TECHBRIEF

Enhancing Vulnerable Road User Detection and Volume Data Through The Use of Infrared Thermal Imaging Sensors

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INTRODUCTION

According to the National Highway Traffic and Safety Administration, 6,516 pedestrians and 938 bicyclists were killed in traffic crashes in 2020—increases of 3.9 percent and 9.2 percent from 2019, respectively (Stewart 2022). Vulnerable road users are at greater risk of serious injury or death if they are involved in a traffic crash (Organisation for Economic Co-operation and Development 1998). As per definitions in the Highway Safety Improvement Program (U.S.C. 23 §148(a)(15), 2021) and Code of Federal Regulations (23 CFR 924.3 §490.205, 2022), a vulnerable road user is a nonmotorist having a Fatality Analysis Reporting System 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 American National Standards Institute D16.1-2007 *Manual on Classification of Motor Vehicle Traffic Accidents* (National Safety Council 2007). Vulnerable road users may include people walking, biking, or rolling. A construction worker on foot would be viewed as a pedestrian and therefore a vulnerable road user, but by definition a motorcyclist would not (Walker 2022).

The challenges associated with collecting nonmotorized data are well documented. FHWA's *Traffic Monitoring Guide and NCHRP Report 797: Guidebook on Pedestrian and Bicycle Volume Data Collection* outline several of those challenges (FHWA 2016; Ryus et al. 2014).

Measuring pedestrian exposure to crash risk has been a topic of discussion among researchers for more than 3 decades. An effective method for measuring exposure has not been agreed upon—in part due to the challenges associated with collecting pedestrian data (FHWA 2016). 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, making it difficult for sensors to differentiate among individuals within the group. Additionally, vulnerable road users are harder to detect at night. A majority (77 percent) of fatal pedestrian crashes in 2020 occurred in the dark, with 75 percent of fatal pedestrian crashes occurring from 6 p.m. to 3 a.m. and 23 percent occurring from 6 p.m. to 8 p.m. (National Center for Statistics and Analysis 2022). One way of improving vulnerable road user detection at night is with infrared thermal detection technology (Fu, Miranda-Moreno, and Saunier 2016; González et al. 2016).

In addition to nighttime detection, however, advanced detection systems have to be able to detect different kinds of vulnerable road users, including scooter riders and wheelchair users. For example, the number of electronic scooter systems implemented in North American cities from 2020 to 2021 increased

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by 30 percent (North American Bikeshare & Scootershare Association 2022). Therefore, as scooter user activity increases, transportation agencies must install systems that can accurately detect these types of vulnerable road users. Furthermore, in consideration of exposure to crash risk, including all individuals is important. If infrared thermal imaging sensors cannot identify wheelchair users, the calculation of exposure would be misrepresented based on missing an entire population.

Past research into the use of infrared thermal imaging sensors to detect individuals using wheelchairs was limited, and the research that did occur was not conducted for all of the conditions being investigated in the current study (El-Urfali et al. 2019).

In calculations of exposure to crash risk, pedestrians of all ages must be considered. For example, studies have shown that child pedestrians are at higher risk of collisions with motor vehicles compared with adults—especially at midblock crossings (Rothman et al. 2012). Furthermore, in 2021, 16 percent of children involved in traffic fatalities were pedestrians (National Center for Statistics and Analysis 2022). Even though crash data on child pedestrians are available (National Center for Statistics and Analysis 2022; Rothman et al. 2012), few studies to date have examined advanced detection systems' ability to detect children and adults with equal accuracy.

To advance the research into viable methods for improving vulnerable road user safety, FHWA developed a technology test bed on the Turner-Fairbank Highway Research Center (TFHRC) campus. The agency designed a vulnerable road user technology test bed to examine technologies and sensors that support pedestrian and bicyclist system concepts, standards, applications, and innovative products (Jannat et al. 2021). As part of the TFHRC vulnerable road user technology test bed, FHWA installed nine infrared thermal imaging sensors. The agency installed and calibrated the sensors based on original equipment manufacturer (OEM) specifications. According to the OEM, the sensors can detect vehicles, pedestrians, and bicyclists. Additionally, the OEM indicates that the sensors do not need light to detect various road users. Instead, they use thermal energy emitted from road users, which enables a sensor to detect vehicles and vulnerable road users at night, over long distances, or in adverse weather conditions such as fog, rain, and snow. Better understanding the ability—and applicability—of these sensors under various conditions could help State and local departments of transportation determine whether to suggest implementing them as part of safety initiatives and whether the count data from infrared thermal imaging sensors could calculate pedestrian exposure.

OBJECTIVES

The purpose of this research was to evaluate the appropriateness and applicability of infrared thermal imaging sensors for collecting vulnerable road user count data—under variable conditions—that can provide information for measuring exposure to crash risk. In that effort, the research team tested the infrared thermal imaging sensor's ability to detect the following:

- Single pedestrians in three scenarios.
    - Adult.
    - Adult wearing heavy clothing.
    - Child.
- Multiple adult pedestrians.
- Bicyclists.
- Scooter users.
- Wheelchair users.

Testing occurred under different conditions, including light, dark, slow crossing, fast crossing, and crossing location.

METHOD

Apparatus

The following subsections are descriptions of the technologies and testbed used and analyzed in this study.

