Final Report

Integration of a Robust Automated Pedestrian Detection System for Signalized Intersections

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Project No.

FDOT BDV25-977-44

Prepared For

Florida Department of Transportation

December 2019

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Prepared for:

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Metric Conversion Chart

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	squareinches	645.2	square millimeters	mm^2
ft^2	squarefeet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

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16. Abstract

Improving pedestrian safety and making roadway facilities safer and friendlier for pedestrians are among the top priorities and transportation goals in Florida. The actuation of pedestrian “Walk” signal indications at signalized intersections and the triggering of rectangular rapid flash beacons (RRFBs) or high-intensity activated crosswalks (HAWKs) at midblock crosswalks, require a pedestrian to push a button. However, 40%–50% of pedestrians of pedestrians do not push the button. The Center for Urban Transportation Research (CUTR), in close coordination with the Florida Department of Transportation (FDOT), researched automatic pedestrian detection systems for use at midblock crosswalks to automatically activate the RRFBs, and at signalized intersections to automatically place a pedestrian call to the traffic signal controller. The CUTR research team reviewed various automatic pedestrian detection systems for their functionality and performance. Three systems were selected for this research. They were first tested under controlled conditions, and at midblock and intersection locations. One of the three systems was able to meet all desired performance requirements. This system was further deployed and evaluated at two midblock crosswalks and one signalized intersection. The evaluation results showed that the system produced an overall 92% detection system accuracy at midblock locations, with only 2% false detections. The system was able to detect pedestrians 94% of the time and place a pedestrian service call 90% of the time at a signalized intersection. An important contribution of this research project is the work conducted to connect the automatic pedestrian detection systems to a traffic signal controller to place a pedestrian call when a pedestrian is detected and to remove the call when the pedestrian walks out of the detection zone prematurely before the call is served. Testing showed that the system was able to detect the disappearance of pedestrians 98% of the time and removed the pedestrian call 97% of the time when they left the detection zone early. This result showed the capability of the automatic detection system and the advanced traffic signal controller with a custom script to administer removal of a pedestrian call when it is not needed. This capability is useful for minimizing unnecessary vehicle delay. This research provided a key step to apply automatic pedestrian detection to further enhance pedestrian safety at signalized intersections and midblock crosswalks, and reduce unnecessary vehicle delay.

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Executive Summary

Improving pedestrian safety and making roadway facilities safer and friendlier for pedestrians are among the top priorities and transportation goals in Florida. The actuation of pedestrian "Walk" signal indications at signalized intersections and the triggering of rectangular rapid flash beacons (RRFBs) or high-intensity activated crosswalks (HAWKs) at midblock crosswalks, require a pedestrian to push a button. However, some issues and concerns with this arrangement have been raised:

- Studies have shown that 40%–50% of pedestrians do not use the push buttons or find them physically difficult to use.
- Pedestrians may think the system is malfunctioning if there is no indication or confirmation that the push button has been pressed or the pedestrian signal has been activated.
- Unnecessary delay for vehicles may occur if pedestrians press the push button but walk away or cross streets before receiving the "Walk" signal.
- Visually impaired pedestrians may have difficulty finding the push button.
- Push buttons may get stuck or be inoperable.

With the development of emerging technologies, automated pedestrian detection can potentially be used to supplement or even replace push buttons to trigger pedestrian Walk signals, RRFBs, or HAWKs or to cancel pedestrian calls when not needed. The idea of automated pedestrian detection and related applications can be traced back to the early 2000s (*9*). However, significant concerns were noted about missed detection and false activation at that time. In the United Kingdom and Australia, automated pedestrian detection devices called Puffin (Pedestrian User-Friendly Intelligent) crossings have been used for several years, but this kind of application for signalized crossings has not been as widely accepted in North America.

There are many sensor and detection technologies for pedestrian detection, including, but not limited to, infrared, microwave, and thermal sensors; pressure mats; and computer-assisted video. Each has its strengths and weaknesses in terms of accuracy, cost, installation, and maintenance requirements, liability, and accessibility, etc. To ensure pedestrian safety and benefits, it is of practical importance to research and identify the most effective detection technologies for automated pedestrian detection and to determine system availability to integrate and develop an accurate, reliable, and cost-effective automated pedestrian detection system for signalized intersections and midblock crossings. Also, to avoid unnecessary delay for vehicles, it is important for a system to detect disappearance of a pedestrian when he or she leaves the area to help cancel the pedestrian call already placed in the traffic signal controller. This passive detection also applies to midblock crosswalks with HAWKs, RRFBs, and full pedestrian signals.

The CUTR team researched existing detection technologies and available systems that can detect pedestrians and provide output that can be used to place or cancel a call at a traffic signal controller or activate a HAWK or RRFB. Several manufacturers provide systems or sensors that can be used as standalone or with software. After initial review, the research team eliminated several systems based on their limitations or availability, and acquired three systems that met the criteria for testing. Two systems use microwave radar technology, and one uses thermal machine vision technology.

The research team tested the three systems in a controlled environment under the same conditions, and collected data to further investigate and understand their functionality. The results from controlled tests in the lab showed that these three systems met the basic requirements for initial field testing. The systems were then tested at a midblock crosswalk and a signalized intersection on the Tampa campus of the University of South Florida, and were compared for detection accuracy and for functionality and limitations under real scenarios.

Based on data collected during these tests, the three systems were evaluated on how well they detected pedestrians passing in a detection zone under different movement scenarios, wearing different clothing, and under daytime or nighttime light conditions. It was found that the thermal machine vision system had highest detection accuracy (90%) for the desired movement scenarios (i.e., pedestrians approach crosswalks), and a lowest detection rate (5%) for the scenarios in which detection was not desired (i.e., pedestrians walk away from crosswalks).

This thermal machine vision system was then deployed at three locations: two midblock locations and one signalized intersection. At the midblock locations, the system was able to accurately detect an average of 92% in the desired scenarios, with a 2% false positive rate (detect under undesired scenarios). At the signalized intersection, the system was able to detect pedestrians 94% of the time and place a pedestrian service call 90% of the time. Furthermore, the system was able to detect the disappearance of pedestrians 98% of the time and removed the pedestrian call 97% of the time when they left the detection zone early. This result showed the capability of the automatic detection system and the advanced traffic signal controller with a custom script to administer removal of a pedestrian call when it is not needed. This capability is useful for minimizing unnecessary vehicle delay. Based on the research findings, the research team further developed recommendations for enhanced setup and configuration to achieve high detection results and proper functionality.

This research successfully tested three automatic pedestrian detection systems on the market, selected the best system to conduct pilot deployments at one signalized intersection and two midblock crosswalks with RRFBs, documented data analysis and research findings in detail, and provided a key step to apply automatic pedestrian detection to further enhance pedestrian safety at signalized intersections and midblock crosswalks, and reduce vehicle delay.

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1 Introduction

Pedestrian safety is an ongoing major concern throughout the United States, especially in Florida, which tends to experience higher crash rates for pedestrians and bicyclists in lower socioeconomic areas (*1*). Improving pedestrian safety and making roadway facilities much safer and friendlier for pedestrians are among the top priorities and transportation goals for the Florida Department of Transportation (FDOT). The actuation of pedestrian "Walk" signal indications at signalized intersections and the triggering of rectangular rapid flash beacons (RRFBs) or high-intensity activated crosswalks (HAWKs) at midblock crosswalks, require a pedestrian to push a button. However, some issues and concerns with this arrangement have been raised:

- Studies have shown that 40%–50% of pedestrians do not use the push buttons or find them physically difficult to use (*2*)
- Pedestrians may think the system is malfunctioning if there is no indication or confirmation that the push button has been pressed or the pedestrian signal has been activated.
- Unnecessary delay for vehicles may occur if pedestrians press the push button but walk away or cross streets before receiving the "Walk" signal.
- Visually impaired pedestrians may have difficulty finding the push button.
- Push buttons may get stuck or be inoperable.

Automated pedestrian detection technologies capture the presence of people waiting to cross the street and automatically activate the pedestrian "Walk" signal, without requiring pedestrians to push a button, and some detectors can detect slow-speed pedestrians and automatically extend the "Walk" phase until they safely cross the street. Figure 1 shows an example of an automated pedestrian detection system.

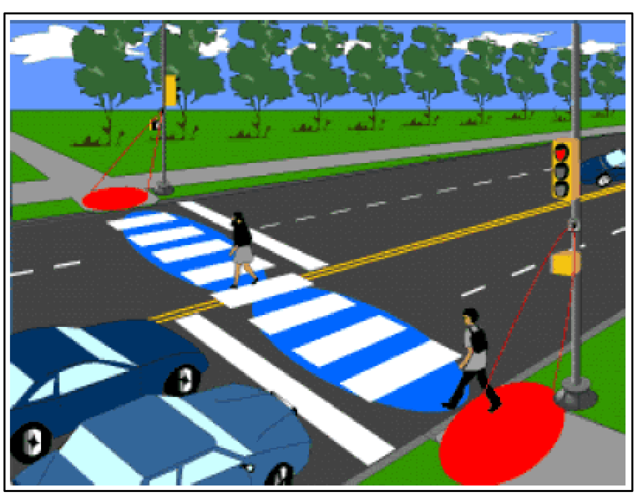


Figure 1. Example of automated pedestrian detection system (*3*)

This study focused on the application of automated pedestrian detection technology at the following locations (*4*):

- *Intersection crossing detection at signalized intersections or flashing midblock pedestrian corridors* – Automated pedestrian detection systems are mounted such that the device can monitor one or more intersection crosswalk corridors or flashing midblock pedestrian corridors. Upon detecting a pedestrian, a call is sent to the signal controller. The pedestrian “Walk” signal depends on the time given to cross. All these depend on how fast the device can detect and transmit the signals to the onsite controller.
- *Curbside detection at signalized intersections* – Pedestrians can be detected only when present within the detection zone, and a call is sent to the signal controller. At these locations, automated pedestrian detection systems can monitor one or more departure zones at the signalized intersection.
- *Curbside detection at flashing midblock pedestrian corridors* – Similar to an automated pedestrian detection system fixed at a signalized intersection, these can monitor one or more departure zones but usually at a flashing midblock pedestrian corridor.

There are many sensor and detection technologies for pedestrians, including but not limited to infrared, microware, and thermal sensors; pressure mats; and machine vision. Each technology has strengths and weaknesses in terms of detectability, accuracy, implementation and maintenance cost, reliability, accessibility, etc. To ensure safety benefits for pedestrians at signalized intersections, it is of practical importance to identify and determine the availability of and most effective detection technologies or combination thereof for automated pedestrian detection to integrate and develop an accurate, reliable, and cost-effective system for signalized intersections and midblock locations. It also is important for the system to be able to detect the behavior of pedestrians leaving the detection zone and automatically cancel a placed call for a pedestrian signal so that unnecessary vehicle delay can be avoided.

2 Literature Review on Automated Pedestrian Detection Technologies

An extensive review of previous studies on automated pedestrian detection systems and a current market review were performed to identify products that can meet the required criteria. Advantages and disadvantages of these technologies and systems were compared and documented, and specific technical information was sought from vendors and manufacturers. Based on findings from the literature review, key technologies and available systems were documented for further investigation.

Several systems are currently on the market that use one or more of these technologies to achieve some level of detection and/or counting. The technologies reviewed include laser scanner, infrared sensor, microwave radar sensor, computer visioning (automated video imaging), thermal imaging, radio beam, piezoelectric sensor/strip, pressure and acoustic/seismic sensor, inductive loop, pneumatic tube, magnetometer, and fiber optic pressure sensor. Features and applications of each technology are summarized below.

2.1 Laser Scanner

A laser scanner is a type of technology that can be used to automatically detect pedestrians or objects through the emission of infrared laser pulses and detection of the reflected pulses (Figure 2). These scanners follow a procedure similar to image processing in terms of data interpretation. Pedestrians can be detected by using multiple laser scanners connected by a local area network (LAN). For vehicles, a vehicle model setup application is used to monitor vehicle motion. More than one scanning plane is needed in a multilayer scanner to compensate for vehicle pitch motion.

Figure 2. BEA LZR-I30 laser scanner (*5*)

A study conducted by the Minnesota Department of Transportation (MnDOT) (*6*) on automated pedestrian detectors determined that laser scanners give accurate results for distance in centimeters and for angles ranging from 0.25–1 degrees, depending on the frequency of the scanner. However, Bu et al. (*7*) noted that due to the features of optical-based image sensors, laser scanners limit the detection range during adverse weather conditions such as fog or snow.

When compared to microwave radar or ultrasonic, laser scanners have more complex signal processing.

Automatic pedestrian detectors also have been developed based on motion or the appearance of pedestrian information. Viola et al. (*8*) developed a detector by combining both motion and appearance detection technologies, with the detection algorithm scanning over two consecutive frames of a video sequence. This style of system implementation runs at about 4 frames/sec and can detect pedestrians at very small scales (20×15 pixels) with very low false detections. These detection algorithms are quick in execution and processing and can cover an entire image zone at every scale. The detectors are trained by using large datasets to achieve high detection rates and very low false detections.

2.2 Infrared Technology (Active and Passive Infrared Sensors)

Infrared technologies are similar to motion sensors that are commonly used to operate automatic doors and home security systems. In general, infrared technologies consist of both passive and active infrared technologies. Figures 3 and 4 show examples of passive and active infrared sensor devices, respectively. A passive infrared system detects an object in the camera's field of view and measures the energy emitted from the object. Infrared technologies can be used for classification purposes, but the results may not be accurate due to variations in emitted energy of an object according to weather conditions (*9*). In addition, infrared detection systems cannot determine the number of objects detected, nor can they identify pedestrian movements.

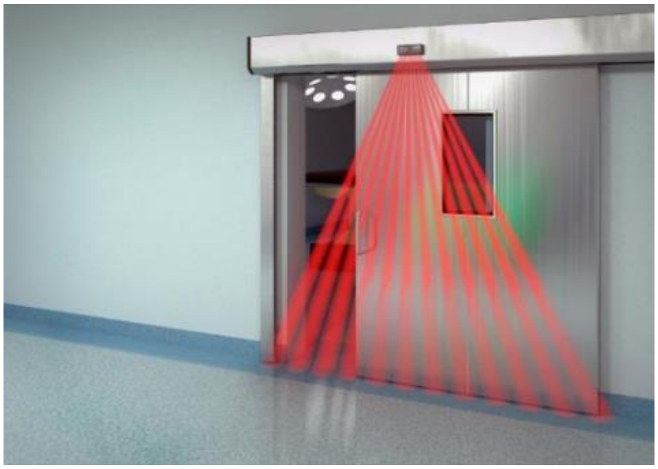


Figure 3. Active infrared sensor (for automatic door opening) (*10*)

Figure 4. Eco-Counter CITIX-IR passive infrared sensor (*11*)

Another type of infrared detector is an active infrared sensor, which works by illuminating the detection zone with low-power infrared energy supplied by light emitting diodes (LEDs) with higher levels of energy supplied by laser diodes (*12*). The detection process is conducted such that the lower-power infrared energy is reflected from the objects in the detection zone and is focused by an optical system onto a detector matrix mounted on the focal plane of the optics. The reflected energy is then converted into electrical signals by energy-sensitive components in the sensors. An advantage of active infrared sensors is that the variations in received signal levels resulting from environment (weather, temperature, etc.) can be effectively accounted for in the processing. Therefore, this type of sensor is effective for pedestrian, bicycle, and vehicle detection and counts and can extract information regarding speed, classification detection, and queue measurements.

2.3 Microwave-Radar Technologies

Microwave radar technology works similar to an ultrasonic sensor, as indicated in (*7*). A transmitter produces electromagnetic waves rather than soundwaves in ultrasound sensors and transmits through antennae. Microwave detectors produce a beam of energy at a certain frequency, and the difference between the beam of energy emitted by the device and the beam that was reflected (Doppler effect) helps to detect the object. This device can yield more accurate results for smaller and slow-moving objects (e.g., pedestrians) than for larger and fast-moving objects (e.g., vehicles).

Microwave radar technology is classified into distinct categories based on the transmission of electromagnetic waves (*13*–*15*), including Ultra-Wide Band (UWB) radar, frequency- or phase-modulated signal radar, and Doppler radar. UWB radar is a new and improving technology in ITS applications; with centimeter precision, it can detect motion by sensing pedestrians and motorized vehicles. Radio wave pulses can be received and transmitted by UWB radar with great precision. Frequency- or phase-modulated waves (frequency-modulated continuous waves [FMCWs]) detect the distance to an object based on the time lapse of the return signal. With constant frequency, Doppler radar transmits a continuous electromagnetic wave and can detect a moving object with relative speed larger than a certain threshold, because the wave from Doppler radar has a frequency shift when it is reflected from a moving object, which is helpful to determine moving speed.

Dharmaraju et al. (*15*) discussed FMCWs, a type of microwave detector with a saw-tooth waveform and constant transmitting frequency changes that can provide both motionless and passing detection changes of an object (e.g., pedestrian). Figure 5 shows an image of MS Sedco SmartWalk XP microwave detector.

Figure 5. MS Sedco SmartWalk XP pedestrian presence sensor (*16*)

2.4 Computer Visioning (Automated Video Image Processing)

Computer visioning is a general concept that includes all types of video-based techniques for automated detection and count purposes through computer models or algorithms instead of manual detection or counting. As noted by Chan et al. (*17*), video image processing is based on the intelligent analysis of digital images from video cameras to detect pedestrian presence and/or count pedestrian volume. The fundamental processing mechanism is that the applied video image processing algorithm subtracts the static background from the image and examines the remaining elements to determine if there are any pedestrians. De Leon et al. (*18*) explained the detailed mechanism of computer stereo vision. In video image processing, the images of the same scene are taken by two cameras that are separated by a small baseline distance. The computer compares the two images and determines the matching parts by making relative shifts (called disparity values) on the computer stereo images, placing one image on top of the other and translating them. The optimal disparity values are calculated when objects in the images are best matched, and software processing is carried out based on these disparities to calculate the distances of objects from the camera.

With the assistance of infrared detection technology, video image processing is capable of automated pedestrian detection in low-light conditions. This is because infrared sensors are not as sensitive as video image processing technology to changes in illuminance magnitude and have an ability to detect pedestrians without illuminating the environment. Figure 6 shows an image of an AGD 640 detector that works in a combination of infrared detection and stereovision.

Figure 6. AGD 640 Stereo vision pedestrian detector (*19*)

2.5 Thermal Technology

Thermal technology is a combination of passive infrared and automated image processing technologies (*20*, *21*). Thermal cameras operate similar to passive infrared sensors and generate infrared images by detecting body temperature. They are mounted above the detection area, which allows both detection and movement monitoring functions. A major advantage of thermal sensors is that they are not affected by variations in ambient light. Thermal cameras as an emerging technology are commercially-available in the US, including a recently-available thermal sensor product for pedestrian detection, the FLIR TrafiOne Smart City Sensor (Figure 7) (*22*). It is able to control traffic signals by detecting pedestrians and bicycles that are approaching or waiting at curbside or walking on the crosswalk, is capable of thermal detection in complete darkness, through shadows, and under sun glare, and can provide real-time detection and monitoring 24/7. FLIR TrafiOne is connected to the traffic signal controller via dry contact outputs or via TCP/IP network communication to allow for more dynamic control of traffic signals based on presence or volume information.

Figure 7. FLIR TrafiOne thermal imaging sensor for pedestrian detection (*22*)

2.6 Radio Beam Sensors

According to (*6*), radio beam sensors are defined as two types: those that can detect metal objects and those that are purely reflective sensors. Metal-detection sensors are generally used for bicycle detection, and reflective sensors can be used for both pedestrian and bicycle detection. Radio beams work similar to active infrared sensors in pedestrian detection and counting, where a radio signal, rather than an infrared beam, is emitted. This feature allows radio beam sensors to be securely installed under certain cover or behind objects, which prevents vandalization or theft. Radio beam sensors, like magnetometers, also require single-file travel for bicyclists and pedestrians; false counting may occur when there are side-by-side bicyclists or pedestrians. Therefore, radio beam sensors are fitted for low-volume routes such as rural routes, mountain trails, etc. (*23*). Figure 8 shows examples of radio beam sensors (*24*).

a) RBXL-EB in black metal post

b) RBX-EB in recycled plastic post

Figure 8. Chamber electronics radio beam sensors (*24*)

Ryus et al. (*25*) tested radio beam technology at four locations, including three multi-use path sites and one wide sidewalk site. Two devices were installed on multiuse paths to distinguish bicyclists from pedestrians and two were used to count all users. The study identified that radio beam sensors that did not distinguish bicyclists from pedestrians yielded an average undercounting of 3.63% and a total deviation of 28.13%. However, the sensors that distinguished bicyclists from pedestrians yielded average undercounting rates of 31.6% for bicyclists and 26.7% for pedestrians. Because the volumes at these sites were low, percentage deviations were high, with a relatively small number of missed detections.

2.7 Piezoelectric Sensor or Strip

Piezoelectric sensors use the piezoelectric effect to measures changes in pressure, acceleration, strain, etc., by converting them into an electrical charge. They are simple pedestrian detection applications that can detect the presence and absence of a pedestrian within a detection zone; the sensors and cables are generally "disguised" in a road mat, also called "pressure mat" (*17*). Performance is satisfactory when there is direct physical contact between the pedestrian and the piezo mat, and it can be implemented with other sensors. Piezoelectric sensors are used in the UK's Pedestrian User-Friendly Intelligent (PUFFIN) crossings (*26*) and the Dutch Pedestrian Urban Safety System and Comfort at Traffic Signals (PUSSYCATS) system (*6*).

