Pedestrian Test Bed Phase II

Final Report

June 18, 2019

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16. Abstract

Incidents involving pedestrians and bicyclists comprise a large proportion of traffic fatalities every year. These dangerous conflicts tend to occur more frequently under conditions in which the pedestrian is difficult to detect, such as crowded urban settings and under low visibility. The recent surge of connected vehicle technology has led to the development of vehicle-to-pedestrian (V2P) systems that can detect and communicate the presence of at-risk pedestrians or bicyclists through augmented sensors and communication systems. These technologies may therefore be effective in averting incidents between these vulnerable road users and vehicles. This report presents the development and implementation of a multi-functional Pedestrian Technology Test Bed at the FHWA Turner-Fairbank Highway Research Center (TFHRC), along with a standardized, holistic, and flexible assessment plan strategy. These tools were applied to the assessment of commercially available V2P technologies to identify their strengths and weaknesses and reveal their potential effectiveness for improving pedestrian safety. The vision for the test environment is to support continued research, testing, and demonstration of connected pedestrian/bicyclist system concepts, standards, applications, and innovative products aimed to maximize road user safety.

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Pedestrian, bicyclist, vulnerable road user, safety, vehicle-to-pedestrian technology, test bed, connected vehicle, pedestrian detection.

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SI* (MODERN METRIC) CONVERSION FACTORS

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
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	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
		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		
		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")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS AND SYMBOLS

AEB	automatic emergency braking
CCTV	closed-circuit television
CRSS	Crash Report Sampling System
CV	connected vehicle
DOT	department of transportation
DSRC	dedicated short-range communication
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
GES	General Estimates System
NASS	National Automotive Sampling System
NHTSA	National Highway Traffic Safety Administration
OBU	Onboard unit
OEM	Original equipment manufacturer
P2I	pedestrian-to-infrastructure
PCAM	pedestrian crash avoidance/mitigation
PSM	personal safety message
RSU	roadside unit
SPaT	signal phase and timing
TFHRC	Turner-Fairbank Highway Research Center
TTC	time to collision
V2P	vehicle-to-pedestrian
V2V	vehicle-to-vehicle