TFHRC Vulnerable Road User Technology Test Bed

The research team conducted testing on the TFHRC vulnerable road user technology test bed. The test bed comprises 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.

Infrared Thermal Sensors

The research team selected four thermal imaging sensors located on the TFHRC vulnerable road user technology test bed. Two of the sensors have a detection distance of 6–100 ft, with fields of view (FOVs) measuring 90 degrees horizontally and 69 degrees vertically. The two other sensors have a detection distance of 32–245 ft, with FOVs measuring 45 degrees horizontally and 35 degrees vertically. All four infrared thermal imaging sensors are long-wave infrared (7–14 µm). They have capabilities for vehicle and bicycle presence detection, vehicle and bicycle counting, pedestrian counting, traffic data collection, and traffic flow monitoring. The sensors have three primary types of detection zones: vehicle, bicycle, and pedestrian. Detection zones are designated areas within a sensor's

FOV. The detection zones can be applied in the graphical user interface of the infrared thermal imaging sensor's software. Detection zones outline an area meant to detect specific entities traversing through the zones.

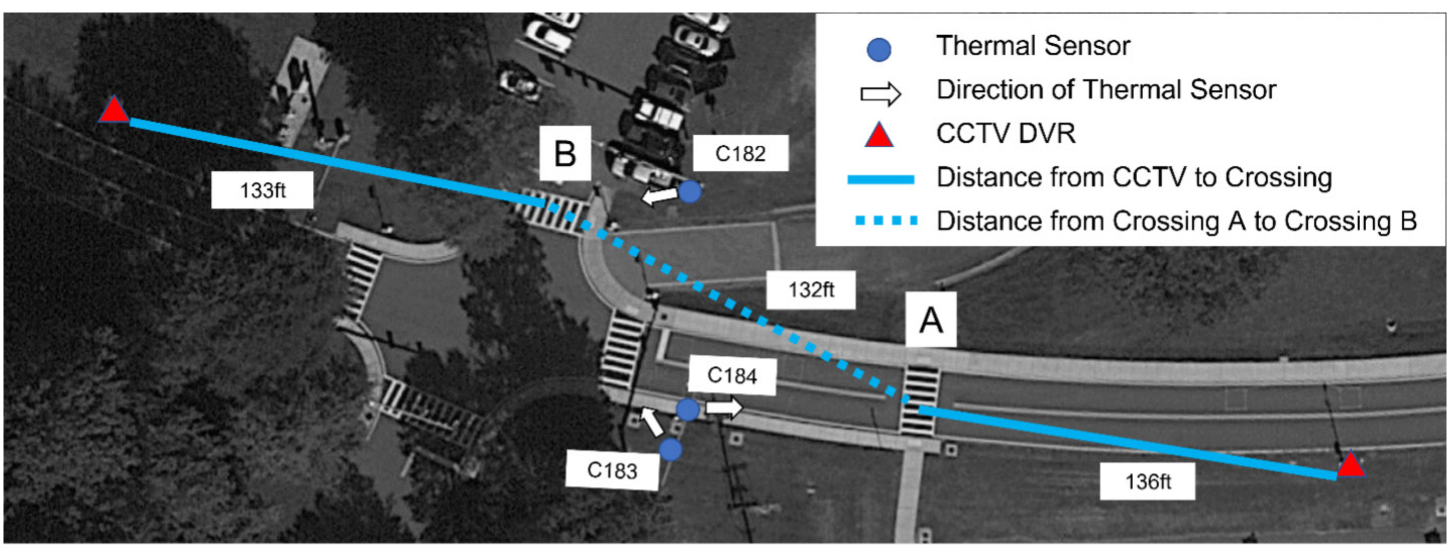
The sensors are designed to track and measure the size of any thermal signature they can see within their FOV based on the detection algorithm the OEM developed. When a thermal signature moves into a designated detection zone, the sensor determines whether the size of the thermal signature falls within the accepted size range for the type of detection zone being used (e.g., if set to a vehicle zone, a sensor would detect vehicles rather than bicyclists). If it so detects, the sensor will begin to send tracking data, which can then be recorded. Sensors transmit video, tracking, and count data across the network on which they are installed. Transmission of count data and thermal video data is continuous—regardless of whether a thermal signature is in a detection zone—and the rate of transmission can be changed as needed. Every 10 s, the sensors transmit a message that includes the total number of thermal signatures detected in each zone during that 10 s period. After a signature enters a detection zone, it is counted in the cycle after it leaves that detection zone. The output of the count data also includes a classifier as to the entity being detected based on the kind of detection zone used: vehicle, bicycle, and pedestrian.

The research team defined pedestrian detection zones for all crosswalks within the FOV of the selected sensors when setting up the thermal sensors and used only data from the zones located at the selected crosswalks. For this study, the devices were set to pedestrian detection zones in part because the pedestrian-detection-zone setting could supposedly detect pedestrians and bicyclists as well as other vulnerable road user types, but also because the bicycle-detection zone setting is supposed to detect only bicycles and ignore all other cross traffic. This setting is primarily for use in designated bicycle areas on roadways. In addition, the materials the research team used for the sensors and system noted that pedestrian sensors and bicycle sensors not be used at the same location.

For this study, the cost of each sensor was approximately $4,200. The power over Ethernet® (PoE) interface was approximately $250 per sensor. PoE is a networking feature defined by IEEE Std 802.3 and IEEE Std 802.3af (Institute of Electrical and Electronics Engineers 2002, 2003) that enable Ethernet cables to supply power to network devices over an existing data connection. As a result, the total equipment cost of this study was approximately $17,800.