As noted in the Federal Highway Administration (FHWA) PEDSAFE study, PUFFIN crossings have been used in the UK for several years. This type of device was developed using pressure-sensitive mats or infrared sensors to detect pedestrians who are waiting to cross. The device also helps in detecting when a pedestrian leaves the area and cancels the pedestrian "Walk" signal. PUFFIN crossings also can increase the length of a pedestrian "Walk" signal for slower-walking pedestrians and reduce pedestrian and motorist waiting time to avoid unnecessary delay. The PUSSYCATS system is an intelligent crossing system for automated pedestrian detection and consists of a pressure-sensitive mat to detect pedestrians who are waiting to cross, infrared sensors to detect pedestrians on the crosswalk, and roadside pedestrian display (*9*, *27*). Both systems were developed based on pressure sensors and infrared detectors to identify pedestrians at curbside and in a crossing. By adjusting signal timing to pedestrian presence and behavior, these systems can increase traffic safety and operation efficiency at pedestrian crossings. However, piezoelectric sensors require cumbersome installation and are not as portable as other automated detection techniques. Figure 9 shows a model of a piezoelectric sensor.

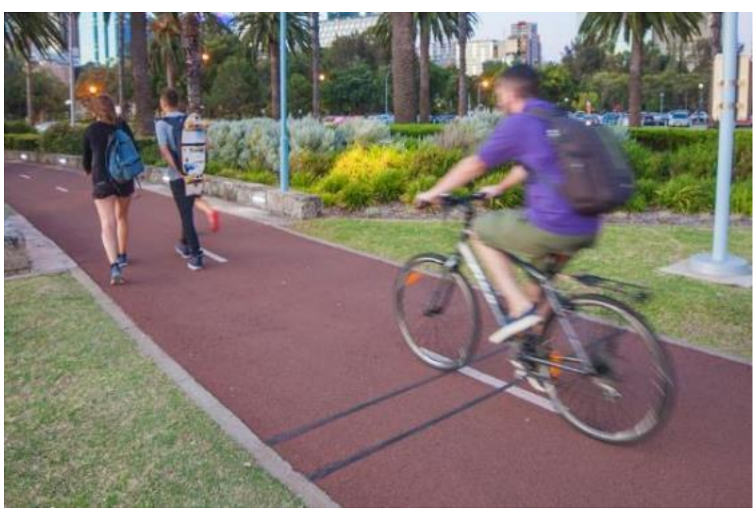


Figure 9. RidePod® BP bike + people piezoelectric counter (*28*)

2.8 Pressure, Acoustic, or Seismic Sensors

Pressure sensors can detect pedestrians and bicycles based on force applied on the sensor (*29*). Piezoelectric sensors/strips are a type of pressure sensor. Acoustic sensors work by detecting the passage of sound waves caused by feet and bicycle tires or other wheels, whereas seismic sensors identify energy waves through the ground. Both pressure and acoustic/seismic sensors are installed just below the natural surface paths or paved surfaces; implementation cost is typically low, and they are mostly vandal-proof. Pressure and acoustic pads are used primarily to count pedestrians on unpaved trails, but pressure pads also can count bicyclists (*21*). The placement and size of pressure sensors are critical elements to defining the functionality of pressure sensors, such as directing, counting, and gathering direction information. Given typical pad sizes, these sensors also are used primarily at locations where pedestrians and bicyclists travel single file, and multiple pads (sensors) are needed to cover the whole travel file if pedestrians and/or bicyclists travel side-by-side. When installed properly, pressure and acoustic sensors can serve as permanent continuous counters; however, they may become dysfunctional in extreme cold conditions when the ground is frozen solid (*6*). Figure 10 shows a model of a pedestrian pressure slab sensor.

Figure 10. Eco-Counter SLAB pedestrian counter (*30*)

2.9 Inductive Loops

Inductive loops are a "traditional" method of traffic detection; according to Dharmaraju et al. (*15*), they have been used as traffic detection sensors since the 1950s. These loops are buried in the road underneath the pavement and are used primarily for traffic counts (*31*). The purpose of these loops is to detect and count only metal objects (e.g., vehicle and bicycles); they do not measure the weight of the vehicle or count actual axes. Figure 11 shows typical inductive loops for bicycle detection and counting. These loops are buried in shallow (75–100mm) slots cut on the pavement surface; the slots are cut in a square shape, approximately 2m×2m, with three turns of wire looped in the cuts. The trails or feeder wires are twisted and fed back to electronics at the road edge, so when a metal object passes over the loops, the object is detected.

The main advantage of inductive loops is that they provide a permanent bicycle count station (*32*). However, it should be noted that with recent advancements in structural materials, bicycles made of composite materials (primarily carbon fiber) are not detectable by inductive loops. Therefore, additional effort is needed to identify carbon fiber bicycles in bicycle-related data collection and research. As the percentage of people using carbon fiber bicycles in current traffic flow is very low, the minimal counting errors are acceptable.

Figure 11. Inductive loop detector for bicycle detection (*33*)

2.10 Pneumatic Tubes

The use of pneumatic tubes (Figure 12) is another traditional detection method (*15*); they are suitable for bicycle detection and counts but not practical for pedestrians. Pneumatic tubes operate by using an air switch to detect short burst(s) of air from a passing motorized or non-motorized vehicle, and vehicle type is validated by a data logger, based on certain predefined criteria (i.e., axle spacing, etc.). Unlike inductive loops, pneumatic tubes are fixed above the pavement surface. Several studies on the use of pneumatic tubes for counting bicycles have been published (*21*, *25*, *29*, *34*). Given their long history of use, pneumatic tubes or similar equipment have been employed by most agencies.

The advantage of pneumatic tubes is that they are easy to use, highly portable, highly accurate in detection and counts, and relatively low cost (*6*). The major disadvantage is that their rubber material may gradually age or fail to maintain its nature under high or low temperature weather conditions. In addition, these tubes are easily moved or vandalized due to their high portability, so regular monitoring is necessary to ensure the success of traffic counts and detection. Also, pneumatic tubes can be a potential hazard to users such as pedestrians with disabilities on shared paths where they are implemented, and personnel must be well-trained to install and monitor the devices. According to Benz et al. (*29*), at locations where both bicyclist and pedestrian counts are needed, pneumatic tubes can be implemented jointly with infrared sensors.

Figure 12. Pneumatic tubes stretched across road (*35*)

2.11 Magnetometers

Similar to inductive loop detectors, magnetometers detect vehicle activities based on changes in the normal magnetic field as metal parts pass. Magnetometers are used primarily in vehicle detection to identify the presence and movement of vehicles (*21*). Since bicycle detection was not originally considered a function of magnetometers, it may be possible to use existing motorized traffic magnetometers for counting bicyclists, but the installation and configuration may not be optimal for precise bicyclist counting, especially when implemented on roadways with mixed vehicle and bicycle traffic. According to (*21*), magnetometers perform best in rural locations due to their high sensitivity to ferrous objects. As for bicycle detection, according to the *Traffic Detector Handbook* (*36*), "Magnetometers are sensitive enough to detect bicycles passing across a four-foot span when the electronics unit is connected to two sensor probes buried six inches deep and spaced three feet apart." Therefore, given the limited detection range of magnetometers, they are implemented preferably in location where bicyclists travel single-file, such as rural bike paths, mountain bike trails, etc. Otherwise, more than one sensor must be installed across the path (*37*).

Installation of magnetometers also requires ground excavation and in-ground deployment, and therefore, a high level of effort. According to Ryus et al. (*21*), the major strength of magnetometers is that they are battery-powered and vandalism-proof, but major limitations include limited detection range and application. Using existing magnetometers for bicycle detection also causes increased equipment needs. For example, a 30-ft detection area for automobiles would require 5 magnetometers and 1 electronic data logger, but 10 magnetometers and 4–5 data loggers would be needed to cover the same 30-ft detection area to detect bicycles (*29*). Figure 13 shows a model of magnetometers.

Figure 13. Sensys FlexMag magnetometer sensors (*38*)

2.12 Fiber Optic Pressure Sensors

In general, fiber optic sensors are of small size, low mass, high accuracy, and fast dynamic-response capabilities and are widely used in industry, including chemical, medical, and automotive (*39*). They consist of a light source that provides light to a transducer, and a modulated light from the transducer is then sent to a signal processor. Normally, the light source for the fiber optics is an LED or laser, which convert electrical power into a light with different spectral characteristics. Fiber optic pressure sensors detect changes in the amount of light transmitted through the imbedded fiber optic cable based on the pressure applied on the cable, where counter-sensitivity can be adjusted based on the weight value to be counted. Fiber optic pressure sensors are ideal for challenging pressure-monitoring applications in submerged and harsh environments and have been widely used in Europe as the basis for "bicycle barometers," permanent bicycle counting stations that show bicycle counts. Figure 14 shows a basic fiber optic pressure sensor device, and Figure 15 shows a bicycle barometer.

Figure 14. OPP-C fiber optic pressure sensor (*39*)

Figure 15. Fiber optic bicycle barometer (*20*)

The summary of existing automated pedestrian/bicycle detection and counting technologies is provided in Table 27 in Appendix. The pros and cons of each technology is also provided in the table.

3 Selection of Automated Pedestrian Detection Systems for Testing and Evaluation

Building on findings from literature review, researchers focused next on review of available pedestrian detection/counting systems on the market, investigation of the functions and capabilities of candidate systems, and finalization of the systems for testing under a controlled environment and pre-deployment field testing. The ultimate goal was to select, integrate, and implement at least one automated pedestrian system via a pilot deployment at both midblock and signalized intersection locations to evaluate its capabilities and accuracy under various environment conditions and pedestrian movement scenarios as well as any limitations of the system.

To successfully integrate a robust automated pedestrian detection system at signalized intersection and midblock locations, the following procedure and methods were established:

- **Step 1:** Research and identify available automatic pedestrian detection systems on the market.
- **Step 2:** Contact vendors and manufacturers to acquire detailed information on features, capabilities, pricing, and availability of their systems.
- **Step 3:** Review available and acquired information to develop a short list of candidate systems.
- **Step 4:** Select and acquire automated pedestrian detection systems for testing and evaluation from the short list.
- **Step 5:** Conduct initial tests in controlled conditions in a lab to examine and verify system functionality and limitations.
- **Step 6:** Conduct pre-deployment field tests to compare and evaluate the selected systems on their system performance and accuracy.
- **Step 7:** Deploy and integrate the system with the best performance in Step 6 that meets the criteria and has the highest accuracy in the field at both signalized intersection and midblock locations.
- **Step 8:** Evaluate the best system via field deployment and integration at both signalized intersection and midblock locations for their detection accuracy, reliability, performance, and potential constraints.

For consideration of good automatic pedestrian detection systems for testing and evaluation, a system should possess at least some of the following functions and capabilities:

- Detect pedestrian(s) in waiting areas of a signalized intersection or midblock crosswalk with HAWKs, RRFBs, and/or full pedestrian signals.
- Detect pedestrian(s) in waiting areas with various appearances such as wearing a raincoat or holding an umbrella.
- Detect pedestrian(s) in waiting areas under various weather and lighting conditions.
- Identify pedestrian walking directions associated with intended crosswalk(s) use.
- Place a call to a traffic signal controller after detecting pedestrian(s) in waiting areas of a signalized intersection or trigger HAWKs, RRFBs, or full pedestrian signals at midblock locations.
- Remove a pedestrian call from a traffic signal controller once pedestrians leave the waiting area at a signalized intersection.

The following aspects and performance measures were considered for selecting, evaluating, or integrating the selected automatic pedestrian detection systems:

- Accuracy
- Strengths and limitations
- Level of effort and cost
- Installation requirements
- Maintenance requirements
- Liability and accessibility
- Typical application environment

This section discusses the review and selection process from available pedestrian detection and counting systems on the market, candidate systems, and the final three selected systems for both controlled and pre-deployment field testing and evaluation.

3.1 Available Pedestrian Detection and Counting Systems

Based on the literature review on existing technologies and applications for pedestrian and bicyclist detection and counting, the research team searched available automated pedestrian detection systems on the market and made inquiries about specific technical information on promising products from vendors and manufacturers. The following details several available systems identified for further review and investigation. A summary of usage and product features for these available automatic pedestrian detection systems is provided in Table 1.

Table 1. Summary of Available Products for Automated Pedestrian Detection

Product	Technology	Usage	Product Features
FLIR TrafiOne Smart City Sensor (*22*)	Thermal sensor	Detection of vehicles, bicyclists, pedestrians	• All-in-one sensor • 24/7 detection and in various weather conditions, no need for additional lighting • Low maintenance • Simple and quick configuration over secure Wi-Fi connection • Wi-Fi monitoring capabilities (optional) • Visual HD stream (optional)
Eco Counter Slabs (30)	Pressure/ Piezoelectric sensor	Count, detect	• Installed in trails or paths reserved for pedestrians • Can be installed in natural and urban environments • Invisible • Superior reliability • Measures direction of travel • Areas with little or snow cover
Eco Counter PYRO Sensor/ PYRO Box (*41*)	Passive Infrared and pyroelectric technology	Count, detect	• Ideal in environments such as sidewalks, malls, park entrances, trails • Ability to measure direction of travel of pedestrians and cyclists • Cyclists detected quickly • Two people slightly staggered detected separately • Long battery life (10 years) without being charged • Easy to conceal; waterproof, vandalproof
Eco Counter CITIX Sensor (*11*)	Infrared radiation	Count, detect	• Applicable in urban environments, busy sidewalks, closed streets • Ability to measure direction of travel • Unparalleled accuracy in high pedestrian traffic • Highly customizable to unique site configurations
Miovision Scout (*42*)	Video detector	Count, detect	• Portable device technology • Easy installation • Ability to collect intersection data for non-traditional periods, up to several days at a time • Decrease lead time by 20% for data collection • Uses single equipment (one camera), thus reducing complexity • Optimizes engineering work with turning movement count studies • Uses machine learning and AI, increasing smart sense performance in situations such as shadows, glare, weather conditions, nighttime hours • Vendor allows technology users to access full suite of video-based applications from single platform • Traffic Link platform provides functionalities such as clean, clear data visualization, understanding metrics, and their cause

Table 1. Summary of Available Products for Automated Pedestrian Detection (Cont'd)

Product	Technology	Usage	Product Features
			• Open data API allows connection with software already in use • Technology is reliable, has been deployed in most extreme climates • Data are 95% accurate, full classification
SenSource (*44*)	Thermal imaging, 3D video	Count, detect	• Robust operation with counting accuracy up to 99% • Overhead mounted, tamper-resistant, minimal maintenance • Directional counting in any high-volume traffic area/height situation • Differentiates adults from children • Plug-and-play configuration • TCP/IP connectivity • Mounting height from 7.5–18 ft • Remote support by SenSource
MS SEDCO SMARTWALK XP(*16*)	Microprocessor Analyzed Doppler Microwave	Detect	• Specifically designed for pedestrian detection at curbside area of crosswalk or roadside at trail crossing • Ignores stationary vehicles but still detects pedestrians • Minimizes false activations from vehicle traffic • Low power requirement • Fast installation and alignment • Automatically activates pedestrian signal, detects pedestrian in crosswalk area
MetroTech Automated Pedestrian Detection System (*46*)	LIDAR Technology	Detect	• Works in all lighting conditions, night or day • Works in most weather conditions (reduced performance in dense fog or rain) • 360 degrees field of view • More than 200-meter range • Complements/confirms camera image • Maintain anonymity

3.2 Review of Candidate Automated Pedestrian Detection Systems

The research team contacted vendors and manufacturers through phone calls, emails, and meetings to collect detailed information on their systems, and check with vendors and manufacturers on the possibility of acquiring the systems for future system testing and evaluation of their systems to determine if they possessed the needed functions and capabilities.

A short list of automatic pedestrian detection systems and system vendors contacted is provided in Table 2. The technologies used in these automatic pedestrian detection systems included machine vision, thermal, microwave, and lidar. The information acquired through the vendors and manufacturers was first compared against the requirements of the project as outlined in the project scope of work. All vendors were extended ample time to provide information and products. The research team also offered to cover expenses if the vendor or manufacturers needed to demo their products.

Table 2. Candidate Automatic Pedestrian Detection Systems and Vendors Contacted

#	Product	Brand	Vendor	Technology
1	CITIX-IR	Eco-Counter	Eco-Counter, Inc.	Thermal machine vision
2	ClearCount-3DX	SenSource	SenSource, Inc.	Machine vision
3	SmartSense	Miovision	Miovision Technologies, Inc.	Machine vision
4	Heimdall	Siemens		Microwave
5	IntelliSection	MetroTech	MetroTech Net, Inc.	Lidar
6	SmartWalk™ XP	MS SEDCO	Temple, Inc.	Microwave
7	TrafiOne	FLIR	Control Technologies, Inc.	Thermal machine vision

A detailed description of each product in the short list and the required information for the pedestrian detection system are presented below.

3.2.1 CITIX-IR

CITIX-IR is a thermal camera with passive infrared sensor technology manufactured by Eco-counter and is a recommended solution for long-term counting of pedestrians on high-traffic sidewalks/areas and detecting their direction of travel (Figure 16). As the system uses thermal imaging for detection, there is no infringement on privacy. The ultra-sensitive system detects the heat emitted by people moving through the detection area and performs well in both day and night conditions. Eco-counter states that its CITIX-IR camera is the most advanced and precise counting system available on the market.

Use of this system has already proved to be efficient in Victoria, Canada, where eight cameras are installed in the Downtown area to measure the impact of cultural events and develop long-term user trends. These systems gather valuable information that can be used to attract new businesses to justify new investments in infrastructure *(47)*. The sensor, however, cannot provide input for the static presence of a person in the detection area. This is the main reason this system cannot be used for this project.

Figure 16. Eco-Counter CITIX-IR sensor
Source: Eco-Counter, Inc.

3.2.2 ClearCount-3DX

The ClearCount-3DX sensor is a three-dimensional people counter that counts pedestrians who enter the detection area and track their paths (Figure 17). Each sensor allows for up to eight independent counting lines and can monitor simultaneously both forward and backward crossings. The basic functionality of the 3DX includes zone occupancy, showing the current number of people present in a particular zone. Zones can be defined as activation zones for a dedicated counting line to perform a respective logical function. The 3DX contains a mechanism to define up to four different privacy protection levels to fulfill every possible data privacy requirement. No video stream leaves the sensor; only metadata are sent out *(48)*.

The analytics tab in the built-in web graphic user interface (GUI) contains four visualizations:

1. Persistent count data chart that allows visualization of data inside the built-in database
2. Start/stop point map that shows where a person has been generated and deleted
3. Heat and height map
4. Height map showing average person height in the scene

Figure 17. SenSource ClearCount-3DX sensor
Source: SenSource, Inc.

3.2.3 SmartSense

The SmartSense system uses machine learning and artificial intelligence to detect and actuate intersections from a single camera (Figure 18). It conducts multimodal turning movement counts, including bicyclists, and pedestrian data also are captured to improve traffic signal operations.

Machine learning and artificial intelligence allow SmartSense to perform better in many situations that cause traditional video detection to perform sub-optimally, including shadows, glare, bad weather, and nighttime hours. SmartSense technology completes the company's traffic link solution, which also includes a 360-degree fisheye camera and an IoT-connected hub that allows traffic professionals to remotely access the intersection. Together, these components make up a powerful artificial intelligence toolkit that uncovers insights about the intersection *(49)*. At testing time, the software to provide detection for pedestrians was not yet available.

Figure 18. Miovision SmartView camera, Smartlink, and SmartSense
Source: Miovision Technologies, Inc.

3.2.4 Heimdall

The Heimdall sensor (Figure 19) can be configured for several applications, including curbside detection of pedestrians. Using an advanced "dual antenna" design, it provides dependable sensing of pedestrians waiting to cross at crossings. The unique use of two integrated antennas allows the detector to provide excellent performance at a wide range of crossings without the need to use complex and expensive set-up software. By using advanced radar for this application, the problems inherent in other solutions, which rely on video techniques, are eliminated. Heimdall curbside units operate as well in the dark as in fully-lit conditions and are completely immune to the effects of shadows *(50)*.

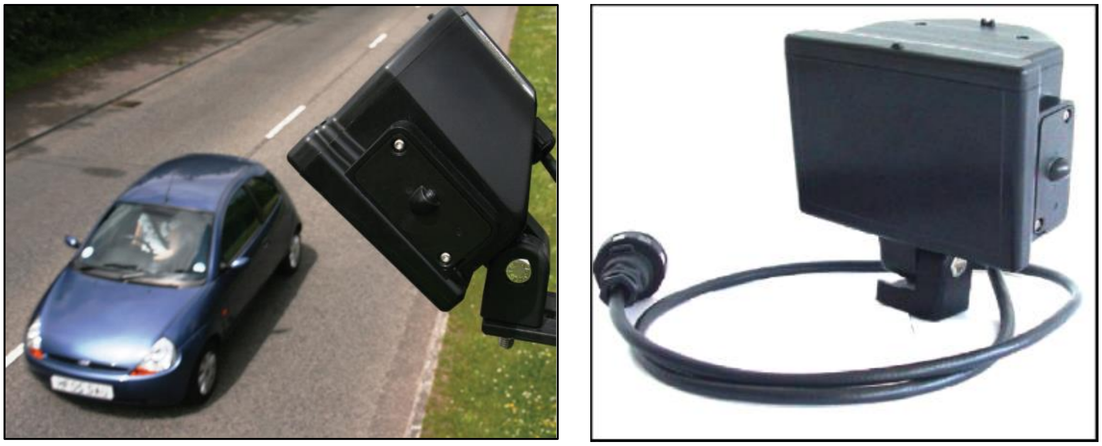


Figure 19. Siemens Heimdall sensor
Source: Siemens

3.2.5 MetroTech Automated Detection

MetroTech's solution includes lidar sensors, camera sensors, and video analytical software. The MTN IntelliSection™ appliance collects data created by the various sensors at the intersection, which are used to report pedestrian location, and notifications can be developed based on predetermined events. The data also can be moved to the Digital Streets Platform, either by local fiber or built-in LTE connectivity, to enable highly-accurate historical data for predictive and planning purposes. The appliance enables communication with roadside units such as pedestrian signalization or interruption systems. The system overall is able to precisely detect the presence and location of pedestrians, continually report pedestrian locations in the form of personal safety messages or other formats, and communicate to on premise, cloud-based infrastructure or roadside infrastructure end points. Data can be continually sent to the end points as pedestrians are detected by the system, and location includes latitude, longitude, elevation, speed, heading, presence, and pedestrian clusters for up to 10 times per second *(51)*.

