3	5	62	100	0.77
Wheelchair user	Intersection	Fast	Night	8	7	1	7	88	100	0.93
Wheelchair user	Intersection	Slow	Day	8	0	8	0	0	—	—
Wheelchair user	Intersection	Slow	Night	8	0	8	0	0	—	—
Wheelchair user	Midblock	Fast	Day	8	7	1	7	88	100	0.93
Wheelchair user	Midblock	Fast	Night	8	7	1	7	88	100	0.93
Wheelchair user	Midblock	Slow	Day	8	8	0	8	100	100	1.00
Wheelchair user	Midblock	Slow	Night	8	8	0	8	100	100	1.00
Three adult pedestrians	Intersection	Fast	Day	24	8	16	8	33	100	0.50
Three adult pedestrians	Intersection	Fast	Night	24	5	19	5	21	100	0.34
Three adult pedestrians	Intersection	Slow	Day	24	8	16	17	33	100	0.50
Three adult pedestrians	Intersection	Slow	Night	24	6	18	6	25	100	0.40
Three adult pedestrians	Midblock	Fast	Day	24	9	15	9	38	100	0.55
Three adult pedestrians	Midblock	Fast	Night	24	8	16	8	33	100	0.50
Three adult pedestrians	Midblock	Slow	Day	24	12	12	12	50	100	0.67
Three adult pedestrians	Midblock	Slow	Night	24	7	17	7	29	100	0.45
Bicyclist	Intersection	Fast	Day	8	1	7	1	12	100	0.22
Bicyclist	Intersection	Fast	Night	8	0	8	0	—	—	—
Bicyclist	Intersection	Slow	Day	8	6	2	6	75	100	0.86

Table 5. LiDAR sensor outcomes and performance metrics by condition. (Continued)

Vulnerable Road User Type	Location	Mode of Travel	Time of Day	Total Crossings (No.)	Total Detections (No.)	Total Misses (No.)	Total Hits (No.)	True Detection Accuracy (%)	System Accuracy (%)	F1 Score
Bicyclist	Intersection	Slow	Night	8	6	2	6	75	100	0.86
Bicyclist	Midblock	Fast	Day	8	6	2	6	75	100	0.86
Bicyclist	Midblock	Fast	Night	8	5	3	5	62	100	0.77
Bicyclist	Midblock	Slow	Day	8	7	1	7	88	100	0.93
Bicyclist	Midblock	Slow	Night	8	6	2	6	75	100	0.86
Scooter user	Intersection	Fast	Day	8	2	6	2	25	100	0.40
Scooter user	Intersection	Fast	Night	8	0	8	0	—	—	—
Scooter user	Intersection	Slow	Day	8	4	4	4	50	100	0.67
Scooter user	Intersection	Slow	Night	8	8	0	8	100	100	1.00
Scooter user	Midblock	Fast	Day	8	0	8	0	—	—	—
Scooter user	Midblock	Fast	Night	8	0	8	0	—	—	—
Scooter user	Midblock	Slow	Day	8	7	1	7	88	100	0.93
Scooter user	Midblock	Slow	Night	8	6	2	6	75	100	0.86

—Not applicable.

The overall true detection accuracy for the LiDAR sensor was 79.88 percent, suggesting overall unacceptable performance (i.e., less than 85 percent), with true detection accuracy less than 85 percent for most of the conditions. However, the single adult pedestrian had 100-percent true detection accuracy for all conditions. The team evaluated each factor independently of the other factors. Table 6 shows the performance metrics for each vulnerable road user condition.

Table 7 shows the performance of the LiDAR sensor at slow and fast speeds. Table 8 shows the performance of the LiDAR sensor at slow and fast speeds, excluding the three-adult-pedestrian condition.

Table 9 shows the performance of the LiDAR sensor during the day and night. Table 10 shows the performance of the LiDAR sensor during the day and night, excluding the three-adult-pedestrian condition.

Table 11 shows the performance of the LiDAR sensor at an intersection and at midblock. Table 12 shows the performance of the LiDAR sensor at an intersection and at midblock, excluding the three-adult-pedestrian condition.

Table 6. Performance of LiDAR sensor across vulnerable road user types.