The sensors were set up along Innovation Drive on the TFHRC campus, as shown in figure 1. Each sensor was set up to observe a primary crosswalk within the TFHRC test bed. Some of the sensors had multiple crosswalks in their FOVs; however, the ability to detect entities within secondary crosswalks outside each sensor's primary crosswalk depended on the sensor's placement angle and distance from the secondary crosswalks. Figure 1 shows the general locations and primary focal crosswalk of each sensor. Each focal crosswalk was located within the OEM-determined FOV and detection distance of its designated sensor.

Figure 1. Photo. TFHRC test bed with infrared thermal imaging sensors, crosswalk, and CCTV DVR locations and distances.



Closed-Circuit Television Digital Video Recorders

The research team used two traditional closed-circuit (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 crossings, respectively. The DVRs were zoomed in to clearly 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 was then compared with the video output of the infrared thermal imaging sensors to verify the quality of the infrared thermal imaging sensor recording.

Video Recording Software

The research team used an open-source video recording software to record live video streams of both the infrared thermal imaging sensors and the CCTV DVRs used in this study. The output included specific placement of the detection zones, which lit up when the sensor detected an entity of the appropriate type. The research team used video data to manually code detections when the count data failed to save properly due to the research team's prematurely ending the saved count feed, which occurred less than 3 percent of the time.

Electric Scooter

The study used a 350-W electric scooter with a 36-V, 15-Ah battery. Manufacturer documentation lists the scooter's top speed at 20 mph, and its load capacity was listed as 220 lb.

Wheelchair

The study used a self-propelled wheelchair. The wheelchair was collapsible, had detachable leg rests, and had a load capacity of 300 lb. The leg rests were attached and used during testing.

Bicycle

The study used a 26-inch manual-cruiser-style bicycle to represent bicyclists.

Belt-Driven Articulating Pedestrian Dummy

The research team used a programmable articulating pedestrian dummy to simulate a child vulnerable road user. The child pedestrian dummy is 45.5 inches tall, roughly the average height of a 6 yr-old child. Disposable heating pads were attached to the dummy to simulate the natural body heat of a human. The average temperature of the disposable heating pads is 140 °F. Pilot testing revealed that applying disposable heating pads or to parts of the dummy (chest, upper arms, upper legs, and back) enabled the infrared thermal sensors to identify the dummy as its own thermal signature and to successfully count the dummy as a pedestrian.

Experimental Design

The research team reviewed existing literature and worked with the FHWA Office of Safety and Operations Research and Development Human Factors Team to identify factors needed to address the objectives for infrared thermal imaging sensors. The existing literature revealed several unknowns regarding these sensors, such as whether wearing heavy, well insulated clothing would inhibit the thermal sensors' ability to accurately detect an individual, whether multiple signatures of body heat in high-population-density clusters crossing the street could make it difficult for infrared thermal imaging sensors to differentiate among multiple pedestrians crossing at the same time, whether electric scooter users can be identified within the detection fields of infrared thermal imaging sensors similar to pedestrians, and how differences in the speeds of various vulnerable road user types might affect thermal sensors' ability to detect said vulnerable road users.

Figure 1 shows the location of the infrared thermal imaging sensors in the intersection. The research team selected crosswalks A and B as the primary crosswalks to test the sensors because of the A and B positions and the number of sensors that can see those crosswalks. Crosswalk A (midblock crossing) was on a vertical curve. For data collection, the team initially chose four infrared thermal imaging sensors located on the TFHRC campus but excluded from the results the data from one sensor due to technical issues. The sensors included C182, C184, C183, and C181. Table 1 outlines the focus and model of each sensor listed in figure 1. C181 was excluded from figure 1 because the data from C181 were not included in the results.

Table 1. Infrared thermal imaging sensor direction, focus, and model.

Crosswalk	Sensor Identification
A	C184
B	C181, C182, and C183

Each infrared thermal imaging sensor is within the detection range, as defined by the OEM, of either the designated intersection or midblock crossing. Table 1 outlines the focus and model of each sensor depicted in figure 1.

The research team conducted pilot testing for the sensors and setup. During piloting, the team tested each condition level (i.e., the characteristics of each condition to be tested) of each factor at least twice to ensure no major issues with the thermal sensor setup or study design. During pilot testing, the team determined that the desired values for fast user conditions for bicyclists and scooter users could not be met due to the roadway geometry of the TFHRC vulnerable road user technology test bed. Therefore, the speeds for the fast condition for these user groups were adjusted to account for this geometry. (See Speed subsection for additional detail.)

During pilot testing, the research team also identified the optimal configuration for the multiple adult-pedestrian condition. Initially, the experiment anticipated having three pedestrians walk across the roadway in a straight line with about 1 inch of separation between them. During each of these pilot testing trials, however, the sensors failed to recognize the three shoulder to shoulder pedestrians. With the pedestrians in this formation, the thermal sensors never produced tracking data or any successful counts. With the pedestrians in a two-and-one configuration (i.e., two side by side followed by one adult pedestrian), the thermal sensors produced tracking data and count data but counted only two or one pedestrian in the detection zone. Therefore, the team chose the two-and-one configuration for this study because it showed that the sensors were still active and working but that other potential limitations restricted the thermal sensors' abilities and accuracy. The team also chose this configuration to replicate a more unorganized way wherein multiple pedestrians might typically cross a crosswalk in the real world. The research team identified four key factors for the study: vulnerable road user type, speed of travel, time of day, and location. Table 2 shows the condition levels for each factor.