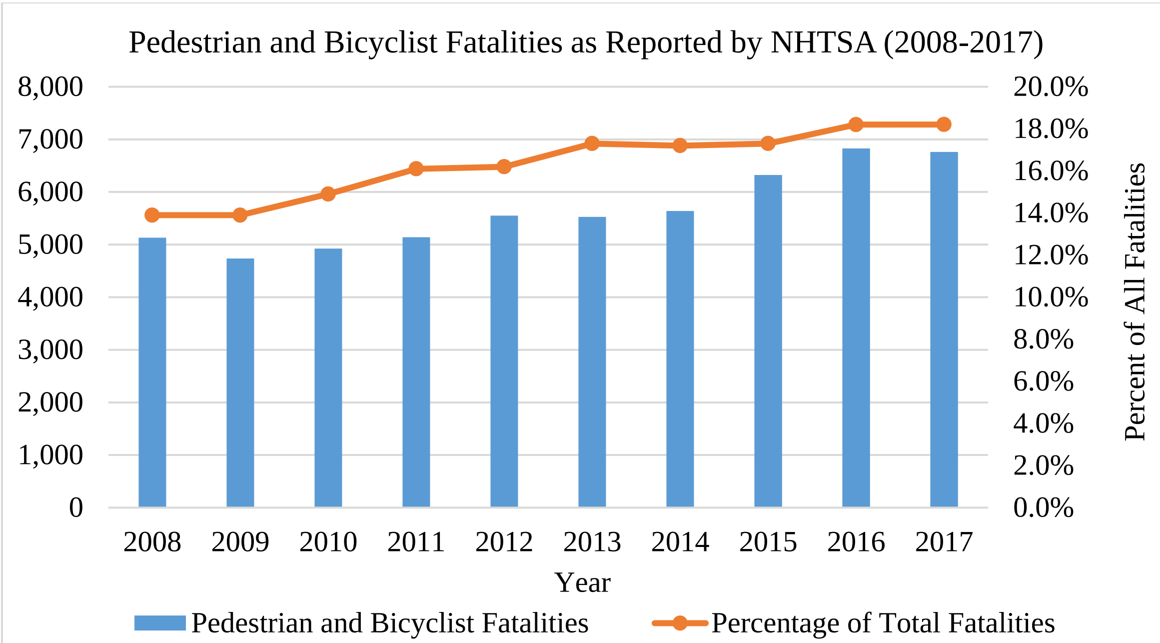
CHAPTER 1. INTRODUCTION

This report is a part of a Federal Highway Administration (FHWA) initiative to improve pedestrian safety by investigating the effectiveness of market-ready pedestrian safety and vehicle-to-pedestrian (V2P) technologies. With that motivation, this research effort included developing a multi-functional Pedestrian Technology Test Bed at the FHWA Turner-Fairbank Highway Research Center (TFHRC) in Mclean, Virginia. The study team acquired and tested multiple commercially available pedestrian safety V2P technologies to identify their real-world effectiveness in improving the safety of pedestrians and bicyclists. It is envisioned that the findings from this report will help to provide insight into both the applicability of V2P communication in the connected vehicle environment and the potential safety effectiveness and limitations of V2P technologies. It will also help guide the development of future V2P systems to maximize road user safety.

Throughout the remainder of this document, the terms “pedestrian” and “V2P” will refer to the broader group of those road users traveling outside of an automobile (unless otherwise specified). In other words, “pedestrian” is inclusive of bicyclists, persons exiting transit, and children in strollers.

BACKGROUND

Pedestrians and bicyclists are referred to as vulnerable road users because of their unprotected state in a mixed traffic environment and their subsequent susceptibility to greater risk of injury during a collision with a vehicle.(1) Recent data from National Highway Traffic Safety Administration (NHTSA) show that, across the United States, pedestrian fatalities have shockingly increased by 31 percent from 2008 to 2017, whereas total traffic fatalities decreased by 0.8 percent over that same period of time.(2,3) In 2017, 5,977 pedestrians and 783 bicyclists died in collisions with highway vehicles, comprising nearly 18 percent of all roadway fatalities. In 2008, pedestrians represented 13.9 percent of total traffic fatalities, and in 2017, that number increased to 18.2 percent, as shown in figure 1.



Source: FHWA.

Figure 1. Graph. Pedestrian fatalities as percentage of all traffic fatalities.(2,3)

These alarming statistics in pedestrian crashes make it necessary to identify potential countermeasures for reducing pedestrian crashes to improve overall road user safety. For the past decade, the United States Department of Transportation (U.S. DOT) Connected Vehicle (CV) Research Program has paid special attention to mitigating such conflicts between vehicles and pedestrians. The V2P component of the CV research program has been designed to address the safety issues of this vulnerable road user. V2P technologies are able to detect pedestrians and alert the vehicle drivers accordingly through visual, audible, or haptic feedback and enable him/her to take remedial action (applying brakes, slowing down, etc.) to prevent a collision.(4) Pedestrian detection systems can be implemented in vehicles, in the infrastructure, or through pedestrian-operated nomadic devices (i.e., a handheld wireless device such as a personal data assistant or smartphone) to provide warnings to drivers. V2P technologies show the potential to provide more opportunities to connect pedestrians, vehicles, and other road users through discrete personal safety messages, potentially reducing the number of vehicle-pedestrian incidences in a way that existing technologies are unable to provide.