Vulnerable Road User Type	True Detection Accuracy (%)	System Accuracy (%)	F1 Score
Single adult pedestrian	100	100	1.00
Child pedestrian dummy	0	—	—
Wheelchair user	66	100	0.79
Three adult pedestrians	33	100	0.49
Bicyclist	58	100	0.73
Scooter user	42	100	0.59
Overall	79.88	100	0.89

—Not applicable.

Table 7. Performance of LiDAR sensor at slow and fast speeds.

Speed	True Detection Accuracy (%)	System Accuracy (%)	F1 Score
Slow	51	100	0.68
Fast	40	100	0.57

Table 8. Performance of LiDAR sensor at slow and fast speeds (excluding three-adult-pedestrian condition).

Speed	True Detection Accuracy (%)	System Accuracy (%)	F1 Score
Slow	61	100	0.76
Fast	45	100	0.62

Table 9. Performance of LiDAR sensor during the day and night.

Time of Day	True Detection Accuracy (%)	System Accuracy (%)	F1 Score
Day	48	100	0.65
Night	43	100	0.60

DISCUSSION

The research team selected six criteria (table 13) to determine the overall ability of the LiDAR sensor. Based on an 85-percent true detection accuracy value as a minimum threshold, the LiDAR sensor consistently detected single adult pedestrian types under all levels and conditions. All other vulnerable road user types had true detection accuracy less than 85 percent.

Criterion 1

The LiDAR sensor had true detection accuracy values greater than 85 percent for the single adult pedestrian type. All other types had true detection accuracy values between 0 and 66 percent. Specifically, the single adult pedestrians had the best detection, with a true detection accuracy value of 100 percent—suggesting the LiDAR sensor and software consistently detected this vulnerable road user type across all other conditions.

In contrast, wheelchair users and bicyclists had true detection accuracy values between 50 and 70 percent. Scooter users and the three-adult-pedestrian condition had true detection accuracy values under 50 percent. The child dummy was not detected by the LiDAR sensor at all. The trajectory of the dummy system used in trial runs may not have been optimal

Table 10. Performance of LiDAR sensor during the day and night (excluding three-adult-pedestrian condition).

Time of Day	True Detection Accuracy (%)	System Accuracy (%)	F1 Score
Day	53	100	0.69
Night	53	100	0.69

Table 11. Performance of LiDAR sensor at an intersection and at midblock.

Location	True Detection Accuracy (%)	System Accuracy (%)	F1 Score
Intersection	38	100	0.55
Midblock	53	100	0.69

Table 12. Performance of LiDAR sensor at an intersection and at midblock (excluding three-adult-pedestrian condition).

Location	True Detection Accuracy (%)	System Accuracy (%)	F1 score
Intersection	44	100	0.61
Midblock	62	100	0.76

Table 13. Criteria and results of ability requirements.

Number	Criterion	Met
1	Can the LiDAR sensor detect a single adult pedestrian, a child-size pedestrian, a wheelchair user, a bicyclist, and a scooter user?	No
2	Can the LiDAR sensor differentiate among pedestrians, bicyclists, scooter users, and wheelchair users?	No
3	Can the LiDAR sensor detect multiple pedestrians?	No
4	Can the LiDAR sensor detect vulnerable road users at varying speeds (fast and slow)?	No
5	Can the LiDAR sensor detect vulnerable road users during the day and at night?	Yes
6	Can the LiDAR sensor detect vulnerable road users at different locations along the roadway (intersections and midblock crossings)?	Yes

for detection, based on the sensor configuration. Follow up testing and validation is needed to confirm the LiDAR sensor tested is unable to detect child-sized pedestrians.

Certain combinations of variable levels involving the wheelchair user, bicyclist, and scooter user types had true detection accuracy values greater than 85 percent. This result suggests the sensor can detect these vulnerable road user types sometimes but are not able to detect these users consistently. Therefore, the LiDAR sensor failed to meet this criterion.