Table 2. Factors and condition levels.

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

Table 3. 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
Heavily clothed pedestrian	2	5
Wheelchair user	2	5
Child pedestrian dummy	2	5
Bicyclist	5	10
Scooter rider	5	10

Time of Day

The experiment used two levels—day and night—to test the sensors' ability to detect vulnerable road users under normal daylight conditions and at night, when there is no ambient sunlight. The research team defined "day" as any time during the period from at least 1 h after sunrise to 1 h before sundown of each day. The team defined "night" as any time during the period from at least 1 h after sundown to 1 h before sunrise. The definitions meant that researchers conducted experiments during the "day" time-of-day level in full daylight and experiments during the "night" time-of-day level, when there was no light from the sun. Additionally, the research team collected ambient metadata including weather (i.e., sunny, partly sunny, and cloudy), although researchers did not collect data during very cloudy or adverse weather.

Location

Two locations along the TFHRC vulnerable road user test bed were chosen for data collection—specifically, an intersection crosswalk and a midblock crosswalk. The intersection and midblock crossings can be seen in figure 1.

System Performance Metrics

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, we can use an F1-score. 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 4 outlines 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 thermal sensors' 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, it would receive a true detection accuracy rate of 50 percent. System accuracy measures the thermal sensors' 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 were accurate detections of actual vulnerable road users, it would mean there were 2 false detections, resulting in a system accuracy rate of 80 percent.

Table 4. 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 sensors. The team used system accuracy in conjunction with true detection accuracy to calculate an F1-score. The team used the F1-score to assess the applicability of the thermal sensors for detecting vulnerable road users. The applicability of the sensors is based not only on the sensors' ability to detect vulnerable road users but also on their ability to minimize false detections.

Following are equations for the chosen performance metrics:

- True detection accuracy:

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

- System accuracy:

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

- F1-score:

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

The research team set the minimal acceptable F1-score for vulnerable road user detection as 0.85. Based on the work of El-Urfali et al. (2019), the team set the minimal acceptable F1-score as 0.85 and the minimal acceptable true detection accuracy as 85 percent. Any scores below those resulted in unacceptable performance, which can be seen in table 5.

Table 5. F1-score and true detection accuracy thresholds.

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

The research team reviewed and analyzed the data to determine the infrared thermal imaging sensor's ability to detect pedestrians, bicyclists, and the other vulnerable road users at the intersection and marked midblock crossing at TFHRC in different conditions (e.g., light and dark, slow and fast crossings, congestion, heavy clothing). Based on a power analysis with a 95 percent confidence interval (±5 percent), the team tested each combination of the chosen factors six times each. Six trials for each of the 56 conditions, with two sensors at the intersection location and one at the midblock, resulted in a total of 504 observations. Collapsing across the various factors resulted in 72 observations for each level of vulnerable road user type, 252 observations for slow and fast levels of speed, 252 observations for day and night levels for time of day, 336 observations for intersection level of location, and 168 observations for midblock level of location. The team executed a single crossing in each trial based on the parameters of the condition being examined, which resulted in a single data point for each sensor used in a trial of each condition. The data point would then have a count of the total number of vulnerable road users the thermal sensors detected, which enabled the research team to identify both misses and false detections.

Data collection occurred over 3 mo. Members of the research team acted as the adult vulnerable road users by moving through a designated intersection crosswalk and a midblock crosswalk. The team recorded count, thermal video, and DVR data during each trial. In addition, the team recorded ambient metadata—including ambient temperature, weather conditions (i.e., sunny, partly sunny, and cloudy), and wind speed— during data collection.

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 sensors C182, C183, and C184. All of the intersection conditions included data from sensors C182 and C183, while all of the midblock conditions included data from sensor C184.

The research team could not assess the true detection accuracy and system accuracy of C181's count data because the count data from the sensors had not been recorded properly. Crossing B was on the fringes of the FOV for C181, and the detection zone went right to the edge of the sensor's FOV. As a result, the sensor could not detect when the vulnerable road user left the end of the detection zone, and the sensor aggregated no count data. Therefore, the team excluded from this analysis all trials involving sensor C181. However, the team knows that C181 can detect vulnerable road users in all the scenarios because C181 still collected tracking data.

Table 6 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 of the thermal sensors. Additionally, the team aggregated total crossings, detections, misses, and hits across all 56 conditions and calculated total true detection accuracy, system accuracy, and F1-score for the infrared thermal sensors.

Table 6. Infrared thermal imaging sensor outcomes and performance metrics by condition.