Given that V2P technologies are relatively new and not yet widespread, it is necessary to document the ways in which their success (or lack thereof) can be objectively measured. It is important to be able to assess the effectiveness of V2P technologies during both the testing and implementation phases. U.S. DOT has undertaken efforts to develop a Pedestrian Technology Test Bed at the TFHRC in McLean, Virginia, to test available technologies for market readiness and real-world implementation. The vision for the test environment is to support continued research, testing, and demonstration of connected pedestrian/bicyclist system concepts, standards, applications, and innovative products.

PROJECT GOALS

The objective of this research can be summarized as follows:

- Develop a standardized and flexible assessment plan strategy and establish a robust Pedestrian Technology Test Bed at TFHRC in McLean, Virginia.
- Acquire and assess a variety of market-ready V2P systems and document their effectiveness.
- Communicate the potential value of the Pedestrian Technology Test Bed and assessment plan for evaluating the safety effectiveness of market-ready V2P technologies, as well as associated research findings, to stakeholders.

PRIOR RESEARCH

This research effort is a continuation of U.S. DOT V2P research initiatives to improve pedestrian safety, as described below. The foundational research leading to the development of the Pedestrian Technology Test Bed consists of efforts previously conducted in earlier research efforts under this project, including a technology scan, focus groups, a needs assessment, and a research implementation plan.[(4)] Based on this research, an assessment plan was developed under Phase I of this project, which led to the establishment of the Pedestrian Technology Test Bed and implementation of the assessment plan using market-ready V2P technologies under Phase II. The tasks previously performed under this effort include:

- Technology Scan and Literature Review: The literature review and technology scan resulted in a summary of pedestrian and bicycle crash characteristics and identified 86 technologies that directly or indirectly relate to the development or implementation of V2P technologies.
- Focus Groups: The completion of two interdisciplinary focus groups informed the development of the Needs Assessment document. The focus groups' participants included leading V2P stakeholders, automotive professionals, consumer electronics developers, pedestrian safety experts, human factors specialists, and others. Group discussions led to the identification of research needs and areas of ambiguity regarding how to address uncertain and uncommon conflict situations.
- Needs Assessment: The needs assessment combined results from the technology scan, literature review, and focus groups to identify gaps in knowledge related to V2P safety applications.
- Research Implementation Plan: The plan described the near-term research activities that USDOT could undertake to address V2P safety issues. These potential near-term research activities were developed through a series of incremental steps that identified current gaps in knowledge and technology as they relate to V2P communications among safety applications.

- Vehicle to Pedestrian (V2P) Test Bed Phase I –Developed the context and initial set up for establishing the Pedestrian Technology Test Bed. An assessment plan was also developed under Phase I to test the market ready V2P technologies under Phase II.

V2P TECHNOLOGIES

V2P technologies are an emerging type of technology intended to detect pedestrians using external sensors and communicate that information to other road users, particularly drivers, and the infrastructure to avoid crashes. Some systems are also capable of intervening to prevent the crashes if the driver fails to respond adequately. Thus, V2P technologies can create integrated smart community solutions for improved road user safety and mobility.

Communication Strategies

V2P technologies can provide notifications to the drivers, pedestrians, or both in variety of ways through external sensors and communication devices. The Phase I V2P Technology Scan and Literature Review identified three major communication strategies between vehicles and pedestrians (and bicyclists), as listed below:[(4)]

- *Bilateral detection and notification Systems*: Technologies which provide collision alerts to both drivers and pedestrians in parallel.
    - Bilateral detection and notification systems are based on a multi-way communication between all relevant road users. In this case, pedestrians and drivers mutually detect and notify one another if there is a potential collision situation. Bilateral systems use wireless detection and notification methods including technologies such as dedicated wireless communication, Wi-Fi, GPS tracking, or any combination thereof. These wireless systems are extremely versatile and work very well in real-time. They typically work in all environmental and light conditions and function well at a variety of vehicle speeds. They can also detect pedestrians or bicyclists that are hidden from view due to roadway alignment, roadside obstacles, or other sight obstructions.