Criterion 2

The LiDAR sensor was unable to differentiate among vulnerable road user types. The proprietary data processing software used in conjunction with the LiDAR was coded to differentiate between pedestrians, bicyclists, and vehicles but was unable to distinguish between pedestrians and bicyclists when reading the output as an out-of-crosswalk walking event. (The research team used this event to record and observe discreet crossing events.)

No coding existed for scooter users or wheelchair users, nor was differentiating between adult or child pedestrians possible. Over time, the software could be updated to classify more specific vulnerable road user types as needed; thus, if demand were to be high enough, future implementation may be possible. However, the sensor was unable to identify most of the vulnerable road user types used in this study at the time of this writing. Therefore, the LiDAR sensor failed to meet this criterion.

Criterion 3

For the three-adult-pedestrian condition, the LiDAR sensor had true detection accuracy of less than 50 percent. The sensor was unable to successfully differentiate among multiple pedestrians or to successfully detect all three pedestrians in any trials. However, the sensor did detect two pedestrians in some trials. In these trials, the sensor most likely detected the two pedestrians standing adjacent in the formation as a single pedestrian rather than as two separate pedestrians and detected the pedestrian standing behind the two adjacent pedestrians separately. Therefore, more separation between pedestrians may possibly lead to more accurate detection.

However, triangular pedestrian formations are common in the real world, and pedestrians may even hold hands while crossing. Therefore, a more accurate detection technology is needed to improve real-world vulnerable road user volumetric data collection when multiple pedestrians are present in the roadway, and the LiDAR sensor failed to meet this criterion.

Criterion 4

Speed did seem to affect the sensor's ability to detect different vulnerable road user types. Specifically, vulnerable road users moving at slower speeds were more easily detected than users moving at higher speeds, with a true detection accuracy of 51 percent and 40 percent, respectively, and 61 percent and 45 percent when controlling for the three adult pedestrians. This difference is significant, but—based on the specific condition breakdowns shown in table 6—the discrepancy can be seen primarily for scooter users and bicyclists. Wheelchair users at the intersection were detected at faster speeds but had a true detection accuracy of 0 percent when traveling slowly. Therefore, the LiDAR sensor failed to meet this criterion.

Criterion 5

Day or night did not seem to influence the LiDAR detection outcomes. Little difference existed in the true detection accuracy and F1 scores of the day condition and night condition when collapsing across all other variables. The detection rates for both levels were still low, but this result was likely due to the inability of the sensor to detect certain types of vulnerable road users rather than poor performance due to the time of day or lighting. Therefore, the LiDAR sensor successfully met this criterion.

Criterion 6

A slight difference existed between intersection and midblock locations for true detection accuracy and F1 scores. Specifically, true detection accuracy and overall F1 scores were lower for the intersection crossing than for the midblock crossing. This result was surprising, as the midblock was at the edge of the detection range of the LiDAR, and the intersection crossing was the closest possible point to the LiDAR sensor. However, pedestrians crossing at the intersection started crossing almost directly under the LiDAR sensor itself. Based on the nature of the LiDAR and the range and angle of the lasers used to make the point-cloud data, pedestrians crossing at the intersection may have been detected less frequently due to not starting or due to being within the point cloud for long enough during the cross to be recognized as a crossing event.

If a second LiDAR sensor were implemented in the intersection across from the current one, this difference between intersection and midblock may not have occurred. Additionally, depending on the location of the sensor and where the pedestrian starts crossing from, these sensors may not have the ability to improve pedestrian volumetric data under real-world conditions. Ultimately, the sensors can detect agents at both the intersection and midblock. Therefore, the LiDAR sensor successfully met this criterion.

CONCLUSION

Identifying and implementing advanced detection technologies that can accurately count vulnerable road users, regardless of time of day and mode of travel, may improve vulnerable road user safety. After implementing the appropriate advanced detection systems and measuring vulnerable road user exposure to crash risk, practitioners or researchers will be able to identify and compare at-risk locations. Researchers can prioritize safety interventions at the locations with the highest exposure rates, which may lead to a reduction in the number of fatal crashes.