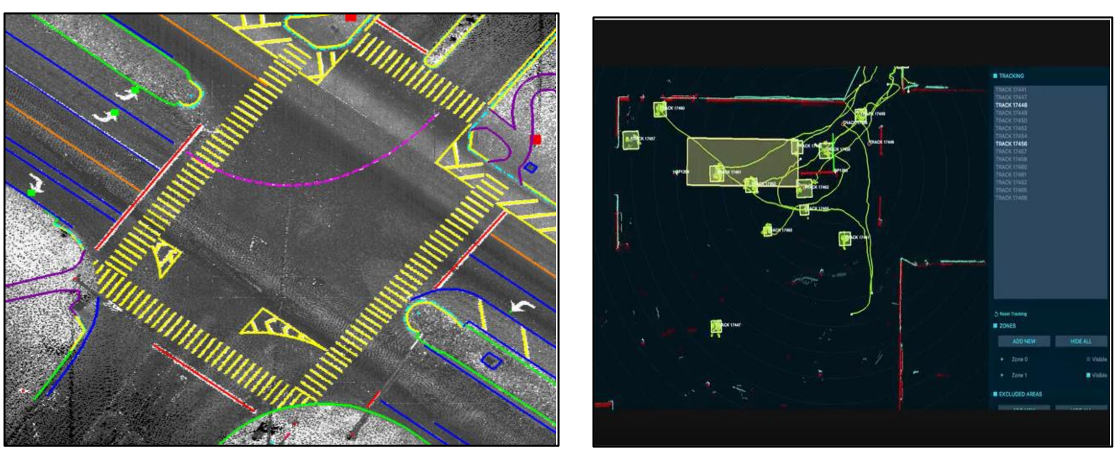


Figure 20. IntelliSection Appliance system
Source: Metrotech-Net, Inc.

3.2.6 SmartWalk™ XP

SmartWalk™ XP is a microprocessor-analyzed Doppler microwave with micro-motion technology and also is a solar trail and crosswalk presence sensor (Figure 21). The product was designed by MS Sedco to provide short-range pedestrian presence detection in the targeted curbside area of a crosswalk or roadside at a trail crossing, making it an excellent alternative to manual push buttons that require human interaction. The microwave technology makes it capable of providing pedestrian presence detection in a targeted curbside area while ignoring stationary vehicles. The software also was improved to avoid false activations from nearby moving vehicular traffic or pedestrians not intending to use the crosswalk. SmartWalk™ XP is ideal for activating warning lights at trail crossings, allowing them to flash only when a pedestrian on the trail approaches the crossing. This increases the effectiveness of the warning lights, as they are activated only when a pedestrian is present. This also makes the SmartWalk™ XP perfect for solar appliances *(52)*.

SmartWalk™ XP can be used as a standalone device or in combination with SmartWalk™ XM to complete the crosswalk activation and occupancy sensor system. This system, the only of its kind, provides increased pedestrian safety by activating the crosswalk signal (XP) and detecting pedestrians in the crosswalk area (XM) with no specific action required by the pedestrian.

A study *(53)* provided results on SmartWalk™ XP with dual crossing with single curb ramps with 53,000 vehicles and 10,000 pedestrians per day and conditions analyzed such as weather, temperature, wind and wind chill, humidity, and time of day. The overall performance sensitivity of using XP was 60%, and the overall performance selectivity was 23%. It also was noted that false calls were different by site.

Figure 21. MS SEDCO SmartWalk™ sensor
Source: MS Sedco, Inc.

3.2.7 FLIR TrafiOne

FLIR TrafiOne is an all-round detection sensor for traffic monitoring and dynamic traffic signal control. Offered in a compact and affordable package, it uses thermal imaging and Wi-Fi technology to adapt traffic signals based on the presence detection of vehicles, bicycles, and pedestrians while generating high resolution data at intersections and in urban environments (Figure 22). FLIR TrafiOne helps traffic engineers to improve traffic flows, reduce vehicle idling time, monitor congestion, enhance safety for vulnerable road users, collect data, and measure travel and delay times for different transport modes *(54)*. It uses thermal imaging to detect the presence of vehicles and bicyclists at a stop bar or in advance as well as pedestrians and bicyclists at a crossing or on a curb. Thermal imaging cameras can see in total darkness and through shadows and sun glare, thus providing reliable traffic detection 24/7. FLIR TrafiOne is connected to the traffic signal controller via dry contact outputs or via TCP/IP network communication to allow for more dynamic control of traffic signals based on presence or volume information *(54)*.

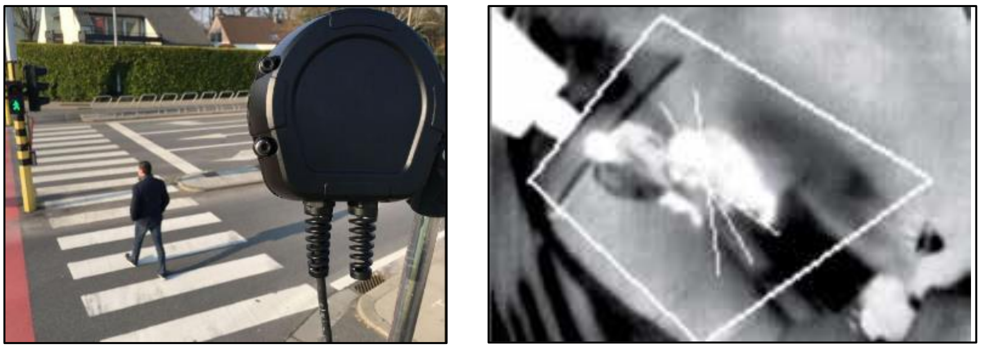


Figure 22. FLIR TrafiOne sensor
Source: FLIR Systems, Inc.

Table 3 provides technical specifications for these systems and sensors. All information was provided by the vendors or manufacturers.

Table 3. Summary of System or Sensor Technical Specifications

System/Sensor	Attribute	Technical Data
CITIX-IR (47)	Dimensions (LxWxH)	14 x 13.3 x 8 cm
	Weight	1.7 kg
	Operating temperature range	-40° C to +50° C (-13 F to 120 F)
	Waterproofness	IP 66
	Typical supply current	100 mA at 12 V
	Housing	Die-Cast Aluminum
	Coating	Grey powder coat (RAL7001)
	Detection range	4.25 m x 4.25 m
	Mounting height	3 m–4 m
ClearCount-3DX *(55)*	Working principle	3D stereo vision distance measurement
	Installation angle	+/- 15° in x-axis, +/- 5° in y-axis
	Operation temperature	0°-50° degree C
	Storage temperature	-20°–70°
	Air humidity	20–80%
	Connection	RJ-45 Ethernet
	Power supply	PoE class 0 (IEEE 802.3af)
	Power consumption	<5W
	Required illumination	Min. 2 lux
	Data storage	Up to 120 days

Table 3. Summary of System or Sensor Technical Specifications (Cont'd)

System/Sensor	Attribute	Technical Data
	Max. people tracking	Up to 200 people simultaneously
	Multisensor	Up to 6 sensors
	Dimensions (LxWxH)	13 x 9.4 x 3 cm
	Weight PC2	350gr
	Mounting height	Up to 6 m
SmartSense ***(56)***	Dimensions	246 mm x 266 mm x 58.4 mm
	Power supply	Power source req: 110 V-AC uninterrupted (non-GFCI required); option for NEMA 5-15R or terminal block wiring
	Power adapter output	48 VDC @ 100W. Video analyzer power consumption: max 100W
	Operation temperature	-34 º C to 74º C (-29.2º F to 165º F)
	Humidity	5%-95% RH non-condensing
	Display	128X64 OLED display
	Control	5-button
	Processor	Dual GPU plus 12 computing cores
	Ports	4 x Ethernet RJ45 (2 x available with PoE)
	SDLC	SDLC port for detector actuation
	GPIO header block	16 x I/O pins for actuation
	USB	1 x USB 2.0 port
	Sensor	4K, 9-megapixel, 360° fisheye lens
	Angular field of view	Horizontal: 182", Vertical: 176"
	Voltage	PoE
	Format	H264 natively, download as H264, stream as MPEG1
	Resolution	512 x 512
	Frame rate	15 fps
Heimdall ***(57)***	Radio	EN 300440
	Supply voltage	24 V AC ± 20% (48 to 63 Hz), or 24 V DC ± 20%
	Typical supply current	143 mA (AC), 113 mA (DC), 186 mA (AC) with wireless or serial data options, 147 mA (DC) with wireless or serial data options
	Operating frequencies	24.05 GHz to 24.25 GHz, 13.4 GHz to 14.0 GHz (curbside and on-crossing)
	Dimensions	150 mm (h) x 135 mm (w) x 90 mm (d) (to bottom of mounting bracket)
	Weight	Less than 1.6 Kg (including bracket)
	Standard connection	Defined Bulgin Buccaneer connector and pin-out or internal screw connector for connection of customer-defined termination
	Operating range	Wait areas up to 4.5 m wide
	Wait area width	Typically, 1.0 m (typical 2.0 m adjacent to pedestrian demand unit)
	Detector location	On pole with associated pedestrian demand unit
	Detector mounting height	from 3.3 m to 4 m
SmartWalk™ XP ***(58)***	Dimensions	4"W x 4"H x 7"L
	Enclosure	Powder coated aluminum
	Weight	4 lbs
	Operating frequency	24.125 GHz (K-band)
	Detection method	Microprocessor Analyzed Doppler Microwave
	Detection pattern	Adjustable
	Detection angle	Adjustable

Table 3. Summary of System or Sensor Technical Specifications (Cont'd)

System/Sensor	Attribute	Technical Data
	Detection mode	Selectable approach-only, depart-only, bidirectional
	Call extension time	0.1 to 5 sec
	Power requirements	12–24 V AC or DC±10%
	Power consumption	2 W max
	Relay output	Form C, rated at 1 Amp @ 24V DC (N.O. and N.C.)
	Output power	5mW typical, 2mW minimum
	Relay contact ratings	0.5A:50 V AC, 1A:24 V DC
	Temperature range	-34 ° C–74° C (-29.2° F–165° F)
	Mounting height	10–12 ft
	Mounting	Heavy-duty bracket predrilled and slotted for pole mount
	Power supply	12 V DC ±10 %
TrafiOne ***(59)***	Input power	12 – 42 V AC/DC
	Power consumption	3 Watt
	Outputs	1 N/O and 1 N/C dry contacts direct, 16 N/C dry contacts via TI BPL2 interface
	Ethernet	10/100 MBps
	PoE	PoE A and PoE B
	Powerline communication	Up to 2 MBps via TI BPL2 interface
	Wi-Fi	IEEE 802.11
	Shock & vibration	NEMA TS2 specs
	IP Rating	IP67
	Temperature range	-40°C to +60°C (-40°F to +140°F)
	FCC	FCC part 15 class A
	Housing materials	Aluminum housing with PC GF10 sunshield
	Bracket	PA GF30 mounting clamps and aluminum tube
	Visual sensor resolution	1080 x 1920 HD color CMOS
	Visual sensor frame rate	30 fps
	Visual sensor lens	HFOV 95°
	Visual sensor streaming Video	RTSP
	Visual sensor compression	H.264, MPEG-4, MJPEG
	Thermal sensor resolution	160 x 120
	Thermal sensor frame rate	9 FPS
	Thermal sensor detector type	Focal Plane Array (FPA) uncooled VOx microbolometer LWIR sensor, 8–14 µm wavelength
	Thermal sensor streaming video	RTSP
	Visual sensor compression	H.264, MPEG-4, MJPEG
	# detection zones	8 vehicle presence, 8 pedestrian presence
	Configuration	Web page via secure Wi-Fi or Ethernet

3.3 Selection of Automated Pedestrian Detection Systems

After review of candidate systems, the research team contacted all vendors in Table 3 to determine if their products were ready and available for acquisition for lab and field testing. The following systems were removed due to limitations of sensors to provide the required outcome, as indicated below:

1. *CITIX-IR* – not ready at testing time; used primarily for counting.

2. *ClearCount-3DX* – worked only indoors, needed light, was primarily for counting.
3. *SmartSense* – Not ready in time for controlled and field testing.
4. *MetroTech Automated Detection* – vendor in process of developing new low-cost solution, but updated system not ready at testing time.

The research team acquire the following three automated pedestrian detection systems to continue lab and field testing in the next step:

1. Heimdall
2. SmartWalk™ XP
3. TrafiOne

The research team engaged USF's Facilities Management Department and with its signal controller vendor (Peek Traffic Corporation) to establish parameters for final field deployment at a USF-campus traffic intersection. The team also worked with a master technician with Peek to establish connection of the automatic pedestrian detection systems to the traffic signal controller.

4 Testing in a Controlled Environment

This section presents the details on testing, evaluation and results for three selected automated pedestrian detection systems in a controlled environment. It first describes the test components, procedure, and methods, followed by the evaluation criteria and performance measures used in the controlled tests. The test results from each automatic pedestrian detection system are presented in detail.

4.1 Test Components, Procedure, and Methods

For the controlled tests, the research team determined the test components and set up a robust test procedure to evaluate each automated pedestrian detection system on its capabilities and limitations. The controlled tests included the following components:

- Test the system's functionality and confirm that it can 1) detect approaching pedestrians and 2) maintain detection on presence of pedestrians in its field of view.
- Test the system's capability to work in various weather and light conditions experienced in Florida (day, night, rain, fog).
- Test the system's capability to detect different configurations of pedestrians and bicyclists.

Each sensor was installed on a standard pole at the height and angle recommended by the manufacturer. The testing environment was inside the CUTR ITS lab. The test procedure was as follows:

1. Install system detection sensor per manufacturer guidelines.
2. Determine detection area.
3. Run tests with pedestrians and bicyclists in different configurations (wearing basic clothing, wearing raincoats, holding umbrella, etc.) passing the detection area.
4. Run the same tests by changing environment (day, night, rain, fog).

The test method includes conducting the following tests for all sensors of three automatic detections systems:

- Walking pedestrian (normal speed)
- Walking pedestrian (fast speed)
- Pedestrian holding umbrella
- Pedestrian with winter clothing (jacket, gloves, scarf, winter hat)
- Walking bicyclist
- Riding bicyclist

4.2 Evaluation Criteria for Controlled Tests

To ensure that the automatic detection system could successfully and accurately detect the presence or disappearance of pedestrians and bicyclists at a signalized intersection and place or cancel pedestrian calls to the traffic signal controller and at a midblock location could trigger an RRFB, HAWK, or pedestrian signal, the evaluation criteria used for controlled tests needed to cover all typical pedestrian and bicyclist movements and capabilities. The following evaluation criteria were used for the control tests. An automated pedestrian detection system must be able to:

- Detect entry of pedestrian and/or bicyclist in its zone (instantaneous)
- Detect presence (constant for a longer time)
- Detect exit of pedestrian and/or bicyclist from its zone
- Provide input to traffic signal controller of changing conditions (entry, presence, exit)
- Work under multiple lighting and weather conditions

4.3 Performance Measurement

Each system was evaluated using the performance measures shown in Table 4. Each combination was run multiple times to obtain sample data for analysis.

- **True Detection** – pedestrian/bicycle in detection zone and correctly detected
- **False Positive** – detection triggered but no pedestrian/bicyclist (i.e., vehicles, other object, or nothing in detection zone)
- **False Negative** – non-detection of pedestrian/bicycle present in detection zone
- **Total Number of Detections** – total number of detections triggered by automated pedestrian detection system, equal to sum of true detections and false detections
- **Total Number of Pedestrian/Bike Presence** – total number of pedestrian and/or bicycles present in detection zone during data collection

Calculation of Measures:

- Detection System Accuracy (% of True Detections) = $\frac{Number\ of\ True\ Detections}{Total\ Number\ of\ Detections}$
- False Detections (%) = $\frac{Number\ of\ False\ Detections}{Total\ Number\ of\ Detections} =$ 1-Detection Sys. Accuracy
- True Detection Accuracy (%) = $\frac{Number\ of\ True\ Detections}{Total\ Number\ of\ Pedestrian/Bike\ Presence}$
- % of Missing Detections = $\frac{Number\ of\ Missing\ Detections}{Total\ Number\ of\ Pedestrian/Bike\ Presence}$

Table 4. Lab Test Scenario Setting and Performance Measures

Time of Day	Weather	Light	Detection	Performance Measures
Daytime	Clear	Natural	All ped/bike modes (all shapes)	Detection System Accuracy, % of False Positives, True Detection Accuracy, % of False Negatives
Daytime	Rain/fog (lab simulation)	Natural	All ped/bike modes (all shapes)	Detection System Accuracy, % of False Positives, True Detection Accuracy, % of False Negatives
Daytime	Clear	Lab light	All ped/bike modes (all shapes)	Detection System Accuracy, % of False Positives, True Detection Accuracy, % of False Negatives
Daytime	Rain/fog (lab simulation)	Lab light	All ped/bike modes (all shapes)	Detection System Accuracy, % of False Positives, True Detection Accuracy, % of False Negatives
Nighttime	Clear	None	All ped/bike modes (all shapes)	Detection System Accuracy, % of False Positives, True Detection Accuracy, % of False Negatives
Nighttime	Rain/fog (lab simulation)	None	All ped/bike modes (all shapes)	Detection System Accuracy, % of False Positives, True Detection Accuracy, % of False Negatives
Nighttime	Clear	Partial	All ped/bike modes (all shapes)	Detection System Accuracy, % of False Positives, True Detection Accuracy, % of False Negatives
Nighttime	Rain/fog (lab simulation)	Partial	All ped/bike modes (all shapes)	Detection System Accuracy, % of False Positives, True Detection Accuracy, % of False Negatives

4.4 Test Results

Each of three selected automatic pedestrian detection system was installed and tested using the procedure and method described above. Observations, discussion, and test results for each system are provided below.

4.4.1 Heimdall

The Heimdall sensor can be configured for several applications, including curbside detection of pedestrians. Using an advanced “dual antenna” design, it provides dependable sensing of pedestrians waiting to cross at crossings. The unique use of two integrated antennas allows the detector to provide excellent performance at a wide range of crossings without the need to use complex and expensive set-up software. By using advanced radar for this application, the problems inherent in other solutions, which rely on video techniques, are eliminated. Heimdall curbside units operate as well in the dark as in fully-lit conditions and are completely immune to the effects of shadows. Figure 23 shows the testing of the Heimdall sensor.

a) Installed on a pole *b) Detection LED*

Figure 23. Heimdall testing

A summary of lab tests for the Heimdall system is shown in Table 5. The system was able to perform pedestrian detection and provide input to the traffic signal controller. A few instances were observed in which the system did not perform per requirements, as shown in Table 6.

Table 5. Heimdall Testing Summary

Detection System Accuracy (%)	100%
False Detections (%)	0%
True Detection Accuracy (%)	93%
False Negative Detections (%)	0%

This system had the characteristics shown in Table 6 based on the requirements described previously. Siemens provides two sensors for this application. The Kerbside detector was configured to detect pedestrians waiting to cross, and the Crossing detector was installed and directed towards the crosswalk to provide detection while a pedestrian was crossing on the crosswalk. The Crossing sensor was configured to provide detection for pedestrian walking towards or away from the sensor.

Table 6. Heimdall System Requirements Summary

Requirement	Met?	Notes
Detect entry of pedestrian and/or bicyclist in its zone (instantaneous)	Yes	Sensor detected entry in zone from any direction
Detect presence (constant for longer time)	Yes	Unlike SmartWalk, Heimdall did not drop presence of pedestrian staying still for a few seconds
Detect exit of pedestrian and/or bicyclist from its zone	Yes	Dropped detection as soon as pedestrian left zone
Provide input to traffic signal controller of changing conditions (entry, presence, exit)	Yes	Provided constant input during detection
Work under multiple lighting and weather conditions	Yes	Tested under daylight, nighttime, simulated rain and fog conditions.

The shape of the detection area was at its largest size, as shown in blue circle in Figure 24; the smallest area is shown as a red hatched area. The adjustment was not gradual and could be set at either one or the other boundary. Also, by tilting the unit at an angle and increasing the height, the detection area could target the desired location. This area was produced when the sensor was at 95 inches from the floor.