Vulnerable Road User Type	Location	Mode of Travel	Time of Day	Total Crossings	Total Detections	Total Misses	Total Hits	True Detection Accuracy (%)	System Accuracy (%)	F1-Score
Single adult pedestrian	Intersection	Fast	Day	12	11	3	9	75	82	0.78
Single adult pedestrian	Intersection	Fast	Night	12	12	0	12	100	100	1.00
Single adult pedestrian	Intersection	Slow	Day	12	13	1	11	92	85	0.88
Single adult pedestrian	Intersection	Slow	Night	11	11	0	11	100	100	1.00
Single adult pedestrian	Midblock	Fast	Day	6	3	3	3	50	100	0.67
Single adult pedestrian	Midblock	Fast	Night	6	6	0	6	100	100	1.00
Single adult pedestrian	Midblock	Slow	Day	6	4	2	4	67	100	0.80
Single adult pedestrian	Midblock	Slow	Night	6	6	0	6	100	100	1.00
Heavily clothed pedestrian	Intersection	Fast	Day	12	14	0	12	100	86	0.92
Heavily clothed pedestrian	Intersection	Fast	Night	12	12	0	12	100	100	1.00

Table 6. Infrared thermal imaging sensor outcomes and performance metrics by condition. (Continued)

Vulnerable Road User Type	Location	Mode of Travel	Time of Day	Total Crossings	Total Detections	Total Misses	Total Hits	True Detection Accuracy (%)	System Accuracy (%)	F1-Score
Heavily clothed pedestrian	Intersection	Slow	Day	12	12	0	12	100	100	1.00
Heavily clothed pedestrian	Intersection	Slow	Night	12	13	0	12	100	92	0.96
Heavily clothed pedestrian	Midblock	Fast	Day	6	5	1	5	83	100	0.91
Heavily clothed pedestrian	Midblock	Fast	Night	6	6	0	6	100	100	1.00
Heavily clothed pedestrian	Midblock	Slow	Day	6	7	0	6	100	86	0.92
Heavily clothed pedestrian	Midblock	Slow	Night	6	6	0	6	100	100	1.00
Child pedestrian dummy	Intersection	Fast	Day	12	12	1	11	92	92	0.92
Child pedestrian dummy	Intersection	Fast	Night	12	12	0	12	100	100	1.00
Child pedestrian dummy	Intersection	Slow	Day	12	12	0	12	100	100	1.00
Child pedestrian dummy	Intersection	Slow	Night	12	12	0	12	100	100	1.00
Child pedestrian dummy	Midblock	Fast	Day	6	6	0	6	100	100	1.00
Child pedestrian dummy	Midblock	Fast	Night	6	6	0	6	100	100	1.00
Child pedestrian dummy	Midblock	Slow	Day	6	6	0	6	100	100	1.00

Table 6. Infrared thermal imaging sensor outcomes and performance metrics by condition. (Continued)

Vulnerable Road User Type	Location	Mode of Travel	Time of Day	Total Crossings	Total Detections	Total Misses	Total Hits	True Detection Accuracy (%)	System Accuracy (%)	F1-Score
Child pedestrian dummy	Midblock	Slow	Night	6	6	0	6	100	100	1.00
Wheelchair user	Intersection	Fast	Day	12	12	0	12	100	100	1.00
Wheelchair user	Intersection	Fast	Night	12	12	0	12	100	100	1.00
Wheelchair user	Intersection	Slow	Day	12	11	1	11	92	100	0.96
Wheelchair user	Intersection	Slow	Night	12	12	0	12	100	100	1.00
Wheelchair user	Midblock	Fast	Day	6	5	1	5	83	100	0.91
Wheelchair user	Midblock	Fast	Night	6	6	0	6	100	100	1.00
Wheelchair user	Midblock	Slow	Day	6	6	0	6	100	100	1.00
Wheelchair user	Midblock	Slow	Night	6	6	0	6	100	100	1.00
Three adult pedestrians	Intersection	Fast	Day	36	18	18	18	50	100	0.67
Three adult pedestrians	Intersection	Fast	Night	36	11	25	11	31	100	0.47
Three adult pedestrians	Intersection	Slow	Day	36	17	19	17	47	100	0.64
Three adult pedestrians	Intersection	Slow	Night	36	13	23	13	36	100	0.53
Three adult pedestrians	Midblock	Fast	Day	18	11	7	11	61	100	0.76
Three adult pedestrians	Midblock	Fast	Night	18	12	6	12	67	100	0.80
Three adult pedestrians	Midblock	Slow	Day	18	8	10	8	44	100	0.62

Table 6. Infrared thermal imaging sensor outcomes and performance metrics by condition. (Continued)										
Vulnerable Road User Type	Location	Mode of Travel	Time of Day	Total Crossings	Total Detections	Total Misses	Total Hits	True Detection Accuracy (%)	System Accuracy (%)	F1-Score
Three adult pedestrians	Midblock	Slow	Night	18	12	6	12	67	100	0.80
Bicyclist	Intersection	Fast	Day	12	12	0	12	100	100	1.00
Bicyclist	Intersection	Fast	Night	10	10	0	10	100	100	1.00
Bicyclist	Intersection	Slow	Day	12	12	0	12	100	100	1.00
Bicyclist	Intersection	Slow	Night	12	12	0	12	100	100	1.00
Bicyclist	Midblock	Fast	Day	6	6	0	6	100	100	1.00
Bicyclist	Midblock	Fast	Night	6	6	0	6	100	100	1.00
Bicyclist	Midblock	Slow	Day	6	5	1	5	83	100	0.91
Bicyclist	Midblock	Slow	Night	6	6	0	6	100	100	1.00
Scooter user	Intersection	Fast	Day	12	13	0	12	100	92	0.96
Scooter user	Intersection	Fast	Night	10	9	1	9	90	100	0.95
Scooter user	Intersection	Slow	Day	12	13	0	12	100	92	0.96
Scooter user	Intersection	Slow	Night	10	10	0	10	100	100	1.00
Scooter user	Midblock	Fast	Day	6	6	0	6	100	100	1.00
Scooter user	Midblock	Fast	Night	6	6	0	6	100	100	1.00
Scooter user	Midblock	Slow	Day	6	6	0	6	100	100	1.00
Scooter user	Midblock	Slow	Night	6	6	0	6	100	100	1.00
Total	N/A	N/A	N/A	641	523	129	512	79.88	97.90	0.88

N/A = not applicable.