This study evaluated LiDAR sensor detection capabilities for six vulnerable road user types and found that the LiDAR sensor did not perform consistently. The sensor was able to detect the single adult pedestrian type very well; however, other vulnerable road user types were either not detected at all (e.g., child pedestrian dummy) or only detected sometimes. Vulnerable road users crossing during the day versus at night did not seem to make a difference in the detection outcome, as no consistent patterns were observed, suggesting that the sensor works equally well during the day and at night. However, the research team noted discrepancies in this sensor's ability to detect certain vulnerable road user types.

The inability of the LiDAR sensor to differentiate between pedestrians, bicyclists, scooter users, and wheelchair users is a weakness. The detection algorithm and the data libraries need further development so that the sensor and roadside data processing software not only detect but define the different types of vulnerable road users. However, LiDAR sensors have the potential to improve overall count data for individual vulnerable road users.

The improvement in vulnerable road user count data could serve to better measure vulnerable road user exposure to crash risk. The sensor could not accurately detect three pedestrians crossing in a closely clustered, triangular formation. The inability to detect multiple closely clustered vulnerable road users may potentially lead to lower overall counts of vulnerable road users and overestimations of crash risk exposure. This inability is a major weakness, considering that pedestrians often cross roadways in closely spaced groups (FHWA 2016).

The results of the current study helped identify specific areas for improvement in LiDAR sensor technology. Advancements in how sensors identify entities and differentiate among entities may help improve sensor accuracy where multiple vulnerable road users are present. For example, if sensors use advanced, edge-based artificial intelligence detection in conjunction with LiDAR, the sensors may be able to accomplish the following:

- Accurately differentiate among multiple vulnerable road users.
- Count vulnerable road users individually rather than as one entity.
- Correctly register vulnerable road users of difference sizes and heights.

Further research into LiDAR sensors and other advanced pedestrian detection systems (e.g., fusion models of multiple detection systems) may potentially help researchers discover an effective method for acquiring accurate count data to better understand vulnerable road user exposure on the Nation's roadways. Additional research is needed to test LiDAR sensors' capabilities to obtain consistent, accurate counts in a real-world setting.

ACKNOWLEDGMENTS

The original map for figure 1 is the copyright property of Google® Earth™ and can be accessed from https://www.google.com/earth (Google 2024). FHWA modified the map to note locations of sensors, crosswalk labels, and distances.

REFERENCES

American National Standards Institute. 2007. *Manual on Classification of Motor Vehicle Traffic Accidents*, 7th edition. ANSI D16.1-2007. Itasca, IL: National Safety Council.

El-Urfali, A., L. Pei-Sung, A. Kourtellis, Z. Wang, and C. Chen. 2019. *Integration of a Robust Automated Pedestrian Detection System for Signalized Intersections: Final Report*. Project No. FDOT BDV25-977-44. Tallahassee, FL: Florida Department of Transportation. https://rosap.ntl.bts.gov/view/dot/64442/dot_64442_DS1.pdf, last accessed August 14, 2024.

FHWA. n.d. "Enhancing Vulnerable Road User Detection and Volume Data Through Advanced Imaging Techniques" (web page). https://highways.dot.gov/research/projects/enhancing-vulnerable-road-user-detection-and-volume-data-through-advanced-imaging, last accessed September 4, 2024.

FHWA. 2016. *Traffic Monitoring Guide*. Report No. FHWA-PL-17-003. Washington, DC: Federal Highway Administration. https://www.fhwa.dot.gov/policyinformation/tmguide/tmg_fhwa_pl_17_003.pdf, last accessed August 14, 2024.

FHWA. 2024. *Enhancing Vulnerable Road User Detection and Volume Data Through the Use of Infrared Thermal Imaging Sensors*. Publication No. FHWA-HRT-24-135. https://highways.dot.gov/sites/fhwa.dot.gov/files/FHWA-HRT-24-135.pdf, last accessed August 14, 2024.

GPO. 2024a. "Vulnerable Road User." U.S.C. 23 §148(a)(15). 2024. https://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title23-section148&num=0&edition=prelim#amendment-note, last accessed October 9, 2024.

GPO. 2024b. "Definitions." 23 CFR 924.3 §490.205. https://www.govinfo.gov/app/details/CFR-2024-title23-vol1/CFR-2024-title23-vol1-sec490-205, last accessed October 2, 2024.