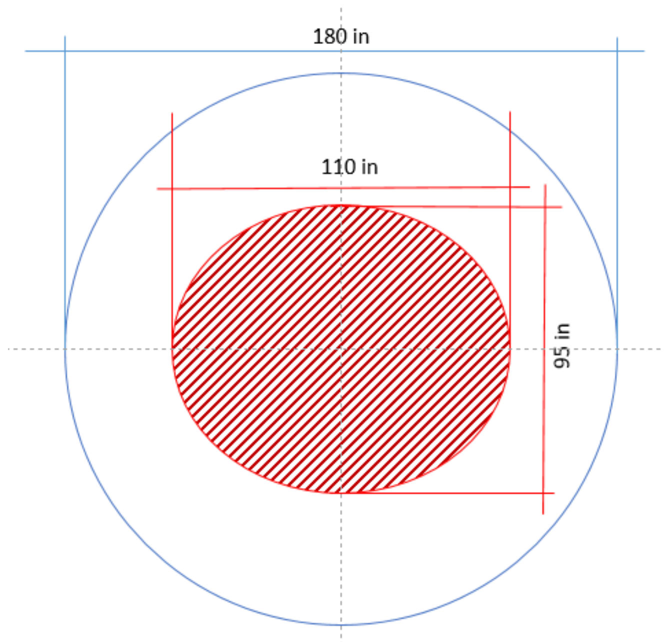


Figure 24. Heimdall Kerbside detection area (approximate)

4.4.2 SmartWalk™ XP

SmartWalk™ XP is a microprocessor-analyzed Doppler microwave with micro-motion technology and also is a solar trail and crosswalk presence sensor. The product was designed to provide short-range pedestrian presence detection in the targeted curbside area of a crosswalk or roadside at a trail crossing, making it an excellent alternative to manual push buttons that require human interaction. The microwave technology makes it capable of providing pedestrian presence detection in a targeted curbside area while ignoring stationary vehicles. The software was improved to avoid false activations from nearby moving vehicular traffic or pedestrians not intending to use the crosswalk. SmartWalk™ XP is ideal for activating warning lights at trail crossings, allowing them to flash only when a pedestrian on the trail approaches the crossing. This increases the effectiveness of the warning lights, as they are activated only when a pedestrian is present.

A summary of lab tests is shown in Table 7. The system was able to perform pedestrian detection and provide input to a traffic signal controller; however, a few instances were observed in which the system did not perform per requirements, as shown in Table 8.

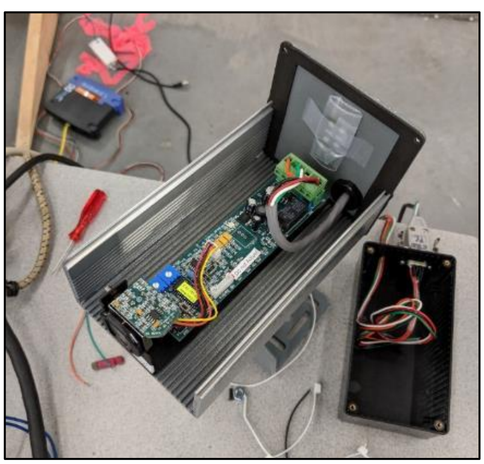
Table 7. SmartWalk XP Testing Summary

Detection System Accuracy (%)	100%
False Detections (%)	0%
True Detection Accuracy (%)	93%
False Negative Detections (%)	0%

Table 8. SmartWalk XP System Requirement Summary

Requirement	Met?	Notes
Detect entry of pedestrian and/or bicyclist in its zone (instantaneous)	Yes	Sensor detected entry in zone from any direction
Detect presence (constant for a longer time)	No	When pedestrian was still for more than 7 secs, sensor dropped detection; if enough movement, sensor detected again; pedestrian looking at phone (not moving) not detected continuously
Detect exit of pedestrian and/or bicyclist from its zone	Yes	If pedestrian moved enough in zone, then yes (see above)
Provide input to traffic signal controller of changing conditions (entry, presence, exit)	Yes	Look above for presence
Work under multiple lighting and weather conditions	Yes	Tested under daylight, nighttime, simulated rain and fog conditions

Figure 25 shows the testing of the SmartWalk XP system in the lab. For the SmartWalk XP system, the detection zone is not customizable, but is fixed, with adjustment for detection sensitivity. The zone has an ellipsoid shape and can change in size by adjustment. The shape of the sensor was tested at a height of 71 inches (5.92 ft) from the floor, as shown in Figure 25b. The shape of the detection area was at its largest size, as shown in blue ellipsis in Figure 26; the smallest detection area is shown in red hatched area. The adjustment is gradual and can be achieved at any size between these two boundaries. Also, by tilting the unit at an angle and increasing the height, the detection area can target the desired location. This area was produced when the sensor was at 71 inches from the floor.



a) inside sensor

b) installed on pole inside lab

Figure 25. SmartWalk™ XP testing

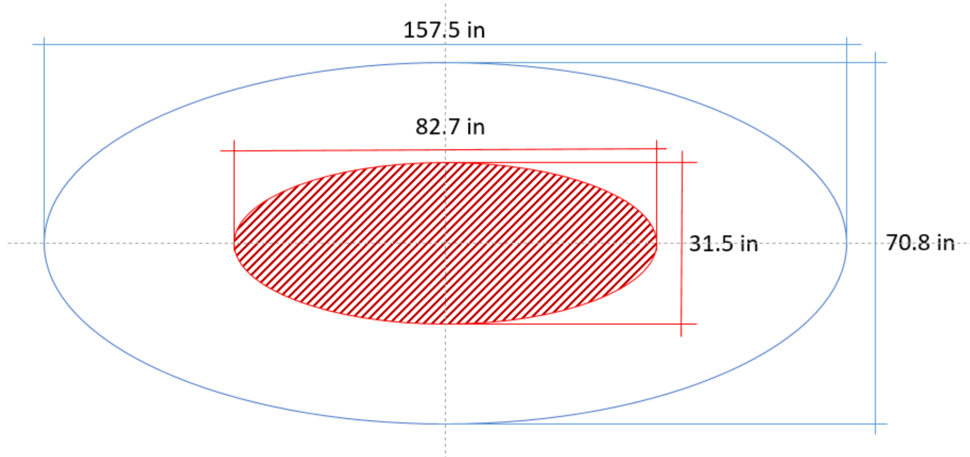


Figure 26. SmartWalk detection area (approximate)

4.4.3 FLIR TrafiOne

FLIR TrafiOne is an all-round detection sensor for traffic monitoring and dynamic traffic signal control. Offered in a compact and affordable package, it uses thermal imaging and Wi-Fi technology to adapt traffic signals based on the presence detection of vehicles, bicycles, and pedestrians while generating high resolution data at intersections and in urban environments. FLIR TrafiOne helps traffic engineers to improve traffic flows, reduce vehicle idling time, monitor congestion, enhance safety for vulnerable road users, collect data, and measure travel and delay times for different transport modes. It uses thermal imaging to detect the presence of vehicles and bicyclists at a stop bar, in advance of the stop bar, at a crossing, or on a curb. Thermal imaging cameras can see in total darkness, and through shadows and sun glare. They provide reliable traffic detection 24/7.

A summary of the FLIR TrafiOne lab tests is shown in Table 9. The system was able to perform all aspects of detection and provide input to the traffic signal controller. Several parameters can be customized to the application, including directional detection and delay to input for the traffic signal controller. Table 10 shows the characteristics based on the requirements described previously.

Table 9. FLIR TrafiOne Testing Summary

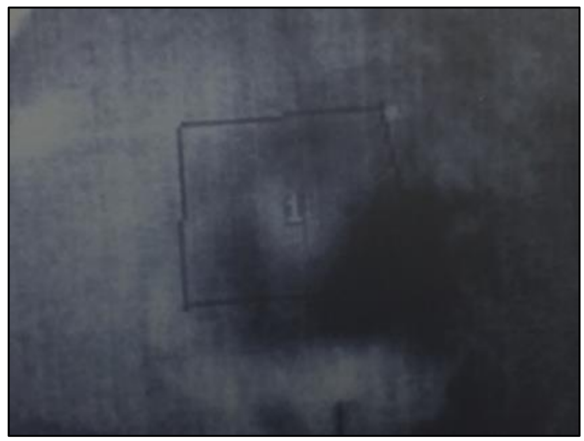
Detection System Accuracy (%)	100%
False Detections (%)	0%
True Detection Accuracy (%)	100%
False Negative Detections (%)	0%

Table 10. TrafiOne System Requirements Summary

Requirement	Met?	Notes
Detect entry of pedestrian and/or bicyclist in its zone (instantaneous)	Yes	Detected entry in zone of anything with heat signature larger than 4 sq. in.
Detect presence (constant for longer time)	Yes	Kept presence information as long as heat signature present inside zone
Detect exit of pedestrian and/or bicyclist from its zone	Yes	Detected exit of heat signature from zone
Provide input to traffic signal controller of changing conditions (entry, presence, exit)	Yes	Provided continuous input or change of condition
Work under multiple lighting and weather conditions	Yes	Tested under daylight, nighttime, simulated rain and fog conditions

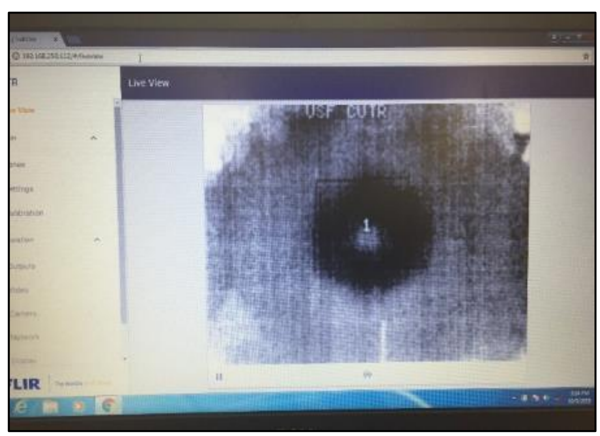
Figure 27 shows the testing of the FLIR TrafiOne system in rain (pedestrian using umbrella) and during simulated fog (system inside fog cloud). The testing showed that the system can perform in all lighting and weather conditions without false positive or false negative detections. It is capable of a flexible detection zone and multiple zones with one unit.

a) in simulated rain



b) output of sensor in rain

c) in simulated fog



d) output in fog

Figure 27. TrafiOne Testing

4.5 Discussion of Testing in a Controlled Environment

Each of three selected automated pedestrian detection systems was tested under exactly the same conditions to show functionality and flexibility in parameter-setting. In addition, the testing was designed to gather information to show differences between the sensors. The test results showed that all sensors were capable of pedestrian detection, but with several differences. The two microwave sensors had limitations in adjustment of the detection area to cover the exact specified pedestrian waiting area because the microwave sensors provided only an approximate detection area. The TrafiOne system provided maximum flexibility in that aspect among the three systems to specify detection area and adjust detection zones.

The performance of the TrafiOne system on true detection accuracy was 100%. On the other hand, the performance for both microwave sensors on true detection accuracy was 93%. The microwave sensors could not always be guaranteed to indicate the presence of a pedestrian waiting in the detection zone. This would be a potential problem when the system must provide input to the traffic signal controller to cancel the pedestrian call placed when the pedestrian was initially detected. In addition, in their software, the two microwave sensors had functions programmed to ignore moving or stationary vehicles (as false detections), which might influence the sensor's detection performance.

Because of satisfactory performance in the controlled tests, these three systems were selected for the next phase of field testing.

5 Field Testing, Data Analysis, and Evaluation Results

Field testing and evaluation are essential for any automatic pedestrian detection system for further improvement, enhancement, or future permanent deployment. Two stages of field testing and evaluation were conducted:

- **Stage 1**, **Concurrent Comparison of Systems** – All three selected automatic pedestrian detection systems were installed at the same location at the same time in the field and evaluated for pedestrian detection capabilities without being connected to traffic control devices or warning lights. This stage was conducted first to determine which systems could meet the criteria for further pilot deployment.
- **Stage 2, Deployment of Systems** – The system with the best test results in Stage 1 was selected for pilot deployment and evaluation at three test locations—a signalized intersection and two midblock crossings. The system was connected to the traffic signal controller at a test signalized intersection and RRFBs at two test midblock crosswalks.

The system with the best performance in Stage 1 was selected for actual pilot deployment and evaluation in Stage 2. The test results from both stages provided important findings and insight for supporting integration of a robust automated pedestrian detection system for signalized intersections and midblock crossings.

For the field tests in Stage 1, three systems including two microwave radar-based systems and one thermal machine vision system were indicated as follows:

- System 1 (Vendor 1) – microwave radar-based system
- System 2 (Vendor 2) – microwave radar-based system
- System 3 (Vendor 3) – thermal machine vision system

For the comparison field test in Stage 1, the three systems were evaluated for three pedestrian types:

- Pedestrian wearing normal clothes
- Pedestrian wearing a raincoat
- Pedestrian holding a large umbrella

These three pedestrian types were selected to represent the majority of pedestrians crossing roads. Several other types were tested as well, such as bicyclists and under nighttime and rain conditions, but data are not presented herein, as they support the same results as the three types presented above.

5.1 Evaluation Criteria and Performance Measures for Field Tests

Similar to the lab testing, the criteria outlined in Table 11 were used to evaluate the selected pedestrian detection systems during the field tests. The performance measures used were True Detection Rate and False Detections, as outlined in detail in Section 4.3.

Table 11. Field Testing Criteria

Criteria	Description	Outcome
Pedestrian detection	System able to detect pedestrian walking inside detection zone	Yes/No
Pedestrian direction	System able to detect pedestrian walking in correct direction	Yes/No
Pedestrian presence	System able to detect pedestrian for as long as pedestrian is inside detection zone and provide output for controller or RRFB activation	Yes/No

5.2 Selection of Test Sites for Stage 1, Concurrent Comparison of Systems

Test sites for Stage 1 included two types—a midblock crosswalk location and a signalized intersection. At these locations, the systems were not connected to any traffic control devices.

5.2.1 Midblock Crosswalk Site

Field testing was conducted at a midblock crosswalk on USF Alumni Driver on USF Tampa campus. This crosswalk was selected because it connects USF College of Engineering complex and the USF Research Park with active pedestrian activities throughout the day. Figure 28 shows the testing setup at this midblock crosswalk.

Figure 28. Concurrent system testing at midblock crosswalk, USF Tampa campus

5.2.2 Signalized Intersection Site

Field testing was conducted at the signalized intersection of USF Holly Drive and USF Myrtle Drive on the USF Tampa campus. This intersection was selected because it is located near a student dormitory and a parking garage with active pedestrian activities throughout the day. Figure 29 shows the testing setup at this intersection at USF.

Figure 29. Concurrent system testing at signalized intersection, USF Tampa campus

5.3 Selection of Test Sites for Stage 2, Deployment of System

The test sites in Stage 2 included two types—a midblock crosswalk location with RRFBs and a signalized intersection with traffic signals. At these locations, the system should be able to detect a pedestrian and activate the RRFBs for a midblock crosswalk or place a pedestrian call to the traffic signal controller, similar to a push button at a signalized intersection.

5.3.1 Midblock Crosswalk Sites

The CUTR team selected two midblock crosswalks for field testing. The first was the crosswalk on Suwannee Street across from the Florida Department of Transportation (FDOT) Burns Building in Tallahassee, Florida, as shown in Figure 30. This crosswalk offers a direct path for FDOT employees between the building and the parking lot across the street. The crosswalk is on a two-lane roadway with relatively high pedestrian activities and low vehicle volume. It is an ideal location for field testing for this research project.

Figure 30. Midblock crosswalk in Tallahassee, FL

The second crosswalk was located on USF Alumni Drive on the USF Tampa campus between the USF College of Engineering complex and the USF Research Park, as shown in Figure 31. It is on a four- lane roadway with heavy pedestrian and vehicle volumes with a posted speed limit of 25 mph.

Figure 31. Midblock crosswalk, USF Tampa campus

5.3.2 Signalized Intersection Site

The signalized intersection on the USF Tampa Campus is located at USF Magnolia Drive and USF Holly Drive (see Figure 32). It is equipped with a mast arm. The equipment at this signalized intersection was upgraded in February 2019. There were heavy pedestrian and vehicle volumes at this test site. Figure 33 shows an aerial view of the signalized intersection, location of the crosswalk on the northern leg, and the location of the two sensors required for each side of the crosswalk. One crosswalk was adequate for testing the functionality of the system.

Figure 32. Signalized intersection, USF Tampa campus

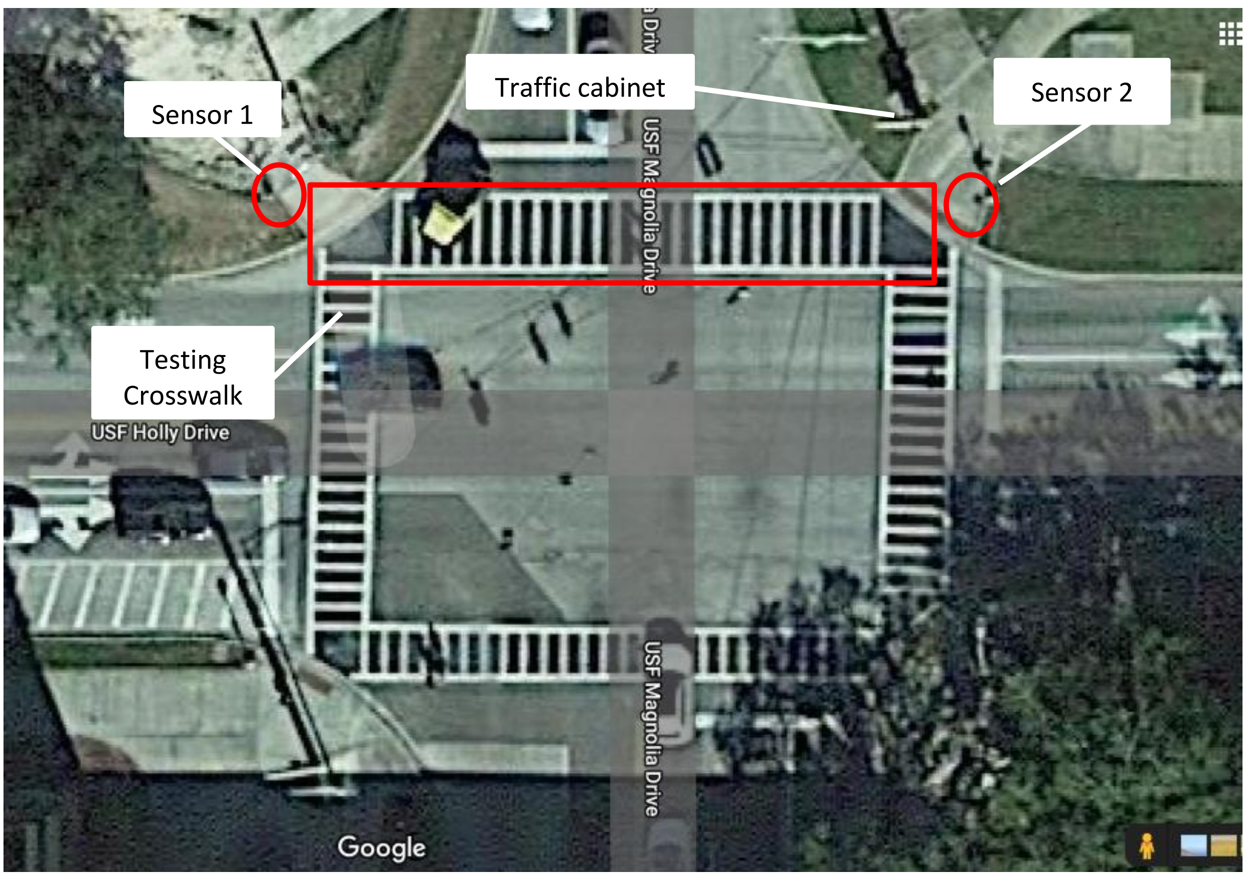


Figure 33. Signalized intersection aerial view

5.4 Design of Test Scenarios of Pedestrian Movements

Based on the field test criteria noted previously and locations of the test sites, test scenarios of pedestrian movements were developed to cover the majority of instances in which a system would need to automatically detect a pedestrian and trigger either warning lights or send a call to the traffic signal controller. The following scenarios were developed for field testing.

5.4.1 Midblock Crosswalk Scenarios

For the midblock crosswalk field test, two kinds of scenarios of pedestrian movements were tested: scenarios 1–5 were desirable scenarios exhibiting the expected movements of pedestrians walking towards the crosswalk and scenarios 6–8 were pedestrians walking out of the crosswalk, having crossed the road. In the second group of scenarios, the system should not detect a pedestrian. Figure 34 shows the desirable scenarios for detection.

- ***Scenarios 1 and 2*** – Pedestrian walks on grass curb and turns to cross on crosswalk. Movement is towards the edge of the detection zone. This behavior would be expected if the pedestrian does not push the button to activate RRFBs unless the pole is very close to the curb.
- ***Scenarios 3 and 4*** – Pedestrian walks on grass curb and turns to cross on crosswalk. Movement path passes towards the center of the detection zone. This behavior is less likely to occur but can still be exhibited if the pole is in the middle of the grassy curb and the pedestrian can push the button while walking along this path.
- ***Scenario 5*** – Pedestrian walks on sidewalk and either turns or directly walks into crosswalk. This is the most expected behavior at this kind of crosswalk. It is important to note that the configurations of midblock crosswalks on Florida roads vary greatly—some have a grassy curb between the road and the sidewalk, and some do not. Some have ADA-compliant ramps; others do not. Regardless of setup, the system should be able to detect pedestrians walking towards the crosswalk with the intention of crossing the road.