The overall F1-score for the infrared thermal imaging sensors was 0.88 (acceptable). The majority of the conditions had F1-scores greater than 0.85. However, the three-adult-pedestrian conditions and most of the conditions with a single adult pedestrian during the day had unacceptable F1-scores.

The team then evaluated each factor independently of the other factors. Table 7 shows the performance metrics for each vulnerable-road-user condition.

Table 7. Performance of thermal sensors across vulnerable road user types.

Vulnerable Road User Type	True Detection Accuracy (%)	System Accuracy (%)	F1-Score
Single adult pedestrian	87.32	93.94	0.905
Heavily clothed pedestrian	98.61	94.67	0.966
Child pedestrian dummy	98.61	98.61	0.986
Wheelchair user	97.22	100.00	0.986
Three adult pedestrians	47.22	100.00	0.642
Bicyclist	98.57	100.00	0.993
Scooter user	98.53	97.10	0.978

Table 8 shows the performance of the thermal sensor at slow and fast speeds. Table 9 shows the performance of the thermal sensor at slow and fast speeds but excludes the three adult pedestrian conditions.

Table 8. Performance of thermal sensors at slow and fast speeds.

Speed	True Detection Accuracy (%)	System Accuracy (%)	F1-Score
Slow	80.37	98.10	0.884
Fast	79.38	97.69	0.876

Table 9. Performance of thermal sensors at slow and fast speeds without the three-adult-pedestrian conditions.

Speed	True Detection Accuracy (%)	System Accuracy (%)	F1-Score
Slow	97.65	97.65	0.977
Fast	95.28	97.12	0.962

Table 10 shows the performance of the thermal sensors during the day and at night. Table 11 shows the performance of the thermal sensors during the day and night but excludes the three adult-pedestrian conditions.

Table 10. Performance of thermal sensors during the day and night.

Time of Day	True Detection Accuracy (%)	System Accuracy (%)	F1-Score
Day	79.01	96.24	0.868
Night	80.76	99.61	0.892

Table 11. Performance metrics of thermal sensors during the day and night without the three-adult-pedestrian conditions.

Time of Day	True Detection Accuracy (%)	System Accuracy (%)	F1-Score
Day	93.52	95.28	0.944
Night	99.52	99.52	0.995

Table 12 shows the performance of the thermal sensors at an intersection and at midblock. Table 13 shows the performance of the thermal sensors at an intersection and at midblock but excludes the three-adult-pedestrian conditions.

Table 12. Performance of thermal sensors at an intersection and at midblock.

Location	True Detection Accuracy (%)	System Accuracy (%)	F1-Score
Intersection	78.35	97.08	0.867
Midblock	82.87	99.44	0.904

Table 13. Performance of thermal sensors at an intersection and at midblock without the three-adult-pedestrian conditions.

Location	True Detection Accuracy (%)	System Accuracy (%)	F1-Score
Intersection	97.51	96.48	0.970
Midblock	94.44	99.27	0.968

DISCUSSION

Evaluation of the Abilities of the Infrared Thermal Imaging Sensors

The research team selected the following six criteria to determine the overall ability of the thermal sensors:

1. Can the thermal sensors detect a single adult pedestrian, a child pedestrian, a pedestrian wearing heavy clothing, a wheelchair user, a bicyclist, and a scooter user?
2. Can the thermal sensors differentiate among pedestrians, bicyclists, scooter users, and wheelchair users?
3. Can the thermal sensors detect multiple pedestrians?
4. Can the thermal sensors detect vulnerable road users at varying speeds (fast and slow)?
5. Can the thermal sensors detect vulnerable road users during the day and at night?
6. Can the thermal sensors detect vulnerable road users at different locations along the roadway (intersections and midblocks)?

The research team determined that criteria 1, 3, 4, 5, and 6 would be based on the true detection accuracy of each level of the factor pertaining to these criteria. The team used a threshold of 85 percent. The team determined the threshold of criterion 2 by reviewing the output of the sensors, which included a classifier for any entity the sensors detected successfully.

Conditions that included the three-adult-pedestrian level of vulnerable road user type were excluded from the evaluation of criteria 1, 4, 5, and 6 because in a collapse across vulnerable road user types, the three-adult-pedestrian conditions negatively skewed the true detection accuracy of the other factors. Therefore, inclusion of the three-adult-pedestrian conditions in determinations of criteria 1, 4, 5, and 6 would not accurately reflect the sensors' ability to detect vulnerable road users in the optimal specified conditions for the criteria being examined. Table 14 shows determination of whether the infrared thermal imaging sensors met the different criteria.

Table 14. Results of ability requirements.