- *Unilateral pedestrian detection and driver notification systems:* Detect pedestrians and alert drivers through the vehicle or infrastructure. In cases, some technologies are also capable of intervening to prevent the crashes if the driver fails to respond adequately. These systems frequently use video detection systems or radar scanners.
    - Unilateral pedestrian detection and driver notification systems (hereafter referred to as driver notification systems) alert drivers to potential collisions with pedestrians. The systems commonly utilize cameras, motion sensors, infrastructure sensors, and laser scanning to detect the pedestrians and in some cases the systems employ collision avoidance protocols if a collision is imminent. Driver notification systems are the most common type of developmentally researched and commercially available V2P-related technology. The database

contains a wide array of systems that are in various stages of development ranging from being in the research and development stage to being commercially available and pre-installed in new vehicles. Additionally, several systems have been specifically designed to service specialty vehicles such as transit buses and heavy-duty trucks.

- *Unilateral vehicle detection and pedestrian notification systems:* Detect vehicles and notify a pedestrian when they are about to be in a dangerous situation using hand-held devices or infrastructure. Typically, these systems operate through a user's mobile phone.
    - Similar to driver notification systems, pedestrian notification systems alert pedestrians to potential collisions with vehicles on the roadway. Most of these systems have been developed using smartphone technologies, including mobile phone cameras, GPS capabilities, and motion sensors. Many of the technologies specialize in promoting pedestrian and bicyclist safety, especially for special user groups, and have the potential to be expanded to include vehicle detection.

Communication Technologies

V2P technologies use a variety of sensors to detect pedestrians in roadway environments. Pedestrian notification alerts are also communicated to the driver in different ways including visual interfaces, audible tones, haptic feedback, or a combination of these. Research of different V2P systems identified the following systems for detecting and notifying pedestrians:

- Direct wireless communications;
- Optical camera-based image processing;
- Infrared sensors;
- Infrastructure-based sensors;
- Laser-based sensors;
- Mobile phone networks;
- Motion sensors.

The V2P Technology Scan and Literature Review document(4) summarized different types of V2P technologies, including information on the author/manufacturer, major technologies for pedestrian detection, notification method, estimated time to marketability, and several other important factors.(5) Research revealed that direct wireless communication is the favored method of wireless vehicle-to-vehicle (V2V) communication due to its extremely low latency in message transmission. The travel information that can be securely transmitted to other enabled devices (i.e., vehicles, infrastructure, and handheld pedestrian devices) through this wireless communication includes, but is not limited to: GPS, position, speed, acceleration, heading, path history, path prediction, transmission state, brake status, and steering wheel angle. Other technologies, such as hand-held devices or wearable technology that use cellular network to update a user's location on a regular basis, provide potential in improving pedestrian safety.

However, these systems require a network connection and are often subject to data transmission charges. Beyond this, since participation in these systems is voluntary, they will only provide safety benefits for users who actually use the systems. The device will not prevent any crashes with pedestrians or road users who opt out of the system, nor will they optimally prevent crashes in which only one of the potential crash subjects utilizes the V2P technology.

V2P Technologies and Crash Factors

V2P technologies show the potential for mitigating pedestrian crash factors that traditional countermeasures are not able to mitigate. The timely detection of pedestrians in the roadway environment and communication of that information to the driver and infrastructure is critical to avoiding crashes. V2P technologies use various communication technologies and strategies, as listed above, to communicate that information between pedestrians, vehicles, and infrastructure. In some cases, V2P technologies can also intervene to prevent the crashes if the drivers fail to respond timely through pedestrian crash avoidance/mitigation (PCAM) systems. PCAM systems are vehicle-based, forward-looking pedestrian detection systems that alert drivers of potential vehicle-pedestrian crashes and/or apply automatic emergency braking (AEB) to prevent potential vehicle-pedestrian crashes.[(6)]