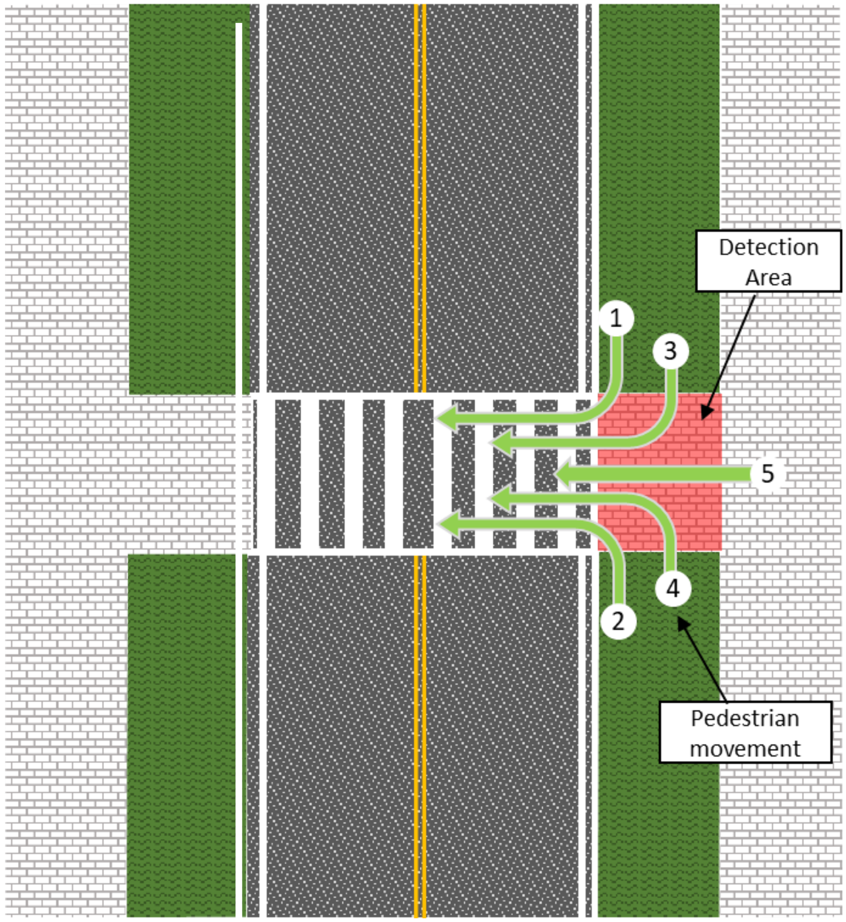


Figure 34. Midblock crosswalk desirable movement scenarios

Figure 35 shows the scenarios (6–10) under which pedestrians should not be detected by an automatic pedestrian detection system.

- ***Scenario 6*** – Pedestrian walks out of crosswalk, having crossed road, towards sidewalk. Path is through detection zone. System should not detect pedestrian under this scenario.
- ***Scenarios 7 and 8*** – Pedestrian walks out of crosswalk but does not pass completely through detection zone; rather, he/she turns out of zone somewhere in middle. This scenario is also possible if there is no grassy curb/shoulder and sidewalk is adjacent to curb.
- ***Scenarios 9 and 10*** – Pedestrian walks inside detection zone but on angle perpendicular to crosswalk without any intention of crossing. This scenario would also occur if there was no grassy curb/shoulder and sidewalk was adjacent to curb.

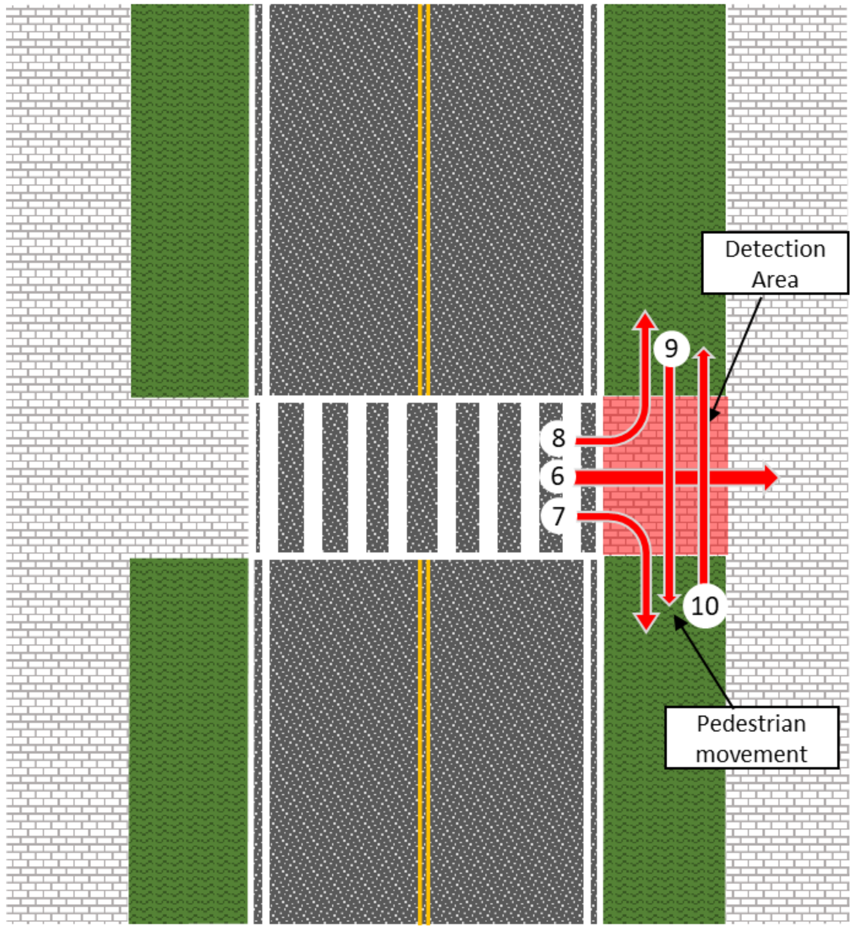


Figure 35. Midblock crosswalk undesirable movement scenarios

5.4.2 Signalized Intersection Scenarios

For signalized intersections, the test scenarios of pedestrian movements are similar to those of the midblock crosswalk. Figure 36 shows the scenarios (1–5) of desirable movements from a pedestrian expected to cross the crosswalk. The difference from the midblock crosswalk is that a pedestrian at a signalized intersection is expected to push the button and then wait for the "Walk" signal. During waiting time, the pedestrian might move around the area in the vicinity of the detection zone or remain still at one location. Regardless of the movement, the system needs to be able to detect the pedestrian when he/she enters the detection zone. The same scenarios would apply to the all crosswalk waiting areas of a signalized intersection.

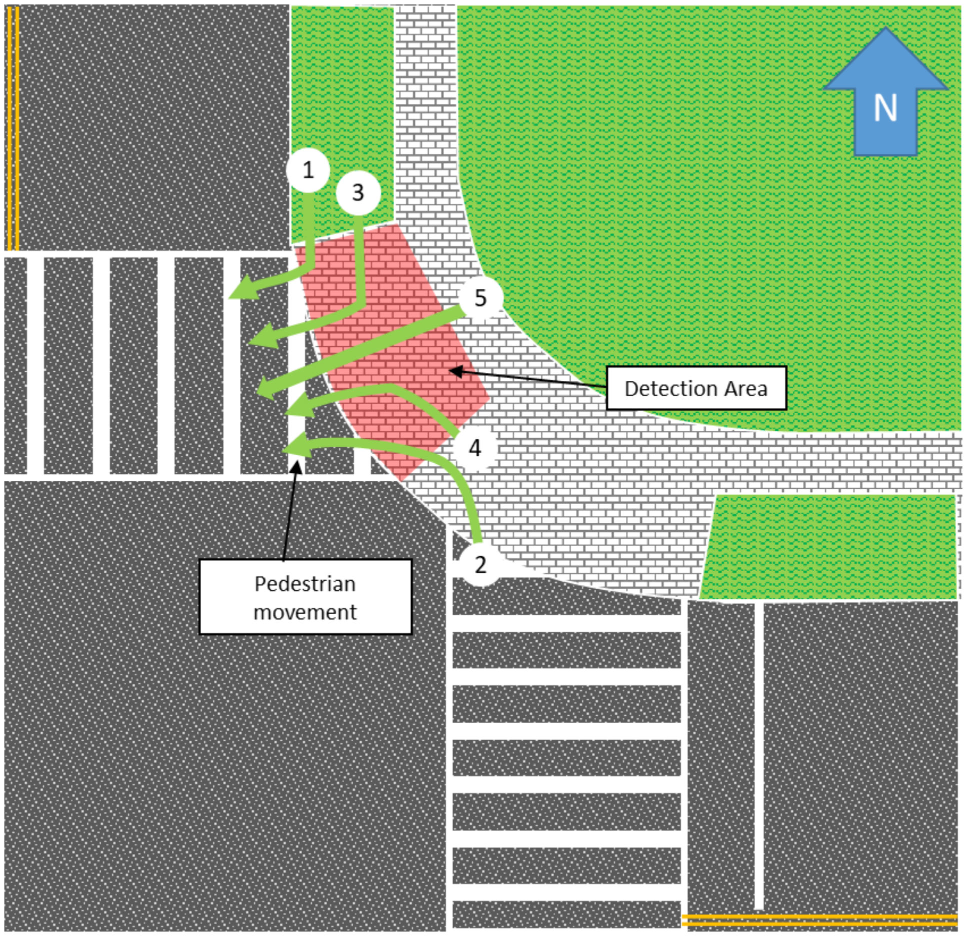


Figure 36. Intersection desirable movement scenarios

Figure 37 shows the scenarios (6–10) in which the movement of the pedestrian should not be detected by the system, as these indicate a pedestrian who has crossed the road and no longer needs to trigger the RRFB or HAWK or place a pedestrian call to the traffic signal controller.

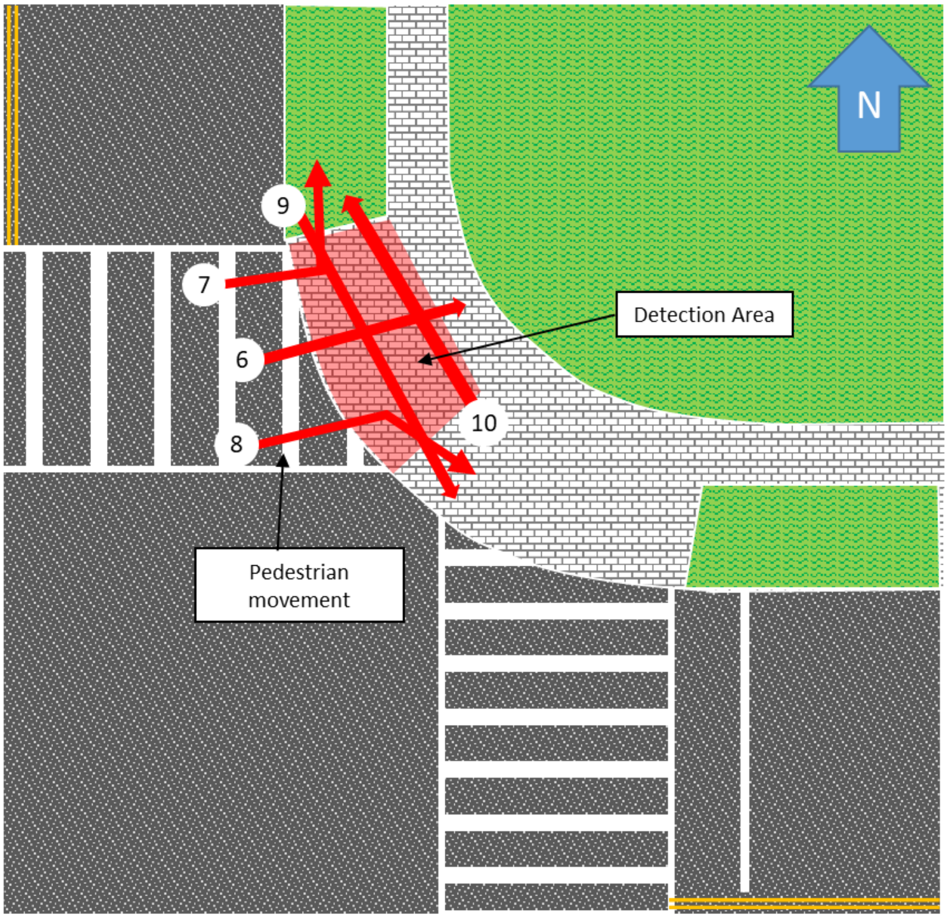


Figure 37. Intersection undesirable movement scenarios

5.5 Installation of Pedestrian Detection System

For the field test in Stage 1, the three systems were concurrently tested at the midblock and intersection locations, as described previously. The systems were installed on a pneumatic telescopic pole that temporarily placed the sensors at the location and at the necessary height to function properly per manufacturer recommendations.

After selection of System 3 as the best-performing system in Stage 1, meeting all criteria for the field deployment, the team conducted field tests in Stage 2 and performed detailed evaluation. In addition to the test site in Tallahassee already deployed by FDOT, CUTR contracted with the System 3 vendor to install the system at the other two sites on the USF Tampa campus and to configure the system to function as outlined in the tests.

5.5.1 Midblock Crosswalk at Suwannee Street, Tallahassee

System 3 was first installed at the midblock crosswalk on Suwannee Street across from the FDOT Burns Building, which had an existing RRFB system. The system was installed parallel to the push buttons; either the system or the push buttons activate the RRFBs. Figure 38 shows the installation of two system sensors on each side of the crosswalk, each powered by the battery and solar panel that power the RRFBs on each side of the road.

Figure 38. Installation of system at midblock crosswalk, Tallahassee

5.5.2 Midblock Crosswalk at USF Alumni Drive, Tampa

A second midblock crosswalk, located on USF Alumni Drive on the USF Tampa campus, was first equipped with RRFBs and, subsequently, with installation of the System 3 pedestrian detection system. Figure 39 shows the installation of the system at the crosswalk. The setup of this midblock location is similar to that in Tallahassee except this location has a grassy shoulder after the curb before the sidewalk, which creates a large ramp towards the crosswalk that can be used as the detection zone.

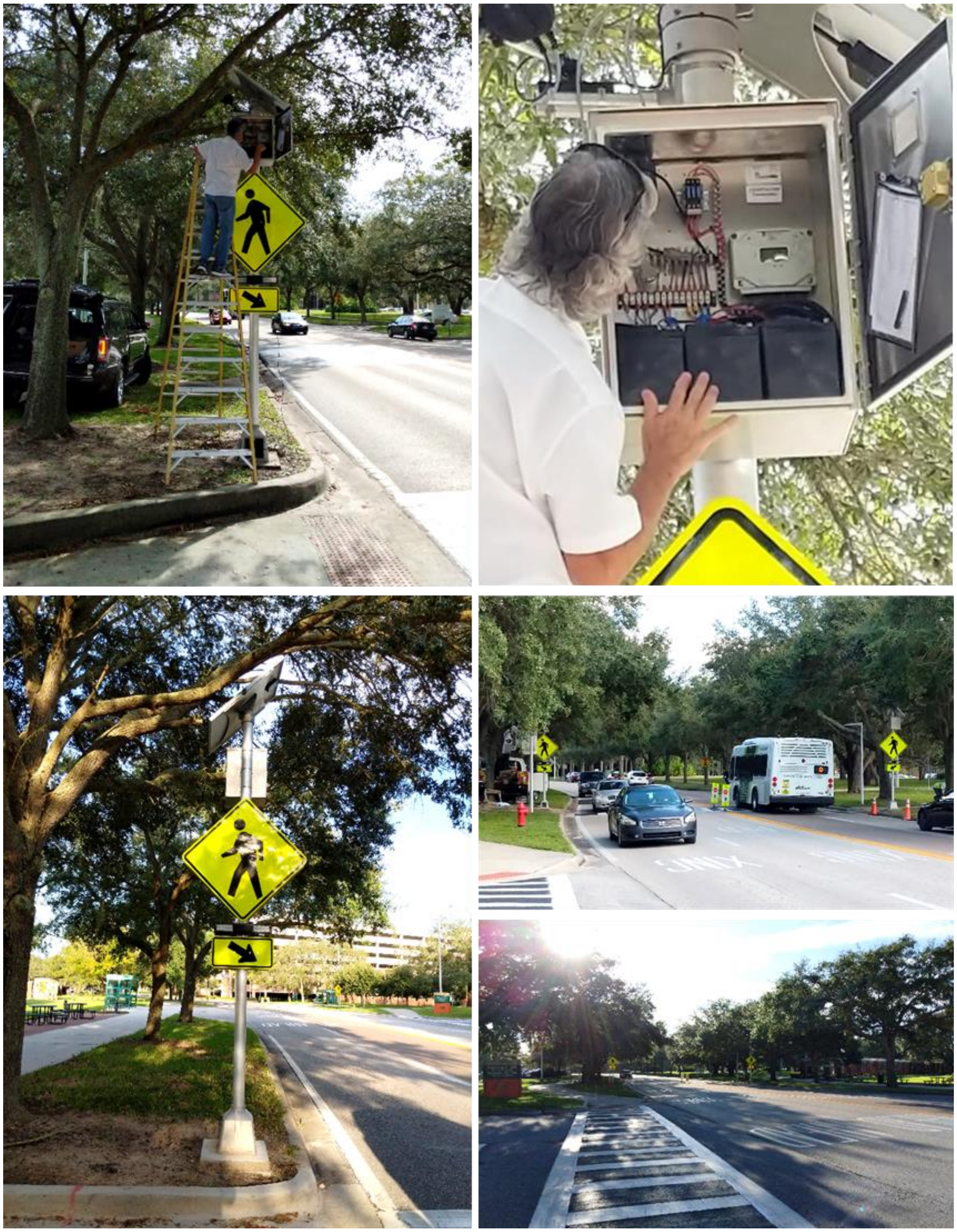


Figure 39. Installation of system at midblock crosswalk in Tampa

5.5.3 Signalized Intersection at USF Magnolia Drive and USF Holly Drive, Tampa

Installation of System 3 at the signalized intersection required two steps. First, it was installed on extension poles attached to pedestrian signal head poles, and the wiring and setup of detection zones was completed. Second, connection of the system's output to the traffic signal controller was completed and programmed by a master technician of the Peek traffic controller manufacturer. Figure 40 shows installation of the system and programming of the controller at the intersection.

Figure 40. Installation of system at signalized intersection, Tampa

5.6 Methodology to Cancel Pedestrian Call

The installation of an automated pedestrian detection system at a signalized intersection has the benefit of not only placing a pedestrian call similar to a push button but also canceling the call if it is no longer needed. On several occasions, pedestrians might arrive at an intersection, push the button for a pedestrian signal, and wait for their call to be served. However, if the pedestrian changes his/her mind or crosses when there is a gap (before the pedestrian "Walk" signal), then the call is no longer needed. Once a call is placed, it cannot be removed from the cycle until it is served. If the pedestrian has already crossed, then the pedestrian call is served unnecessarily, adding frustration and delay to motorists waiting for a green signal.

With an automatic pedestrian detection system, it is possible to program the controller so a call is placed when a pedestrian is detected but removed if he/she is no longer present and before the call is served, resulting in a reduction in delay for unnecessary calls.

CUTR worked with the currently-installed controller manufacturer's master technician to achieve this important feature. Under current National Electrical Manufacturers Association (NEMA) specifications, once a pedestrian call is entered into a cycle (i.e., push button activated), it cannot be removed. The technician used a custom programming script that allowed input from the detection system to enter a pedestrian call as long as the pedestrian was present in the detection zone. Thus, if a pedestrian was detected inside the zone for the duration of the previous phase, then the call was served; if the pedestrian walked out of the zone, then the call was deleted and not served. This script can work in parallel with push buttons and does not render them inoperable. The team used this script to field-test the system at the intersection for both detection and activation/deletion of a pedestrian call.

5.7 Field Data Collection and Analysis for System Comparison

The data collected for the field testing were recorded observations of the public and team members who walked inside the detection zones to trigger the systems. For the first concurrent comparison, the three systems were installed on a temporary basis using a pneumatic pole to collect the necessary data. Video cameras were used to collect the observations in conjunction with the systems' detection output. The videos were then reviewed, and data were compiled into a database for analysis. The data collected are presented in the following sections.

5.7.1 Data Collected at Midblock Crosswalk, Tampa

A summary of data collected at the USF Alumni Drive midblock crosswalk is presented in Table 12. For each system and each scenario, a series of observations was recorded either by observing the public passing by the detection zone or by research team members walking inside the detection zone as pedestrians. Scenarios 1–5 consisted of desirable detection paths (outlined in green), and scenarios 6–10 consisted of undesirable detection paths (outlined in red), as defined previously.

The highest percent of detection rates for scenarios 1–5 and the lowest percent of non-detection rates for scenarios 6–10 are highlighted in green. Detailed observations for the breakdown by pedestrian type (basic, raincoat, umbrella) can be found in the Appendix. A desirable detection system should have high percentages of Detection System Accuracy for scenarios 1–5 and low percentages of False Detections for scenarios 6–10.

The summary results in Table 12 show that System 2 had the highest accurate pedestrian detection rate in two of the first five scenarios and also detected pedestrians at higher rates in scenarios 6–10, in which pedestrians should not be detected. On the other hand, System 3 had the highest Detection System Accuracy in three of first five scenarios and the lowest percent of non-False Detections for scenarios 6–10, in which a pedestrian should not be detected.