Criteria	Met
1. Can the thermal sensors detect a single adult pedestrian, a child pedestrian, a pedestrian wearing heavy clothing, a wheelchair user, a bicyclist, and a scooter user?	Yes
2. Can the thermal sensors differentiate among pedestrians, bicyclists, scooter users, and wheelchair users?	No
3. Can the thermal sensors detect multiple pedestrians?	No
4. Can the thermal sensors detect vulnerable road users at varying speeds (fast and slow)?	Yes
5. Can the thermal sensors detect vulnerable road users during the day and at night?	Yes
6. Can the thermal sensors detect vulnerable road users at different locations along the roadway (intersections and midblocks)?	Yes

Criterion 1

Thermal sensors had true detection accuracies greater than 85 percent for each of the following vulnerable-road-user-type levels: single adult pedestrians, pedestrians wearing heavy clothing, child pedestrians, wheelchair users, bicyclists, and scooter users. Specifically, the pedestrians wearing-heavy-clothing, child-pedestrian, wheelchair-user, bicyclist, and scooter user levels all had true detection accuracies greater than 97 percent. However, the single adult-pedestrian factor had a true detection accuracy of only 87 percent. Table 8 shows that the true detection accuracy of three of the four single-adult-pedestrian conditions that occurred during the day were unacceptable. Specifically, the single adult pedestrian, intersection, day, fast; the single adult pedestrian, midblock, day, slow; and the single adult pedestrian, midblock, day, fast conditions had true detection accuracies of 75, 50, and 67 percent, respectively. The results for those three conditions are surprising considering that the other single-adult-pedestrian conditions had at least 92-percent accuracy, and all of the single adult pedestrian-at-night conditions had true detection accuracies of 100 percent. Furthermore, four conditions in which the pedestrians were heavily clothed during the day had an average true detection accuracy of 95.75 percent. One possible reason for the lower true detection accuracy for the single-adult-pedestrian condition during the day is that no other vulnerable-road-user-type conditions were collected on the same day as that condition; in other words, environmental factors affected the true detection accuracy of the sensors. However, weather and wind speeds for the single-adult-pedestrian conditions during the day were compared with the weather and wind speeds of other conditions, and the other conditions with similar weather and wind speeds did not have scores similar to the single adult pedestrian condition during the day. Additionally, the individual who crossed the road in these conditions was the same as in other conditions in which the individual was detected successfully, so, presumably, the thermal signature of the individual who crossed was not the cause of the lower true detection accuracy.

Another possible explanation for the unacceptable performance of true detection accuracy for the single-adult-pedestrian condition during the day could involve connectivity issues. If the network had connectivity issues with the sensors connected to it on that day of data collection, those issues could have affected the sensors' ability to properly identify or measure the thermal signatures moving through the detection zone. Those findings indicate that the sensors may not always be accurate enough to successfully obtain the count data needed to calculate pedestrian exposure.

Criterion 2

The infrared thermal imaging sensor system used for this study was unable to differentiate among vulnerable road user types. The sensors come equipped with certain types of detection zones (i.e., pedestrian, bicyclist, and vehicle). For this study, the sensors were set to identify any signature within the detection zone as a pedestrian, a bicyclist, or a vehicle. Therefore, all of the vulnerable road user types were identified as pedestrians because the study used the pedestrian detection zone.

Criterion 3

True detection accuracy for the three-adult-pedestrian condition was less than 50 percent. When pedestrians are in tight clusters, they can either be counted as one vulnerable road user or not be counted at all if the total thermal signature detected by the sensor is too large to be considered a "pedestrian." Depending on the direction from which the sensor is set to detect (looking from the side), vulnerable road users maneuvering side by side would be counted as only one vulnerable road user. Based on the specific configuration of the three adult pedestrians in this study, the infrared thermal imaging sensors failed to meet the criterion for detecting multiple pedestrians. Other configurations, such as three pedestrians walking in a vertical line or two pedestrians crossing in one direction and a third crossing in the opposite direction, might produce different results. Considering the lessons learned during pilot testing, most configurations in which pedestrians are within 1 ft of each other would likely result in a high likelihood of missed detections. Additionally, the team positioned sensors C183 and C184 to face the crossings from the side, and for these trials, the two adjacent pedestrians appeared to be a single thermal signature rather than two. That result is based on the configuration of this study. Different configurations or spacings between the three adult pedestrians could result in different outcomes.

Criterion 4

True detection accuracy of the thermal sensors was greater than 95 percent for vulnerable road users traveling at slow and fast speeds. During testing, the research team crossed through the detection zones of the infrared thermal imaging sensors at fast and slow speeds, representing each vulnerable road user type. The sensors met the criterion for detecting vulnerable road users at varying speeds, with a true detection accuracy of more than 95 percent for both fast and slow speeds.

Criterion 5

True detection accuracy of the thermal sensors was greater than 90 percent for both day and night time-of-day conditions. One benefit of infrared thermal imaging sensors compared with regular cameras is a sensor's ability to detect and see entities in the dark. The sensors used in this study were able to detect vulnerable road users successfully and consistently at night with some street lighting just as well as they were able to detect them during the day.

Criterion 6

True detection accuracy of the thermal sensors was greater than 90 percent for both the intersection and the midblock locations. As a result, the infrared thermal imaging sensors met the criterion for detecting vulnerable road users at different locations.

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 could identify and/or compare at-risk locations. Researchers could then prioritize safety interventions at the locations with the highest exposure rates, which could potentially lead to a reduction in the number of fatal crashes.