Google™. 2024. *Google® Earth*™ (software). https://www.google.com/earth, last accessed August 16, 2024.

Jannat, M., S. M. Roldan, S. A. Balk, and K. Timpone. 2021. "Assessing Potential Safety Benefits of Advanced Pedestrian Technologies Through a Pedestrian Technology Test Bed." *Journal of Intelligent Transportation Systems* 25, no. 2: 139–156. https://www.tandfonline.com/doi/full/10.1080/15472450.2020.1807347, last accessed August 14, 2024.

Kuczmarski, R. J., C. L. Ogden, L. M. Grummer-Strawn, and K. Flegal, et al. 2000. "CDC Growth Charts: United States." *Advance Data From Vital and Health Statistics* 314: 1–27. https://www.cdc.gov/nchs/data/ad/ad314.pdf, last accessed August 14, 2024.

NCSA. 2022. *Pedestrians: 2020 Data: Traffic Safety Facts*. Publication No. DOT HS 813 310. Washington, DC: National Highway Traffic Safety Administration.

NCSA. 2024a. *Traffic Safety Facts 2022 Data: Bicyclists and Other Cyclists*. Publication No. DOT HS 813 591. Washington, DC: National Highway Traffic Safety Administration. https://crashstats.nhtsa.dot.gov/Api/Public/Publication/813591, last accessed August 14, 2024.

NCSA. 2024b. *Traffic Safety Facts 2022 Data: Pedestrians*. Publication No. DOT HS 813 590. Washington, DC: National Highway Traffic Safety Administration. https://crashstats.nhtsa.dot.gov/Api/Public/Publication/813590, last accessed August 14, 2024.

North American Bikeshare and Scootershare Association. 2022. *3rd Annual Shared Micromobility State of the Industry Report*. Portland, ME: North American Bikeshare and Scootershare Association.

Organisation for Economic Co-operation and Development. 1998. *Safety of Vulnerable Road Users*. IRRD 895623. Paris, France: Organisation for Economic Co operation and Development.

Rothman, L., A. W. Howard, A. Camden, and C. Macarthur. 2012. "Pedestrian Crossing Location Influences Injury Severity in Urban Areas." *Injury Prevention* 18, no. 6: 365-370. https://www.doi.org/10.1136/injuryprev-2011-040246, last accessed August 14, 2024.

Ryus, P., E. Ferguson, K. M. Laustsen, R. J. Schneider, F. R. Proulx, T. Hull, and L. Miranda-Moreno. 2014. *NCHRP Report 797: Guidebook on Pedestrian and Bicycle Volume Data Collection*. Washington, DC: The National Academies Press.

USDOT. n.d. "NHTSA File Downloads" (web page). https://www.nhtsa.gov/file-downloads?p=nhtsa/downloads/FARS/2022/National/, last accessed November 12, 2024.

Walker, C. J. 2022. Cheryl J. Walker to Division Administrators, memorandum, October 21, 2022. "Action: Vulnerable Road User Safety Assessment Guidance (Due date: November 15, 2023)." https://highways.dot.gov/sites/fhwa.dot.gov/files/2022-10/VRU%20Safety%20Assessment%20Guidance%20FINAL_508.pdf, last accessed August 14, 2024.

Williams, G. M. 2017. "Optimization of Eyesafe Avalanche Photodiode LiDAR for Automobile Safety and Autonomous Navigation Systems." *Optical Engineering* 56, no. 3: 1–9. https://doi.org/10.1117/1.OE.56.3.031224, last accessed August 14, 2024.

Researchers—This study was conducted by Jose A. Calvo, Mafruhatul Jannat, Szu-Fu Chao, Corrigan Salerno, Destinee Young, Sarah Olko, and Pascal Beuse under contract number 693JJ319D000012.

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—LiDAR sensors, vulnerable road users, detection, safety.

DECEMBER 2024

Recommended citation: Federal Highway Administration, *Enhancing Vulnerable Road User Detection and Volumetric Data Quality With LiDAR Sensors* (Washington, DC: 2024) https://doi.org/10.21949/1521523

FHWA-HRT-25-007
HRSO-30/12-24(WEB)E