Since V2P technologies use various communication strategies and technologies, it is important to understand their applicability and suitability in different crash scenarios. The knowledge and understanding of the crash factors are important to form a framework to assess the safety effectiveness of V2P systems. It will also help to identify the gaps and limitations of existing V2P technologies that consumers are using for pedestrian detection and crash avoidance and the areas for improving their capabilities for pedestrian safety. NHTSA's annual fact sheet on pedestrian crashes are great source for reviewing the crash factors. [(2)] NHTSA published another report summarizing pedestrian crash factors and defining ways to connect these crash factors with V2P technology crash avoidance features.[(6)] This report presented results based on an average estimate of yearly crashes for a two-year period from the 2011 and 2012 datasets found in the National Automotive Sampling System (NASS), General Estimates System (GES; replaced by Crash Report Sampling System; CRSS), and Fatality Analysis Reporting System (FARS). These years were chosen because the FARS and GES have a consistent set of data elements post 2011.[(6)] Pedestrian crash factors were reviewed using NHTSA Pedestrian Traffic Safety Fact sheet and NHTSA report.

Pedestrian crash factors can be summarized into the following categories:

- *Environmental conditions*: Includes weather, lighting, and road surface condition. Poor visibility is one of the greatest contributing factors towards pedestrian fatalities. In 2017, 75 percent of the pedestrian fatalities occurred in the dark.[(2)] Wet or dry road surface condition also contributed to crashes by affecting the vehicle's traction at the time of the crash. The NHTSA report indicated that 77 percent of all pedestrian crashes and 88 percent of fatal crashes occurred on dry roads, as reported from GES and FARS 2011 and 2012 annual pedestrian crash average data.(6)

- *Infrastructure:* Includes road geometry, grade, crowded urban settings, and traffic control. In 2017, the majority (80 percent) of pedestrian fatalities occurred in urban settings.(2) Road curvature and grades also contributed to pedestrian fatalities. Thirteen percent of fatal crashes happened on graded roads, whereas five percent of fatal crashes happened on curved roads in 2016.(6)
- *Crash locations*: The majority of pedestrian fatalities in 2017 (91 percent) occurred on roadways and non-intersections compared to roadsides/shoulders, parking lanes/zones, bicycle lanes, sidewalks, medians/crossing islands, driveway accesses, shared-use paths/trails, non-traffic way areas, and other sites (9 percent).(2)
- *Vehicle type and impact point:* The majority (91 percent) of fatal vehicle-pedestrian crashes in 2017 involved single passenger automobiles (including sedans, pickup trucks, and vans).(2) This is not surprising given their dominance in the current passenger vehicle fleet on the road. Also, the majority of fatalities in 2017 occurred when directly struck by the front of the vehicles, rather than the side or rear.(2)
- *Alcohol*: Alcohol plays a major role in pedestrian fatalities. In 2017, alcohol involvement for the driver and/or the pedestrian were reported in 47 percent of all pedestrian fatalities.(2) Enhanced alerts to both drivers and pedestrian will be beneficial to avoid such crashes. Also, system’s automatic braking/steering could be useful if the driver fails to respond adequately due to being intoxicated.(6)
- *Pedestrian movement/predictability:* Improper pedestrian travel on roads, such as darting or dashing into the roadway, contribute to pedestrian fatalities. NHTSA report indicated that 17 percent of fatal crashes occurred when a pedestrian darted or dashed into the road, as reported by the GES and FARS 2011 and 2012 annual pedestrian crash average data.(6)

These crash scenarios emphasize the need for V2P technologies to reduce crashes between vehicles and pedestrians. With timely detection of a pedestrian located in the vehicle’s traverse path, the single vehicle collision can be avoided. Vehicle PCAM systems could also be very beneficial when drivers have very little time to react during dart/dash situations.(6)

Research on the pedestrian crash factors also identified different crash scenarios that are inclusive of the majority of pedestrian-vehicle collision fatalities.(1) These crash scenarios were also identified in the NHTSA report as basic pre-crash scenarios leading to pedestrian crashes.(6) These crash scenarios were considered as the test cases in the assessment plan, which are described in following chapter.