Table 12. USF Alumni Drive Midblock Crosswalk Data Collection Summary

Scenario	System	Detection Result		Grand Total	% Detected	% Undetected
		Detected	*Undetected*			
Scenario 1	System 1	34	26	60	57%	43%
	System 2	32	28	60	53%	47%
	System 3	45	15	60	**75%**	25%
Scenario 2	System 1	43	17	60	72%	28%
	System 2	50	10	60	**83%**	17%
	System 3	48	12	60	80%	20%
Scenario 3	System 1	62	10	72	86%	14%
	System 2	63	9	72	88%	13%
	System 3	68	4	72	**94%**	6%
Scenario 4	System 1	65	4	69	94%	6%
	System 2	67	2	69	**97%**	3%
	System 3	56	13	69	81%	19%
Scenario 5	System 1	95	16	111	86%	14%
	System 2	79	32	111	71%	29%
	System 3	106	5	111	**95%**	5%
Scenario 6	System 1	118	20	138	86%	14%
	System 2	92	46	138	67%	33%
	System 3	16	122	138	**12%**	88%
Scenario 7	System 1	107	16	123	87%	13%
	System 2	74	49	123	60%	40%
	System 3	1	122	123	**1%**	99%
Scenario 8	System 1	108	18	126	86%	14%
	System 2	37	89	126	29%	71%
	System 3	0	126	126	**0%**	100%
Scenario 9	System 1	49	14	63	78%	22%
	System 2	33	30	63	52%	48%
	System 3	5	58	63	**8%**	92%
Scenario 10	System 1	43	14	57	75%	25%
	System 2	26	31	57	46%	54%
	System 3	3	54	57	**5%**	95%

5.7.2 Data Collected at Signalized Intersection, Tampa

A summary of data collected at the signalized intersection at USF Holly Drive and USF Myrtle Drive is provided in Table 13. For scenarios 1–5, in which the system should detect a pedestrian for desirable paths, System 3 had the highest percent of Detection System Accuracy in three of the five scenarios; it also had the lowest percent of False Detections for scenarios 6–10, in which the pedestrian path is not desired to be detected by the system. During the intersection test, the team included instances of a pedestrian waiting inside the detection zone similar to what a pedestrian would do when pushing the button and waiting for the pedestrian call to be served.

Table 13. Intersection Data Collection Summary

Scenario	System	Detection Result		Grand Total	% Detected	% Undetected
		Detected	*Undetected*			
Scenario 1	1	50	13	63	**79%**	21%
	2	23	40	63	37%	63%
	3	42	21	63	67%	33%
Scenario 2	1	52	8	60	87%	13%
	2	48	12	60	80%	20%
	3	57	3	60	**95%**	5%
Scenario 3	1	87	45	132	66%	34%
	2	60	72	132	45%	55%
	3	105	27	132	**80%**	20%
Scenario 4	1	65	16	81	**80%**	20%
	2	59	22	81	73%	27%
	3	60	21	81	74%	26%
Scenario 5	1	42	24	66	64%	36%
	2	46	20	66	70%	30%
	3	57	9	66	**86%**	14%
Scenario 6	1	46	17	63	73%	27%
	2	24	39	63	38%	62%
	3	9	54	63	**14%**	86%
Scenario 7	1	122	19	141	87%	13%
	2	103	38	141	73%	27%
	3	12	129	141	**9%**	91%
Scenario 8	1	56	43	99	57%	43%
	2	21	78	99	21%	79%
	3	3	96	99	**3%**	97%
Scenario 9	1	60	15	75	80%	20%
	2	58	17	75	77%	23%
	3	1	74	75	**1%**	99%
Scenario 10	1	30	33	63	48%	52%
	2	46	17	63	73%	27%
	3	0	63	63	**0%**	100%

5.8 Analysis of Concurrent Comparison of Systems

As noted, the first step before actual deployment of the systems was to test their effectiveness in the field and compare them for the basic function of pedestrian detection. The systems were temporarily set up and tested at a midblock crosswalk and a signalized intersection on the USF Tampa campus, as described previously. To achieve a realistic result and a summary of the multiple scenarios tested, an overall Detection System Accuracy and an overall False Detections were computed for each system, based on proper scenario weights considering typical pedestrian wearing and movements at each of these two locations.

5.8.1 Weights for Pedestrian Wearing and Movement Scenarios

Based on observation data and typical pedestrian attire and movement scenarios, weights were assigned for the USF Alumni Drive midblock location, as shown in Table 14.

Table 14. Weights Assigned at USF Alumni Drive Midblock Location

Description	Weight (%)	Desirable Movement	Weight (%)	Undesirable Movement	Weight (%)
Basic Clothing	97%	Scenario 1	5%	Scenario 6	70%
Raincoat	1%	Scenario 2	5%	Scenario 7	10%
Umbrella	2%	Scenario 3	10%	Scenario 8	10%
		Scenario 4	10%	Scenario 9	5%
		Scenario 5	70%	Scenario 10	5%

Similarly, based on the observed proportions of movements, weights were assigned for the Holly Drive and Myrtle Drive intersection on the USF Tampa campus, as shown in Table 15.

Table 15. Scenario Weights Assigned at Holly Drive & Myrtle Drive Signalized Intersection

Description	Weight (%)	Desirable Movement	Weight (%)	Undesirable Movement	Weight (%)
Basic Clothing	97%	Scenario 1	10%	Scenario 6	20%
Raincoat	1%	Scenario 2	10%	Scenario 7	20%
Umbrella	2%	Scenario 3	10%	Scenario 8	20%
		Scenario 4	10%	Scenario 9	20%
		Scenario 5	60%	Scenario 10	20%

5.8.2 Calculation of Detection System Accuracy and False Detections

The computation formula for weighted Detection System Accuracy, based on pedestrian attire and movement for Scenarios 1–5, is shown in Table 16, and the computation formula for weighted False Detections for Scenarios 6–10 is shown in Table 17. For both tables, the individual weighted portion of the detection rate based on pedestrian attire (Column A) was summed and then multiplied by the scenario type weight (Column B). The results of Scenarios

1–5 were summed to calculate the Accurate Detection Rate, and the results of Scenarios 6–10 were summed to calculate False Detections.

Table 16. Computation of Weighted Accurate Detection Rate

A	B
(detection rate of basic X basic weight) + (detection rate of raincoat X raincoat weight) + (detection rate of umbrella X umbrella weight)	} } X scenario 1 weight + }
(detection rate of basic X basic weight) + (detection rate of raincoat X raincoat weight) + (detection rate of umbrella X umbrella weight)	} } X scenario 2 weight + }
(detection rate of basic X basic weight) + (detection rate of raincoat X raincoat weight) + (detection rate of umbrella X umbrella weight)	} } X scenario 3 weight + }
(detection rate of basic X basic weight) + (detection rate of raincoat X raincoat weight) + (detection rate of umbrella X umbrella weight)	} } X scenario 4 weight + }
(detection rate of basic X basic weight) + (detection rate of raincoat X raincoat weight) + (detection rate of umbrella X umbrella weight)	} } X scenario 5 weight }
= Accurate system detection rate	

Table 17. Computation of Weighted False Detections

A	B
(detection rate of basic X basic weight) + (detection rate of raincoat X raincoat weight) + (detection rate of umbrella X umbrella weight)	} } X scenario 6 weight - }
(detection rate of basic X basic weight) + (detection rate of raincoat X raincoat weight) + (detection rate of umbrella X umbrella weight)	} } X scenario 7 weight - }
(detection rate of basic X basic weight) + (detection rate of raincoat X raincoat weight) + (detection rate of umbrella X umbrella weight)	} } X scenario 8 weight - }
(detection rate of basic X basic weight) + (detection rate of raincoat X raincoat weight) + (detection rate of umbrella X umbrella weight)	} } X scenario 9 weight - }
(detection rate of basic X basic weight) + (detection rate of raincoat X raincoat weight) + (detection rate of umbrella X umbrella weight)	} } X scenario 10 weight }
= False system detection rate	

5.8.3 Detection Accuracy Summary

Tables 18 and 19 show the results for Detection System Accuracy and False Detections for each system at the midblock location and the signalized intersection. Among the threes systems, System 3 had the best performance with 95% detection accuracy and only 2% False Detections for the study midblock location. System 3 also has the best performance with 80% Detection System Accuracy and 6% False Detections for the study signalized intersection. Therefore, System 3 was selected to be deployed for the next phase of field testing.

Table 18. Comparison of Detection System Accuracy at Midblock Crossing

Scenario	System	Detected	Not Detected
Scenarios 1–5	System 1	81%	19%
	System 2	68%	32%
	System 3	**95%**	5%
Scenarios 6–10	System 1	73%	27%
	System 2	37%	63%
	System 3	**2%**	98%

Table 19. Comparison of False Detections at Signalized Intersection

Scenario	System	Detected	Not Detected
Scenarios 1–5	1	75%	25%
	2	70%	30%
	3	**80%**	20%
Scenarios 6–10	1	74%	26%
	2	59%	41%
	3	**6%**	94%

5.9 Field Data Collection and Analysis of Deployed System

The best-performing system meeting all criteria was determined at the pre-deployment stage to be System 3, the thermal machine vision system described in Section 6. The system had the highest Detection System Accuracy when pedestrians were moving on desirable paths and the lowest False Detections (or non-detection rate) when pedestrians were moving on undesirable paths that would lead to false positive activation of the RRFB or pedestrian call. This section focuses on the deployment and evaluation of System 3 at the midblock crosswalks in Tallahassee and Tampa and the signalized intersection in Tampa.

5.9.1 Midblock Crosswalk, Tallahassee

During deployment of the system at the midblock crosswalk in front of the FDOT Burns Building in Tallahassee, the system was connected to the RRFB and triggered the beacons when a pedestrian was inside the zone and moving in the desired direction. Table 20 shows the data collected during daytime for the scenarios that follow the same pattern as those presented previously. Data for scenarios 7 and 8 were not collected. Table 21 shows the data collected during nighttime.

Table 20. Data Collected with Deployed System at Midblock Crosswalk, Tallahassee, Daytime

Daytime	Type	Detected	Not Detected	Total	% Detected	% Undetected
Scenarios 1, 2, 3, 4	Basic	38	6	44	**86%**	14%
	Raincoat	40	4	44	**91%**	9%
	Umbrella	35	9	44	**80%**	20%
Scenario 5	Basic	68	7	75	**91%**	9%
	Raincoat	70	5	75	**93%**	7%
	Umbrella	70	5	75	**93%**	7%
Scenario 6	Basic	4	54	58	**7%**	93%
	Raincoat	2	56	58	**3%**	97%
	Umbrella	0	58	58	**0%**	100%
Scenarios 9, 10	Basic	2	91	93	**2%**	98%
	Raincoat	1	92	93	**1%**	99%
	Umbrella	0	93	93	**0%**	100%

Assuming the same weight for each pedestrian movement scenario, the average Detection System Accuracy for System 3 during daytime conditions was 90% based on Scenarios 1–5 and pedestrian attire types. In addition, the False Detections, on average, was only 2% of pedestrians who passed in the detection zone with movements described in scenarios 6, 9, and 10. The result shows that this system has a highly-accurate detection rate when desirable and a low False Detections when undesirable. Improvements can be made for both system setup and installation location to enhance its performance.

Table 21. Data Collected with Deployed System at Midblock Crosswalk, Tallahassee, Nighttime

Nighttime	Type	Detected	Not Detected	Total	% Detected	% Undetected
Scenarios 1, 2, 3, 4	Basic	33	5	38	**87%**	13%
	Raincoat	32	6	38	**84%**	16%
	Umbrella	25	13	38	**66%**	34%
Scenario 5	Basic	40	3	43	**93%**	7%
	Raincoat	39	4	43	**91%**	9%
	Umbrella	32	11	43	**74%**	26%
Scenario 6	Basic	3	114	117	**3%**	97%
	Raincoat	4	113	117	**3%**	97%
	Umbrella	3	114	117	**3%**	97%
Scenarios 9, 10	Basic	2	57	59	**3%**	97%
	Raincoat	3	56	59	**5%**	95%
	Umbrella	1	58	59	**2%**	98%

During nighttime conditions, the system had an average Detection System Accuracy of 83% and an average False Detections of 3%. Of note is low detection rates for pedestrians holding umbrella; this is likely due to the combination of system setup location and angle and pedestrian movements, wherein the system cannot correctly detect pedestrian shapes due to blockage by umbrellas. Figure 41 shows a team member conducting tests at the midblock crosswalk in Tallahassee.

Figure 41. Data collection at midblock crosswalk in Tallahassee

5.9.2 Midblock Crosswalk, Tampa

The system was deployed at the midblock crosswalk on USF Alumni Drive in Tampa. The difference between this crosswalk and that in Tallahassee is that this one has a grassy shoulder after the curb before the sidewalk, which creates a large ramp towards the crosswalk that can be used as the detection zone. The system was connected so that when the direction of movement was towards the crosswalk (scenarios 1–5), it triggered the RRFBs, and when the direction of movement was away from the crosswalk (scenarios 6,9,10), it did not trigger the RRFBs. Data collected for daytime for this location are shown in Table 22. Results show an average of 99% Detection System Accuracy for desirable movement and 0% False Detections for undesirable movement.

Table 22. Data Collected with Deployed System at Midblock Crosswalk, Tampa, Daytime

Daytime	Ped Type	Detected	Not Detected	Total	% Detected	% Undetected
Scenarios 1, 2, 3, 4	Basic	45	1	46	**98%**	2%
	Raincoat	44	2	46	**96%**	4%
	Umbrella	45	1	46	**98%**	2%
Scenario 5	Basic	52	0	52	**100%**	0%
	Raincoat	52	0	52	**100%**	0%
	Umbrella	52	0	52	**100%**	0%
Scenario 6	Basic	0	54	54	**0%**	100%
	Raincoat	0	54	54	**0%**	100%
	Umbrella	0	54	54	**0%**	100%
Scenarios 9, 10	Basic	0	36	36	**0%**	100%
	Raincoat	0	36	36	**0%**	100%
	Umbrella	0	36	36	**0%**	100%

The same data collection occurred during nighttime, with results shown in Table 23. On average, the system had a Detection System Accuracy of 98% based on scenarios 1–5 and 0% False Detections under scenarios 6, 9, and 10. This shows that the system performed very accurately, as expected. Figure 42 shows testing with an umbrella and a wheelchair.

Table 23. Data Collected with Deployed System at Midblock Crosswalk, Tampa, Nighttime

Nighttime	Ped Type	Detected	Not Detected	Total	% Detected	% Undetected
Scenarios 1, 2, 3, 4	Basic	35	2	37	**95%**	5%
	Raincoat	34	3	37	**92%**	8%
	Umbrella	35	2	37	**95%**	5%
Scenario 5	Basic	45	0	45	**100%**	0%
	Raincoat	45	0	45	**100%**	0%
	Umbrella	45	0	45	**100%**	0%
Scenario 6	Basic	0	50	50	**0%**	100%
	Raincoat	0	50	50	**0%**	100%
	Umbrella	0	50	50	**0%**	100%
Scenarios 9, 10	Basic	0	30	30	**0%**	100%
	Raincoat	0	30	30	**0%**	100%
	Umbrella	0	30	30	**0%**	100%

Figure 42. Data collection at midblock crosswalk in Tampa

5.9.3 Signalized Intersection, Tampa

For deployment at the signalized intersection, CUTR worked with USF administrators, the detection system's vendor, and the traffic signal controller manufacturer to install and connect the system as described previously. Data were collected for the north leg crosswalk of the intersection. Figure 43 shows the location of the crosswalk, detection zone, sensor, and pedestrian direction that triggers the system.

The crosswalks in this intersection share waiting areas and ADA ramps, as shown in Figure 43. This is common in smaller intersections where space is limited and the crosswalks terminate at the same location at each corner. This is not an issue for push buttons, as each button that triggers each direction is labeled and pedestrians can select which push button to press depending on their destination. For an automated detection system, however, it becomes a challenge if the waiting location or movement of pedestrians in the same area could be mistaken for the wrong crosswalk. For example, a pedestrian can walk in the detection zone, but instead of wanting to travel westbound, he/she wants to travel southbound. The system can be set up to recognize specific direction and ignore pedestrians intending to cross at the other side. However, it is difficult to get absolutely correct recognition, resulting in some false positives.

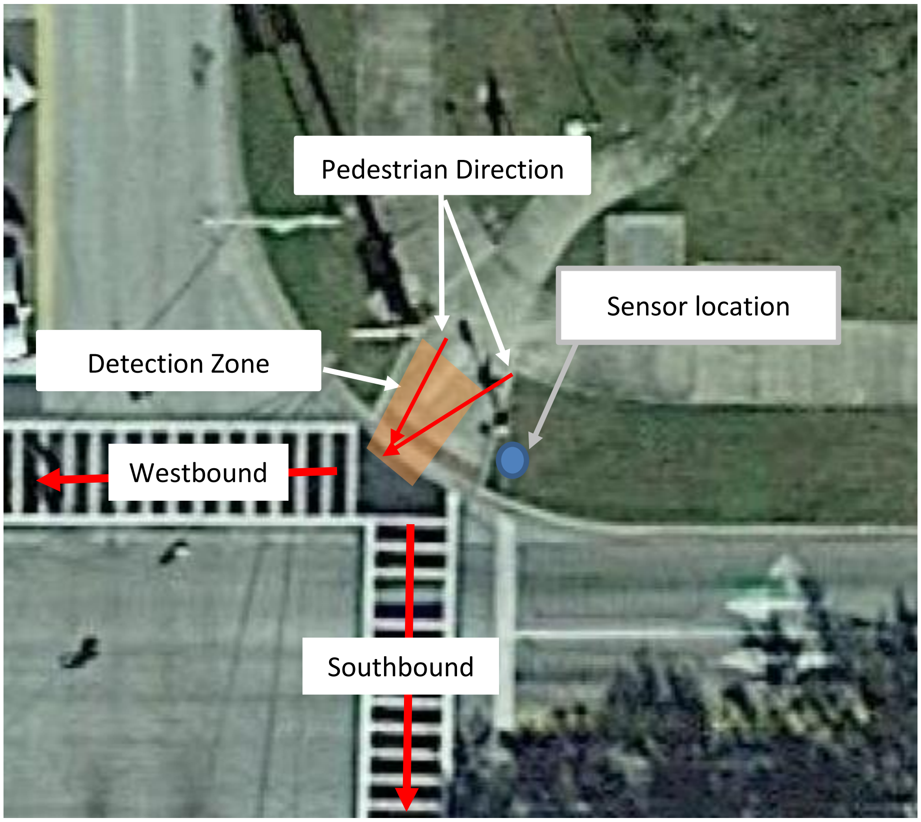


Figure 43. Intersection of USF Magnolia Drive and USF Holly Drive

On the other hand, the system can also ignore or remove a pedestrian call if a pedestrian is no longer present in the detection zone and before the call is served, as described previously.

Data were collected when a pedestrian was present in the detection zone, from the time they arrived until the time the call was served, as shown in Table 24. The data show that the 72 pedestrians present for the entire data collection period were detected 94% of the time and a call was placed and served 90% of the time.

Table 24. Results for Detecting Presence of Pedestrians and Placing Call for Pedestrian Signal at Intersection of USF Magnolia Drive and USF Holly Drive

Detection on Presence of Pedestrians	Call Served		Total
	No	***Yes***	
No	4 (6%)	0 (0%)	4 (6%)
Yes	3 (4%)	65 (90%)	**68 (94%)**
Total	7 (10%)	**65 (90%)**	72 (100%)

Table 25 shows data collected when a pedestrian initially entered the detection zone but left the area before a call should be served. The result indicated that the system was able to detect the disappearance of pedestrians 98% of the time, as they left the detection zone early (crossed on red or in other direction). The system removed or did not place a final call 97% of the time.

This shows the capability of the detection system and the controller with the custom script to administer the removal of a call (or not place a call) when not needed.

Table 25. Result for Detecting Disappearance of Pedestrians and Not Placing Call for Pedestrian Signal at Intersection of USF Magnolia Drive and USF Holly Drive

Detection on Disappearance of Pedestrians	Call Served		Grand Total
	No	*Yes*	
No	1 (2%)	0 (0%)	1 (2%)
Yes	62 (95%)	2 (3%)	**64 (98%)**
Total	**63 (97%)**	2 (3%)	65 (100%)

5.10 Discussion on Field Testing

The three systems tested, including two microwave radar-based systems (Systems 1 and 2) and one thermal machine vision system (System 3), were able to detect pedestrians at different accuracy levels. The vendor for each system was contacted, and setup was confirmed to be accurate. A successful detection system should have a high Detection System Accuracy and low False Detections.

All three systems were able to detect pedestrians to place a call for an RRFB or pedestrian signal, but not all systems were able to have a setting to recognize pedestrians moving in undesirable directions (departure from sensor detection zones) and not place a call; only System 3 was able to do this successfully. The other two systems could detect pedestrians moving in the correct direction to place a call, but could not recognize pedestrians departing from sensor detection zones and not place calls.

In addition, the system must be able to hold the detection while a pedestrian is inside the detection zone, regardless of movement. Only System 3 was able to do this successfully; the other two systems could lose detection while a pedestrian was inside the detection zone, especially if the pedestrian remained relatively still. This is a common occurrence, as pedestrians waiting for a traffic signal often hardly move.

From the observations during testing, System 1 and System 2 exhibited instances in which the detect mode remained activated and did not drop detection when the pedestrian left the zone. When this occurred, the field data collection had to be halted to allow the sensors to reset.