This study found that infrared thermal imaging sensors have many advantages for vulnerable road user detection. As shown in table 14, the sensors were able to detect different vulnerable road user types, vulnerable road users traveling at fast and slow speeds, vulnerable road users during the day and at night, and vulnerable road users at both intersections and midblock crossings. One of the greatest advantages of the infrared thermal imaging sensors is their ability to detect vulnerable road users at night, when visibility is poor.

The inability of these sensors to differentiate between pedestrians, bicyclists, scooter users, and wheelchair users is a definite disadvantage of these sensors. The detection algorithm and the data libraries need further development so that sensors can not only detect but also define the different types of vulnerable road users who are using roadways. However, the sensors do have the potential to improve overall count data for individual vulnerable road users using roadways. The improvement in vulnerable road user count data could serve to better measure vulnerable road user exposure to crash risk.

Additionally, the sensors could not accurately detect three pedestrians crossing in a closely clustered triangular formation. The inability of the sensors to successfully detect multiple, closely clustered vulnerable road users could lead to lower overall counts of vulnerable road users and would make exposure of crash risk seem higher than it actually is. Considering that FHWA's (2016) *Traffic Monitoring Guide* states that pedestrians often cross roadways in closely spaced groups, that inability is a major disadvantage of these sensors.

This study also assessed the ability of the sensors to detect pedestrian dummies with heating pads during infrared thermal imaging sensor testing. The team found that when heating pads were attached to a pedestrian dummy, detection rates for that dummy did not differ from detection rates for a human pedestrian at the same crossing. Using heating pads on articulating pedestrian dummies to test the accuracy of the infrared thermal imaging sensors' ability to detect vulnerable road users may have implications for future testing and use cases of the infrared thermal imaging sensors. One use case is using such dummies to test cooperative perception between infrastructure-based infrared thermal imaging sensors and cooperative driving automation.

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

- Differentiate among multiple vulnerable road users more accurately.
- Count vulnerable road users individually rather than count multiple vulnerable road users as one entity.
- Avoid registering the combined thermal signature of multiple pedestrians as being too large to be a vulnerable road user.

Further research into infrared thermal imaging sensors and other advanced pedestrian detection systems (e.g., light detection and ranging and, possibly, fusion models of multiple detection systems) could help find an effective method of acquiring accurate count data to better understand vulnerable road user exposure on the Nation's roadways. Furthermore, additional research is also needed to test the sensors' ability to obtain consistent, accurate counts in a real world setting.

REFERENCES

Code of Federal Regulations. 2022. "Definitions," 23 CFR 924.3 §490.205.

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*. Tallahassee, FL: Florida Department of Transportation.

Federal Highway Administration. 2016. *Traffic Monitoring Guide*. Report No. FHWA PL 17 003. Washington, DC: Federal Highway Administration.

Fu, T., L. Miranda-Moreno, and N. Saunier. 2016. "Pedestrian Crosswalk Safety at Nonsignalized Crossings During Nighttime: Use of Thermal Video Data and Surrogate Safety Measures." *Transportation Research Record* 2586, no. 1: 90–99. https://doi.org/10.3141/2586-10, last accessed April 10, 2023.

González A., Z. Fang, Y. Socarras, J. Serrat, D. Vázquez, J. Xu, and A. M. López. 2016. "Pedestrian Detection at Day/Night Time with Visible and FIR Cameras: A Comparison." Sensors 16, no. 6: 820. https://doi.org/10.3390/s16060820, last accessed April 10, 2023.

Highway Safety Improvement Program. 2021. U.S.C. 23 §148(a)(15).

Institute of Electrical and Electronics Engineers. 2002. *IEEE Standard for Ethernet*. IEEE Std 802.3 (Superseded).

Institute of Electrical and Electronics Engineers. 2003. *IEEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements*. IEEE Std 802.3af (Amendment to IEEE Std 802.3-2002).

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.doi.org/10.1080/15472450.2020.1807347, last accessed April 10, 2023.

National Center for Statistics and Analysis. 2022. Pedestrians: 2020 Data: Traffic Safety Facts. Report No. DOT HS 813 310. Washington, DC: National Highway Traffic Safety Administration.

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

North American Bikeshare & Scootershare Association 2022. In *3rd Annual Shared Micromobility State of the Industry Report*. Proceedings of the Institute of Transportation Studies. Berkeley, CA: University of California Institute of Transportation Studies.

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

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.

Ryus, P., E. Ferguson, K. M. Laustsen, R. J. Schneider, F. R. Proulx, and T. Hull, and L. Miranda-Moreno. 2014. NCHRP Report 797: *Guidebook on Pedestrian and Bicycle Volume Data Collection*. Berkeley, CA: University of California, Institute of Transportation Studies.

Stewart, T. 2022. *Overview of Motor Vehicle Crashes in 2020*. DOT HS 813 266. Washington, DC: National Highway Traffic Safety Administration.

Walker, C. J. 2022. Cheryl J. Walker to Division Administrators. "Action: Vulnerable Road User Safety Assessment Guidance," memorandum, October 21, 2022. https://highways.dot.gov/sites/fhwa.dot.gov/files/2022-10/VRU%20Safety%20Assessment%20Guidance%20FINAL_508.pdf, last accessed April 11, 2023.

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