A summary of the potential for different V2P technologies to improve pedestrian safety in different pre-crash scenarios is provided at the end of this report, as informed by the assessment performed at the Test Bed.

ORGANIZATION

This report is organized into the following four chapters:

- Chapter 1 provides the background and context for the document and an overview of V2P technologies.
- Chapter 2 describes the assessment plan and FHWA Pedestrian Technology Test Bed developed to evaluate the safety effectiveness of V2P technologies.
- Chapter 3 provides an overview of V2P technology assessment using the assessment plan and Pedestrian Technology Test Bed.
- Chapter 4 discusses the overall findings and logical steps moving forward.

CHAPTER 2. ASSESSMENT APPROACH

In order to identify the effectiveness and applicability of different V2P systems to improve pedestrian safety, they need be tested in a real-world environment. With that motivation, this project established a Pedestrian Technology Test Bed and developed a versatile assessment plan to evaluate the safety effectiveness of the market-ready V2P technologies and document their strengths and limitations. The assessment approach includes eligibility criteria for selecting a V2P system for testing, the test cases under which the system will be evaluated, and the performance criteria for evaluating those systems. This assessment approach was developed under Phase I of the Pedestrian Technology Test Bed project (DTFH61-12-D-00020, Task Order-0024).

ELIGIBILITY CRITERIA

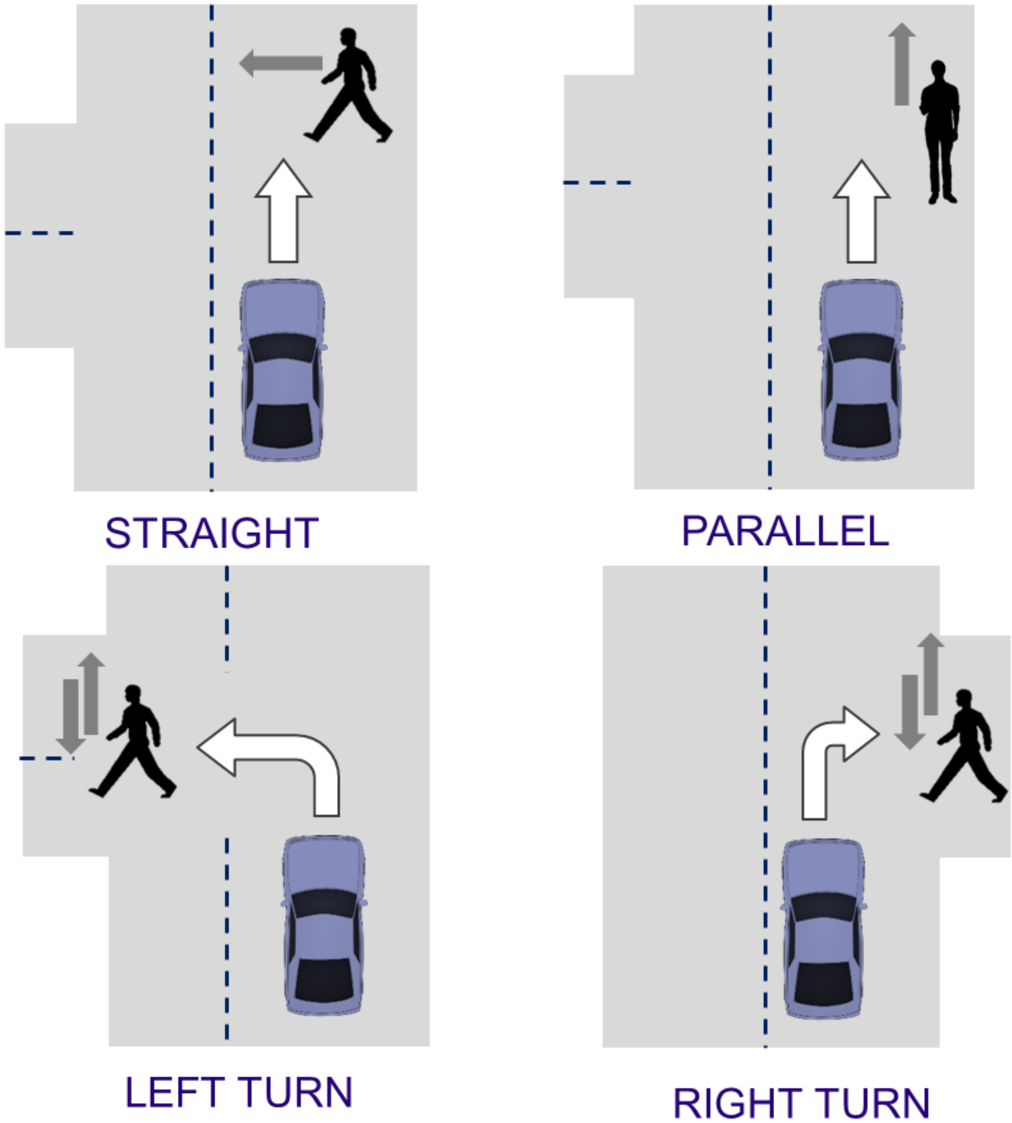
The assessment plan was developed to be flexible while also targeting key system functionalities of the V2P system being tested to identify potential safety benefits. The following criteria were set forth for the selection of systems to be tested:[(4)]