The location, installation, and setup for detection system deployment is very important, as it allows the sensors to be effective towards accurate detection. System 1 and System 2 did not have an exact boundary for their detection. Since their detection depends on microwave transmission, the area is more approximate than in System 3, which provides a clear image via video to be able to set up the zone exactly where it needs to be. System 1 and System 2 can be used at trail crossings, where the path of the incoming pedestrians is simple and accurate. For urban signalized intersections at which pedestrians arrive from all directions and are not necessarily walking on sidewalks, etc., Systems 1 and System 2 could not accurately detect pedestrians to trigger a pedestrian call and remove it if the pedestrian left the sensing area early. Based on the field testing at both midblock and signalized intersection locations, System 3 had the highest Detection System Accuracy and lowest False Detections.

In actual field deployment at the midblock crossing site at FDOT Burns Building, System 3 showed an average 90% Detection System Accuracy and 2% False Detections during the day, and an average 83% Detection System Accuracy and 3% False Detections during nighttime.

In the actual field deployment at the midblock crossing on USF Alumni Drive in Tampa, System 3 showed an average 99% Detection System Accuracy and 0% False Detections during the day, and an average 97% Detection System Accuracy and 0% False Detections during nighttime.

In the actual field deployment at the signalized intersection of USF Magnolia Drive and USF Holly Drive, System 3 showed that it can accurately detect the presence of a pedestrian waiting to cross a street 94% of the time and place a call for a pedestrian signal 90% of the time. The system was also able to detect the disappearance of pedestrians 98% of the time when they left the detection zone early (crossed on red or in other direction). The system was able to remove or did not place a final pedestrian call to the traffic signal controller 97% of the time.

The overall results show that System 3 – thermal machine vision system had the best performance among the three detection systems evaluated and could be applied to both midblock locations and signalized intersections. Several potential improvements and enhancements for System 3 could be made to further increase its accuracy.

6 Major Findings and Observations from a Field Deployment

For the field deployment at the midblock crosswalk locations in Tampa and Tallahassee, the thermal machine vision system produced an overall 92% Detection System Accuracy and only 2% False Detections, as shown in Table 26.

Table 26. Performance of Thermal Machine Vision System at Midblock Deployment Sites

Location	Lighting Condition	Detection System Accuracy	False Detections
Tallahassee	Daytime	90%	2%
	Nighttime	83%	3%
Tampa	Daytime	99%	0%
	Nighttime	98%	0%
Weighted Average		**92%**	**2%**

The deployed thermal machine vision system was able to meet the criteria established by the research team for an automated pedestrian detection system. The following are major findings and observations from the field deployment, which can be used to enhance the thermal machine vision system or other high-quality automatic pedestrian detection system to increase detection accuracy and capability.

6.1 Midblock Crosswalk

The deployed thermal machine vision system was observed to have the following characteristics:

- Can detect pedestrians and slow-moving bicyclists, pedestrians on skateboards, and persons with disabilities (in a wheelchair).
- Can be attached on same pole as RRFBs and pedestrian crossing signs.
- Can detect a pedestrian moving in a specific direction towards a crosswalk and ignore all other directions/movements leaving a crosswalk at midblock locations.
- After detection, can instantaneously trigger RRFBs or other devices, similar to a push button.

The following observations were made during deployment of the thermal machine vision system:

- When the sidewalk is close to a curb without a buffer, the system may exhibit false negatives (i.e., not detect) if a pedestrian does not walk well inside the detection zone. Figure 44 shows the two options encountered on the two midblock crosswalks at which the system was deployed. Figure 44a shows a grassy shoulder/buffer between the sidewalk and the road. The area leading towards the crosswalk most often used as a ramp with ADA-compliant truncated domes can be used as the detection zone for the system, providing a well-established and clear area for detection. Figure 44b shows a sidewalk next to a curb without any buffer between, which is common in urban environments with limited right-of-way. The area that can be used for detection is smaller, and a pedestrian walking on the sidewalk turning into the crosswalk (see Figure 44b) may not be detected in some cases.

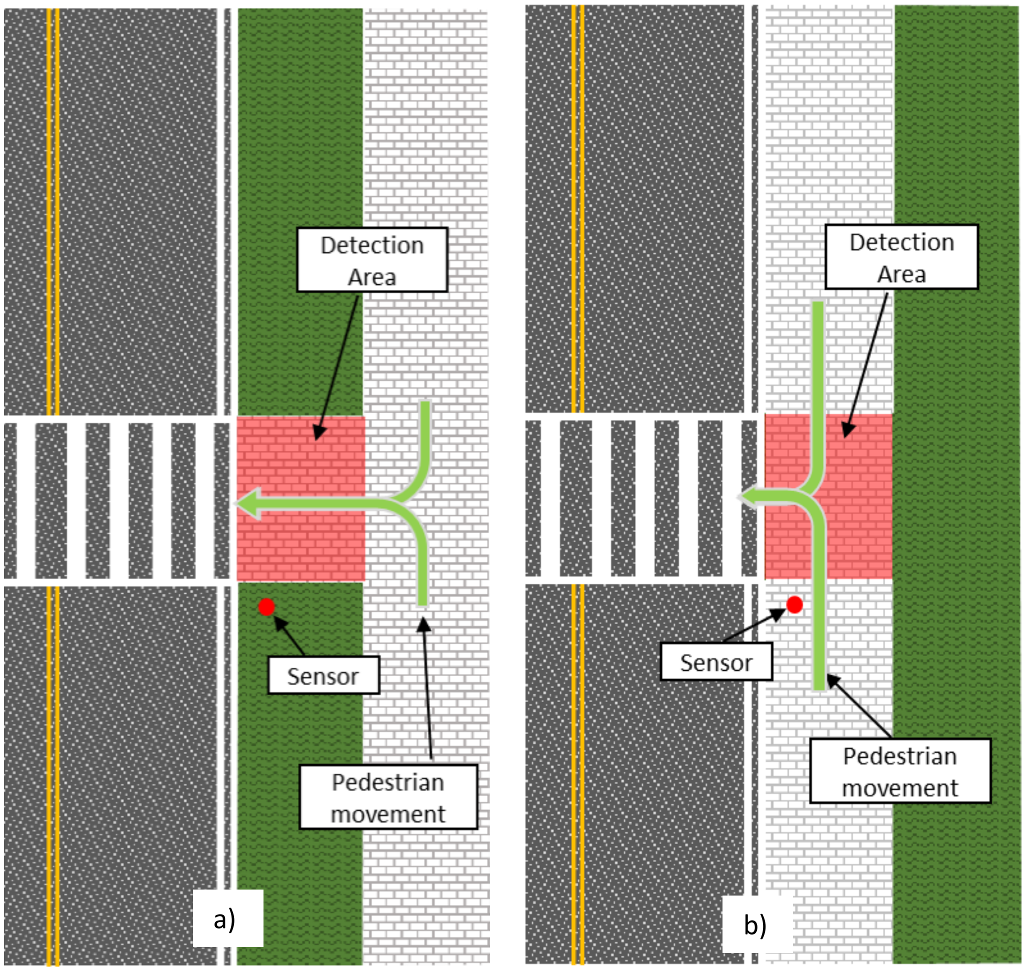


Figure 44. Sidewalk location options

6.2 Signalized Intersection

The selected system was deployed at a signalized intersection on the USF Tampa campus. The system was observed to have the following characteristics:

- Can detect a pedestrian in the desired direction similar to a midblock crosswalk.
- Can provide input to a traffic signal controller to request a pedestrian signal while the pedestrian is in the detection zone (after detection).

- With the connection to the traffic signal controller, can remove a call if the pedestrian walks out of the detection zone before the call is served.

The following observations were made during deployment of the thermal machine vision system:

- At a smaller and urban intersection, the two crosswalks of a corner share the ramp and truncated dome towards the two crosswalks. This creates a difficulty in discerning which crosswalk a pedestrian intends to use, as he/she will walk in the same general area for both crosswalks. Figure 45a shows an intersection where the waiting area and detection zone are separate for northbound and westbound crosswalks. With this configuration, there is no issue in understanding which crosswalk is intended when a pedestrian walks inside each detection zone. Figure 45b shows a different setup, where the area of waiting and detection zone for both crosswalks is shared. In this scenario, when a pedestrian walks into this shared zone, it is not clear where he or she intends to cross. This makes it difficult to use any automated pedestrian detection system.

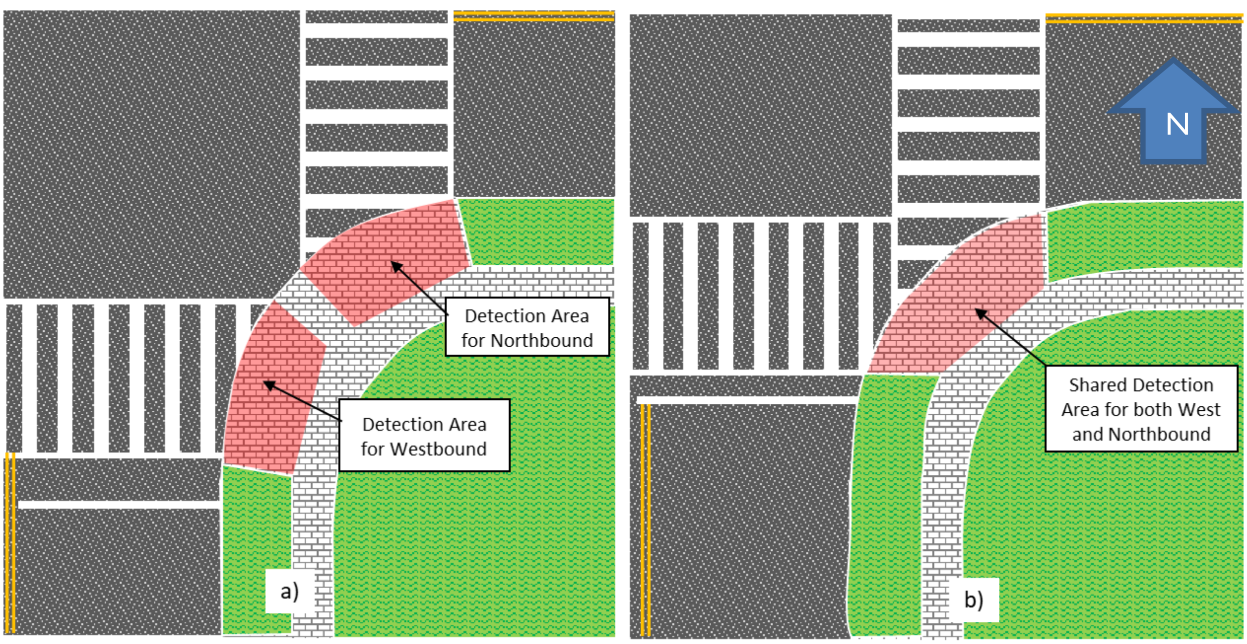


Figure 45. Configurations of detection zone

To overcome this challenge, it is recommended to communicate a detection zone to pedestrians via painting boxes on the ground. Figure 46 shows this concept, where two boxes are drawn in the same area as Figure 45 but clearly instruct pedestrians where to stand to cross at the specific road/crosswalk. This would be similar to the current placards used with instructions at pedestrian push buttons to indicate which button to press for the desired crosswalk. Thus, guesswork would be eliminated, and a clearer understanding of where pedestrians should and should not stand would be communicated for the system to operate as desired.

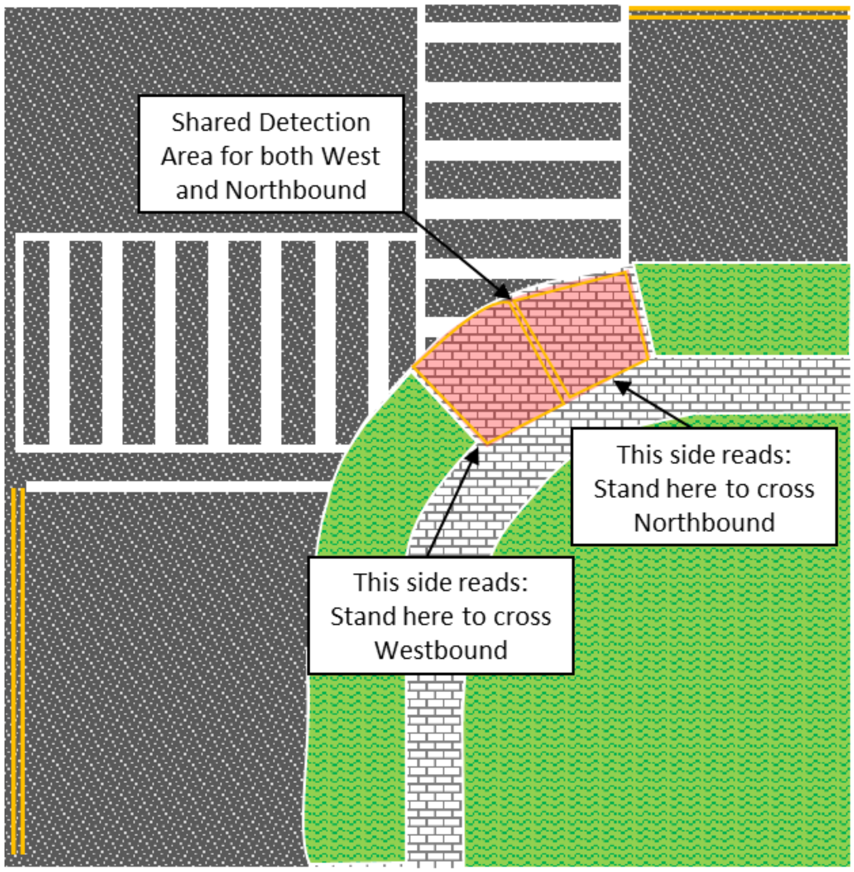


Figure 46. Separation of detection zones

7 System Setup Recommendations

Based on the evaluation results, the thermal machine vision system had the best performance and produced the highest overall Detection System Accuracy of 92% and the lowest False Detections (less than 5%) among the three study systems. Findings indicate that the thermal machine vision system or other similar highly-accurate detection system could be further enhanced and supplemented for the following three components to increase their detection accuracy and capabilities: (1) system installation and setup configuration, (2) detection zone and object movement specifications for system implementations, and (3) use of programming script to place and remove a pedestrian call to a traffic signal controller.

The enhanced automated pedestrian detection system can further increase Detection System Accuracy, reduce False Detections, and ease future deployment of automated pedestrian detection systems at midblock crosswalks or signalized intersections. These three components are presented below.

7.1 System Installation and Setup Configuration

A robust, accurate, and reliable automated pedestrian detection system must be able to achieve and fulfill the following requirements:

- Detect entry of pedestrian and/or bicyclist in its zone (instantaneous)
- Detect presence (constant for a longer time)
- Detect exit of pedestrian and/or bicyclist from its zone
- Specify multiple directional pedestrian and bicyclist movements for detections
- Provide input to traffic signal controller of changing conditions (entry, presence, exit)
- Connect to RRFBs or traffic signal controller via dry contact outputs or TCP/IP network communication
- Work under various lighting and weather conditions

In this study, the thermal machine vision system had highest Accurate Detection Rate and lowest False Detections and was able to accomplish all requirements. It could be used as a final automatic pedestrian detection system, but with some potential refinements and enhancements, its detection accuracy could be increased.

7.1.1 Refinements and Enhancements

Under different testing scenarios at the test sites in this study, CUTR identified areas for improvement and enhancement to increase Detection System Accuracy for the thermal machine vision system or other similar systems. In field tests, the thermal machine vision system had lower Detection System Accuracy for pedestrians holding umbrellas, and, in one test, it had a lower-than-expected Detection System Accuracy for pedestrians wearing basic clothing. These were likely due to blockage by umbrellas and/or the position and angle of the thermal system camera such that the system could not fully or partially recognize the pedestrian features.

Therefore, in the system installation and configuration setup, adequate installation height, detection distance, and position and angle of the thermal camera should be ensured to recognize pedestrian features and detect the presence of pedestrians. If there are no existing poles or infrastructure at the implementation site, a supplemental pole or an extended arm from an existing pole should be considered and installed, as shown in Figure 47.

Figure 47. Use of existing pole or extended arm to properly set up automatic pedestrian system

An accurate pedestrian detection system needs to be able to fully or partially recognize the object features of interest such as pedestrians, bicyclists, pedestrians in wheelchairs, pedestrians wearing raincoats, pedestrians holding umbrellas, and skateboarders under various lighting and weather conditions, as shown in Figure 48. The thermal machine vision system should not be installed vertically above the pedestrian detection zone without larger or acceptable detection angles.

Figure 48. Proper system installation and setup configuration to recognize various pedestrian features

7.2 Detection Zone and Object Movement Specifications for System Deployment

A robust, accurate, and reliable pedestrian detection system for implementation at both midblock and signalized intersection locations should allow users to define adequate detection zones based on the geometrics and layout of the midblock location or signalized intersection. It should allow users to easily visualize and adjust a detection zone as needed; in some cases, several detection zones may be needed.

It is essential to detect the presence of pedestrians and their walking directions to trigger RRFBs at a midblock crosswalk or place a pedestrian signal call at a signalized intersection. Therefore, in each detection zone, the system should allow users to add directional lines or use other methods to specify the area and direction to detect and count people walking.

The thermal machine vision system evaluated in this project was capable of allowing users to clearly define multiple detection zones and add directional lines to specify the area and direction to detect and count people walking, as shown in Figure 49. The system is a mature pedestrian detection system and suitable for implementation at both midblock locations and signalized intersections.

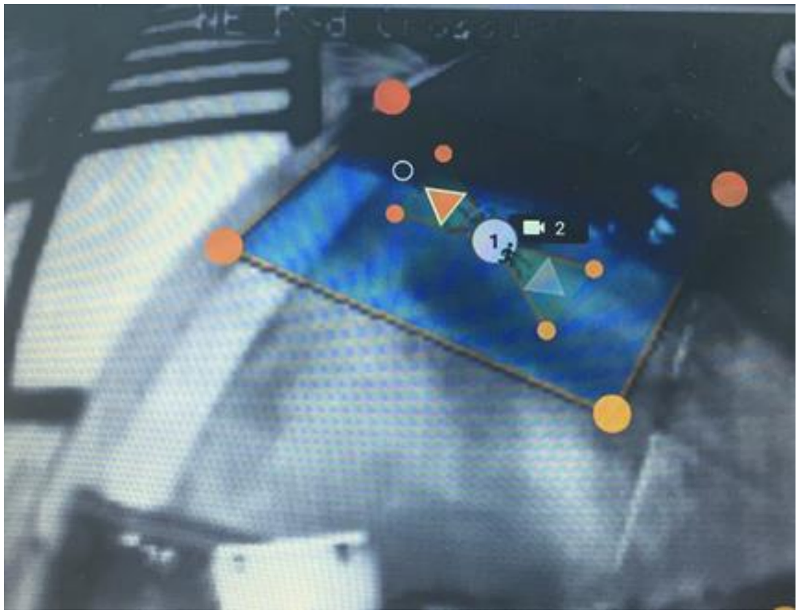


Figure 49. Addition of directional lines to specify area and direction in thermal machine vision system

As noted, at a smaller and urban intersection with two crosswalks at an intersection corner sharing a ramp and truncated dome towards the two crosswalks, difficulty is created in discerning which crosswalk a pedestrian intends to use, as he/she will walk in the same general area for both crosswalks. This is the most difficult intersection layout at which to apply automatic pedestrian detection systems to properly place a pedestrian call to the traffic signal controller. From the deployment experience of the thermal machine vision system at the intersection of USF Magnolia Drive and USF Holly Drive in Tampa, it is recommended to communicate a detection zone to pedestrians via painting boxes on the ground. The automatic pedestrian detection system can add directional lines to specify the area and direction to detect within this specified/painted detection zone to improve detection accuracy.

7.3 Use of Programming Script to Adequately Place Pedestrian Call

It is important that a pedestrian call be placed to a traffic signal controller when at least one pedestrian is present in the detection zone waiting to cross a street. If a pedestrian leaves the detection zone before the last decision point in the signal controller to place a call, the call should be removed if placed already or should not be placed. Under current National Electrical Manufacturers Association (NEMA) specifications, once a pedestrian call is entered into the cycle (i.e., push button activated), it cannot be removed.

To ensure the automatic pedestrian detection system can appropriately place a call to a traffic signal controller, an adequate programming script needs to be developed and integrated into the traffic signal controller that will connect the detection system and the traffic signal controller to allow input of the detection system to enter and hold a call as long as a pedestrian is present in the detection zone.

The CUTR research team successfully used a programming script developed by the manufacturer's master technician for the controller that was installed at the signalized intersection on the USF Tampa campus, as shown in Figure 50. If a pedestrian is still detected inside the detection zone in the last previous phase at an isolated intersection or in the last allowable permissive period for the requested pedestrian call at a coordinated intersection, then a call would be placed and served. If the pedestrian walks out of the detection zone before the decision point, the pedestrian call should be removed if placed already or should not be placed, such that the call would not be served. This script can work in parallel with push buttons and should not render them inoperable.

Thus, to successfully implement or finalize an automatic pedestrian detection system, a programming script should be incorporated into the traffic signal controller to adequately place or remove a pedestrian call when needed.

Figure 50. Integration of programming script into traffic signal controller

8 Conclusions

CUTR successfully tested and evaluated three available pedestrian detection systems on the market that can automatically detect pedestrians and provide necessary input to traffic control devices at both midblock locations and signalized intersections. This research demonstrated that the deployment of a robust integrated automatic pedestrian detection system can effectively solve two key problems on pedestrian safety and vehicle delay. The first problem is that many pedestrians do not push a pedestrian button to cross streets, which could be dangerous. The second problem occurs often at signalized intersections with long cycle lengths in which pedestrians activate pedestrian calls but find gaps and cross streets before the calls are served. It causes unnecessary delay for many vehicles every day. This could frustrate drivers who may think that the intersection's signal timing is not correct, pedestrian push button is stuck, or vehicle detectors on cross streets are malfunctioning. Some drivers may start to ignore pedestrian signal indications.

For the first problem, the best automatic pedestrian detection system among the three systems under evaluation in this research project clearly showed its capability to detect pedestrians and activate the traffic control device automatically without the pedestrians to push a button. This helps increase number of people who do not push the pedestrian buttons to activate traffic control devices. For the second problem, the system successfully demonstrated that it can detect disappearance of pedestrians, and provide inputs to advanced traffic signal controllers to remove pedestrian calls when they are no longer needed.

Based on intensive tests in a controlled environment and subsequently in the field, two microwave radar systems were able to detect pedestrians and provide the necessary inputs for traffic control devices such as traffic signal controllers, RRFBs and Hawks. These systems' detection zones are approximate and can be targeted at the desired area; however, they are not able to maintain detection for a pedestrian who walks into the detection zone and stops or remains idle to wait for the signal. These two systems are suited better for locations with a clear pedestrian movement path, i.e., a trail or a midblock crossing without multiple ways for pedestrians to approach the crosswalk. A third system, a machine vision thermal sensor, was able to accurately detect presence and disappearance of pedestrians at both signalized intersections and midblock locations and, more importantly, to drop detection when a pedestrian is no longer present in the detection zone.

An important contribution of this research project is the work conducted to connect an automatic pedestrian detection system to a traffic signal controller to place a pedestrian call (similar to pressing a push button) when a pedestrian is detected and to remove the call (and not serve it) when the pedestrian walks out of the detection zone prematurely (before the call is served). This was accomplished by working with a custom script provided by a controller manufacturer to place a call when pedestrians were detected and remove it when they were not in the area anymore. This way, vehicle delay will be reduced, as unnecessary pedestrian phases will not be served.

The evaluation results from the field deployment through this research project showed that the thermal machine vision system can produced an overall 92% detection system accuracy at midblock locations, with only 2% false detections. The system was able to detect pedestrians 94% of the time and place a pedestrian service call 90% of the time at a signalized intersection. It was able to detect the disappearance of pedestrians 98% of the time and removed the pedestrian call 97% of the time when they left the detection zone early. This result showed the capability of the automatic detection system and the advanced traffic signal controller with a custom script to administer removal of a pedestrian call when it is not needed. This capability is useful for minimizing unnecessary vehicle delay.

Based on the field observations on system setups and configurations, the CUTR researchers provided recommendations on how to properly set up an automatic pedestrian detection system with public outreach and the use of pavement markings to communicate detection zones to the public for more accurate pedestrian detection results.

This research provided promising evaluation results and built a solid foundation to apply automatic pedestrian detection to further enhance pedestrian safety at signalized intersections and midblock crosswalks, and reduce unnecessary vehicle delay at signalized intersections.

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Appendix

Table 27. Summary of Existing Automated Pedestrian/Bicycle Detection and Counting Technologies

Technology Used	Duration	User Type	Pros	Cons
Laser Scanner	Short or long		• High accuracy • Easy installation • Laser scanners can differentiate according to height information • Larger coverage area	• Different model setup application used to monitor pedestrians and vehicles • More than one scanner plane needs to compensate vehicle pitch motion • More complex in signal processing • Limits detection in severe weather condition
Passive Infrared Sensor	Short or long		• Low cost • Commercially widely available • Not affected by wet or foggy weather • Can be mounted perpendicular to pedestrian movement and can track direction of movement • Multiple sensor arrays can distinguish pedestrians walking in groups	• Single or double sensor counter cannot differentiate between individual or pedestrians in group • Temperature can affect counter performance • Limited coverage area • Tendency to undercount groups or side-by-side travelers • Possible undercounting due to occlusion • Differences between products
Active Infrared Sensor	Short or long		• Portability • Relatively low cost • Easy installation • High accuracy and high precision	• Subject to interference in outdoor settings • Occlusion effects
Microwave Radar Sensors	Long		• Great precision • Insensitive to inclement weather at relatively short ranges encountered in traffic management applications • Direct measurement of speed • Multiple lane operations available	• Continuous wave, Doppler sensors cannot detect stopped vehicles

Table 27. Summary of Existing Automated Pedestrian/Bicycle Detection and Counting Technologies (Cont'd)

Technology Used	Duration	User Type	Pros	Cons
Computer Visioning	Long		• Easy installation • Data verification • Automated process • Ideal for crowded environments • Large coverage area • Potential to count accurately in various conditions (crowded pedestrians, different lighting conditions) • Possible to review to collect pedestrian characteristics • Video can be recorded for manual review	• Most products intended for indoor settings • Development complexity • Non-standard and non-transferable approaches • Malfunctions after installation of equipment • Difficulty of counting pedestrians in crowded settings not yet resolved • Poor weather conditions can affect product performance if device not properly designed
Thermal Imaging	Long		• Easy installation • Bicycle detection can be used to adapt green time for people bicycling • Large detection area • Automatic data extraction • Long durations count at one or more intersections	• Poor weather at night can affect accuracy
Piezoelectric Sensor/Strip	Long		• Easy installation • Minimal maintenance cost • Low power consumption • Capable of counting pedestrians on sidewalks	• Can detect only presence and absence of pedestrian • Not widely used for counting pedestrians outdoors • Need physical contact between pedestrian and pad • Subsurface installation expensive • Limited coverage area
Radio Beam Sensors	Long		• Some devices count bicyclists/ pedestrians separately • Highly portable • Equipment can be hidden easily • More accuracy under proper weather conditions	• Not previously tested in literature • Occlusion errors • Product differences • Temperature, lighting, rain possibly issues results not highly conclusive • False counts possible when bicycles move side-by-side

Table 27. Summary of Existing Automated Pedestrian/Bicycle Detection and Counting Technologies (Cont'd)

Technology Used	Duration	User Type	Pros	Cons
Pressure, Acoustic, or Seismic Sensor	Long		• Highly reliable and accurate • Vandal-proof • Can fit and path width • Certain devices can distinguish pedestrians and bicycles	• Not completely weather-resistant (may be dysfunctional in frozen ground) • Multiple pads needed for wide paths • Installation requires much time
Inductive Loop	Long		• Permanent/temporary installation • High accuracy and precision	• Cannot count pedestrians • Difficulty in detecting some bicycle types (e.g.; carbon material bikes) • Difficult to apply in shared lane environments • Higher volumes slightly affect accuracy • Installation requires pavement cuts • Lessens pavement life due to improper installation • Multiple loops required to monitor location • Installation and maintenance require lane closure
Pneumatic Tubes	Short		• Readily available • Familiar data formats • High accuracy at very high volumes	• Cannot count pedestrians • Safety hazard for some facility users • Accuracy rates not observed to decline with aging tubes
Magnetometer	Long		• Permanent installation • Cost of installation less compared to inductive loops • No need for saw cuts or conduits on pavement • Few models transmit data over wireless radio frequency link	• Bicycles cannot be detected when 4 ft away from detection span • More than one sensor needs to be installed due to less detection range

Table 27. Summary of Existing Automated Pedestrian/Bicycle Detection and Counting Technologies (Cont'd)

Technology Used	Duration	User Type	Pros	Cons
Fiber-optic Pressure Sensors	Long		• EMI/RFI immunity • Noise, crosstalk, and ground loop immunity • Elimination of spark and shock hazards • Useful in explosive environments • Low signal attention for remote measurements • High accuracy, even in harsh environment • Operate continuously at elevated temperature and pressure • Faster dynamic response • Can be used in flammable environments • Optical fibers are chemically inert • High resolution • High dynamic range • Multiplexing capability • Low-temperature sensitivity	• More expensive • Different failure mechanisms and failure modes • Gradual failure over a period • Intrusion of hydrogen into cable leads to failure of physical performance

Table 28. Midblock Detection Results

Scenario 1	System	Detection Result		Grand Total	% Detected	% Undetected
		Detected	Not Detected			
Basic	System 1	16	4	20	80%	20%
	System 2	6	14	20	30%	70%
	System 3	20	0	20	100%	0%
Rain Coat	System 1	3	17	20	15%	85%
	System 2	11	9	20	55%	45%
	System 3	20	0	20	100%	0%
Umbrella	System 1	15	5	20	75%	25%
	System 2	15	5	20	75%	25%
	System 3	5	15	20	25%	75%
Total	System 1	34	26	60	57%	43%
	System 2	32	28	60	53%	47%
	System 3	45	15	60	75%	25%
Scenario 2	**System**	**Detection Result**		**Grand Total**	**% Detected**	**% Undetected**
		Detected	**Not Detected**			
Basic	System 1	19	1	20	95%	5%
	System 2	20	0	20	100%	0%
	System 3	18	2	20	90%	10%
Rain Coat	System 1	4	16	20	20%	80%
	System 2	10	10	20	50%	50%
	System 3	20	0	20	100%	0%
Umbrella	System 1	20	0	20	100%	0%
	System 2	20	0	20	100%	0%
	System 3	10	10	20	50%	50%
Total	System 1	43	17	60	72%	28%
	System 2	50	10	60	83%	17%
	System 3	48	12	60	80%	20%
Scenario 3	**System**	**Detection Result**		**Grand Total**	**% Detected**	**% Undetected**
		Detected	**Not Detected**			
Basic	System 1	22	2	24	92%	8%
	System 2	22	2	24	92%	8%
	System 3	22	2	24	92%	8%
Rain Coat	System 1	20	4	24	83%	17%
	System 2	21	3	24	88%	13%
	System 3	24	0	24	100%	0%
Umbrella	System 1	20	4	24	83%	17%
	System 2	20	4	24	83%	17%
	System 3	22	2	24	92%	8%
Total	System 1	62	10	72	86%	14%
	System 2	63	9	72	88%	13%
	System 3	68	4	72	94%	6%

Table 28. Midblock Detection Results (Cont'd)

Scenario 4	System	Detection Result		Grand Total	% Detected	% Undetected
		Detected	Not Detected			
Basic	System 1	22	1	23	96%	4%
	System 2	23	0	23	100%	0%
	System 3	23	0	23	100%	0%
Rain Coat	System 1	20	3	23	87%	13%
	System 2	21	2	23	91%	9%
	System 3	23	0	23	100%	0%
Umbrella	System 1	23	0	23	100%	0%
	System 2	23	0	23	100%	0%
	System 3	10	13	23	43%	57%
Total	System 1	65	4	69	94%	6%
	System 2	67	2	69	97%	3%
	System 3	56	13	69	81%	19%
Scenario 5	**System**	**Detection Result**		**Grand Total**	**% Detected**	**% Undetected**
		Detected	**Not Detected**			
Basic	System 1	28	9	37	76%	24%
	System 2	22	15	37	59%	41%
	System 3	35	2	37	95%	5%
Rain Coat	System 1	30	7	37	81%	19%
	System 2	28	9	37	76%	24%
	System 3	36	1	37	97%	3%
Umbrella	System 1	37	0	37	100%	0%
	System 2	29	8	37	78%	22%
	System 3	35	2	37	95%	5%
Total	System 1	95	16	111	86%	14%
	System 2	79	32	111	71%	29%
	System 3	106	5	111	95%	5%
Scenario 6	**System**	**Detection Result**		**Grand Total**	**% Detected**	**% Undetected**
		Detected	**Not Detected**			
Basic	System 1	32	14	46	70%	30%
	System 2	14	32	46	30%	70%
	System 3	1	45	46	2%	98%
Rain Coat	System 1	40	6	46	87%	13%
	System 2	38	8	46	83%	17%
	System 3	2	44	46	4%	96%
Umbrella	System 1	46	0	46	100%	0%
	System 2	40	6	46	87%	13%
	System 3	13	33	46	28%	72%
Total	System 1	118	20	138	86%	14%
	System 2	92	46	138	67%	33%
	System 3	16	122	138	12%	88%

Table 28. Midblock Detection Results (Cont'd)

Scenario 7	System	Detection Result		Grand Total	% Detected	% Undetected
		Detected	Not Detected			
Basic	System 1	33	8	41	80%	20%
	System 2	19	22	41	46%	54%
	System 3	0	41	41	0%	100%
Rain Coat	System 1	35	6	41	85%	15%
	System 2	20	21	41	49%	51%
	System 3	0	41	41	0%	100%
Umbrella	System 1	39	2	41	95%	5%
	System 2	35	6	41	85%	15%
	System 3	1	40	41	2%	98%
Total	System 1	107	16	123	87%	13%
	System 2	74	49	123	60%	40%
	System 3	1	122	123	1%	99%
Scenario 8	**System**	**Detection Result**		**Grand Total**	**% Detected**	**% Undetected**
		Detected	**Not Detected**			
Basic	System 1	37	5	42	88%	12%
	System 2	12	30	42	29%	71%
	System 3	0	42	42	0%	100%
Rain Coat	System 1	29	13	42	69%	31%
	System 2	20	22	42	48%	52%
	System 3	0	42	42	0%	100%
Umbrella	System 1	42	0	42	100%	0%
	System 2	5	37	42	12%	88%
	System 3	0	42	42	0%	100%
Total	System 1	108	18	126	86%	14%
	System 2	37	89	126	29%	71%
	System 3	0	126	126	0%	100%
Scenario 9	**System**	**Detection Result**		**Grand Total**	**% Detected**	**% Undetected**
		Detected	**Not Detected**			
Basic	System 1	14	7	21	67%	33%
	System 2	19	2	21	90%	10%
	System 3	0	21	21	0%	100%
Rain Coat	System 1	14	7	21	67%	33%
	System 2	10	11	21	48%	52%
	System 3	0	21	21	0%	100%
Umbrella	System 1	21	0	21	100%	0%
	System 2	4	17	21	19%	81%
	System 3	5	16	21	24%	76%
Total	System 1	49	14	63	78%	22%
	System 2	33	30	63	52%	48%
	System 3	5	58	63	8%	92%

Table 28. Midblock Detection Results (Cont'd)

Scenario 10	System	Detection Result		Grand Total	% Detected	% Undetected
		Detected	Not Detected			
Basic	System 1	12	7	19	63%	37%
	System 2	15	4	19	79%	21%
	System 3	0	19	19	0%	100%
Rain Coat	System 1	12	7	19	63%	37%
	System 2	9	10	19	47%	53%
	System 3	0	19	19	0%	100%
Umbrella	System 1	19	0	19	100%	0%
	System 2	2	17	19	11%	89%
	System 3	3	16	19	16%	84%
Total	System 1	43	14	57	75%	25%
	System 2	26	31	57	46%	54%
	System 3	3	54	57	5%	95%

Table 29. Intersection Detection Results

Scenario 1	System	Detection Result		Grand Total	% Detected	% Undetected
		Detected	Not Detected			
Basic	System 1	14	7	21	67%	33%
	System 2	6	15	21	29%	71%
	System 3	14	7	21	67%	33%
Rain Coat	System 1	21	0	21	100%	0%
	System 2	7	14	21	33%	67%
	System 3	16	5	21	76%	24%
Umbrella	System 1	15	6	21	71%	29%
	System 2	10	11	21	48%	52%
	System 3	12	9	21	57%	43%
Total	System 1	50	13	63	79%	21%
	System 2	23	40	63	37%	63%
	System 3	42	21	63	67%	33%
Scenario 2	**System**	**Detection Result**		**Grand Total**	**% Detected**	**% Undetected**
		Detected	**Not Detected**			
Basic	System 1	20	0	20	100%	0%
	System 2	20	0	20	100%	0%
	System 3	20	0	20	100%	0%
Rain Coat	System 1	14	6	20	70%	30%
	System 2	18	2	20	90%	10%
	System 3	18	2	20	90%	10%
Umbrella	System 1	18	2	20	90%	10%
	System 2	10	10	20	50%	50%
	System 3	19	1	20	95%	5%
Total	System 1	52	8	60	87%	13%
	System 2	48	12	60	80%	20%
	System 3	57	3	60	95%	5%
Scenario 3	**System**	**Detection Result**		**Grand Total**	**% Detected**	**% Undetected**
		Detected	**Not Detected**			
Basic	System 1	30	14	44	68%	32%
	System 2	22	22	44	50%	50%
	System 3	36	8	44	82%	18%
Rain Coat	System 1	28	16	44	64%	36%
	System 2	20	24	44	45%	55%
	System 3	39	5	44	89%	11%
Umbrella	System 1	29	15	44	66%	34%
	System 2	18	26	44	41%	59%
	System 3	30	14	44	68%	32%
Total	System 1	87	45	132	66%	34%
	System 2	60	72	132	45%	55%
	System 3	105	27	132	80%	20%

Table 29. Intersection Detection Results (Cont'd)

Scenario 4	System	Detection Result		Grand Total	% Detected	% Undetected
		Detected	Not Detected			
Basic	System 1	22	5	27	81%	19%
	System 2	23	4	27	85%	15%
	System 3	17	10	27	63%	37%
Rain Coat	System 1	20	7	27	74%	26%
	System 2	21	6	27	78%	22%
	System 3	22	5	27	81%	19%
Umbrella	System 1	23	4	27	85%	15%
	System 2	15	12	27	56%	44%
	System 3	21	6	27	78%	22%
Grand Total	System 1	65	16	81	80%	20%
	System 2	59	22	81	73%	27%
	System 3	60	21	81	74%	26%
Scenario 5	**System**	**Detection Result**		**Grand Total**	**% Detected**	**% Undetected**
		Detected	**Not Detected**			
Basic	System 1	16	6	22	73%	27%
	System 2	16	6	22	73%	27%
	System 3	18	4	22	82%	18%
Rain Coat	System 1	11	11	22	50%	50%
	System 2	15	7	22	68%	32%
	System 3	20	2	22	91%	9%
Umbrella	System 1	15	7	22	68%	32%
	System 2	15	7	22	68%	32%
	System 3	19	3	22	86%	14%
Total	System 1	42	24	66	64%	36%
	System 2	46	20	66	70%	30%
	System 3	57	9	66	86%	14%
Scenario 6	**System**	**Detection Result**		**Grand Total**	**% Detected**	**% Undetected**
		Detected	**Not Detected**			
Basic	System 1	16	5	21	76%	24%
	System 2	8	13	21	38%	62%
	System 3	3	18	21	14%	86%
Rain Coat	System 1	14	7	21	67%	33%
	System 2	9	12	21	43%	57%
	System 3	2	19	21	10%	90%
Umbrella	System 1	16	5	21	76%	24%
	System 2	7	14	21	33%	67%
	System 3	4	17	21	19%	81%
Total	System 1	46	17	63	73%	27%
	System 2	24	39	63	38%	62%
	System 3	9	54	63	14%	86%

Table 29. Intersection Detection Results (Cont'd)

Scenario 7	System	Detection Result		Grand Total	% Detected	% Undetected
		Detected	Not Detected			
Basic	System 1	43	4	47	91%	9%
	System 2	38	9	47	81%	19%
	System 3	5	42	47	11%	89%
Rain Coat	System 1	36	11	47	77%	23%
	System 2	30	17	47	64%	36%
	System 3	4	43	47	9%	91%
Umbrella	System 1	43	4	47	91%	9%
	System 2	35	12	47	74%	26%
	System 3	3	44	47	6%	94%
Total	System 1	122	19	141	87%	13%
	System 2	103	38	141	73%	27%
	System 3	12	129	141	9%	91%
Scenario 8	**System**	**Detection Result**		**Grand Total**	**% Detected**	**% Undetected**
		Detected	**Not Detected**			
Basic	System 1	25	8	33	76%	24%
	System 2	7	26	33	21%	79%
	System 3	2	31	33	6%	94%
Rain Coat	System 1	8	25	33	24%	76%
	System 2	6	27	33	18%	82%
	System 3	1	32	33	3%	97%
Umbrella	System 1	23	10	33	70%	30%
	System 2	8	25	33	24%	76%
	System 3	0	33	33	0%	100%
Total	System 1	56	43	99	57%	43%
	System 2	21	78	99	21%	79%
	System 3	3	96	99	3%	97%
Scenario 9	**System**	**Detection Result**		**Grand Total**	**% Detected**	**% Undetected**
		Detected	**Not Detected**			
Basic	System 1	20	5	25	80%	20%
	System 2	21	4	25	84%	16%
	System 3	0	25	25	0%	100%
Rain Coat	System 1	22	3	25	88%	12%
	System 2	20	5	25	80%	20%
	System 3	1	24	25	4%	96%
Umbrella	System 1	18	7	25	72%	28%
	System 2	17	8	25	68%	32%
	System 3	0	25	25	0%	100%
Total	System 1	60	15	75	80%	20%
	System 2	58	17	75	77%	23%
	System 3	1	74	75	1%	99%

Table 29. Intersection Detection Results (Cont'd)

Scenario 10	System	Detection Result		Grand Total	% Detected	% Undetected
		Detected	Not Detected			
Basic	System 1	11	10	21	52%	48%
	System 2	17	4	21	81%	19%
	System 3	0	21	21	0%	100%
Rain Coat	System 1	10	11	21	48%	52%
	System 2	15	6	21	71%	29%
	System 3	0	21	21	0%	100%
Umbrella	System 1	9	12	21	43%	57%
	System 2	14	7	21	67%	33%
	System 3	0	21	21	0%	100%
Total	System 1	30	33	63	48%	52%
	System 2	46	17	63	73%	27%
	System 3	0	63	63	0%	100%