1. Each system must be able to perform in at least 1 of the test cases (outlined below) using the testbed and equipment provided.
2. The system must provide some measurable communication output. The output can be sent to a pedestrian/cyclist or a driver/vehicle. That communication can take the form of an alert, an intervention, a status state, etc.
3. The system must function within the environment provided. If equipment is not provided by FHWA that will enable the V2P technology function properly, then supplemental equipment must be provided by the manufacturer.
4. Proper installation of the system must be validated.

TEST CASES

The four test cases, in which most of pedestrian-vehicle collision fatalities occur, were defined as follows.

1. A vehicle is traveling straight, on a straight road, and a pedestrian/cyclist makes a perpendicular crossing.
2. A vehicle attempts a right turn at an intersection while a pedestrian/cyclist attempts a straight path roadway crossing.
3. A vehicle attempts a left turn at an intersection while a pedestrian/cyclist attempts a straight path roadway crossing.
4. A vehicle is traveling straight, on a straight road, and a pedestrian/cyclist is traveling straight along the roadway.



Source: FHWA.

Figure 2. Illustrations. Four test cases common to vehicle-pedestrian collisions.(6)

PERFORMANCE MEASURES

The assessment approach produced in Phase I[4] also includes holistic and broad performance measures to evaluate the effectiveness of a V2P system (table 1). These measures were selected to provide a broader guideline on the system's efficacy, rather than measure the success or failure of a system. Also, these performance measures must be specifically tailored for each V2P system to properly capture its functionality.

Table 1. Performance measures described in Phase I.[(4)]

Measure	Questions	units
Accuracy of detection	When does the alert sound?	ft (distance to ped)
	When is there a visual warning?	ft (distance to ped)
	When does the vehicle intervention (e.g., braking) take place?	ft (distance to ped)
	Time to collision (TTC) at response	distance/travel speed
Reliability of detection		response over trials
User interface and notification quality	Is the alert clear	yes/no
	Is the system overtaking clear	yes/no
Response selection	E.g., volume	dB
	Luminance	Lux
	Rate (of beep and/or flash)	Hz
User access to technology	On the market, may be cost prohibitive. But access is available	description
Readiness	(on the market now, so full readiness)	description
Institutional and infrastructure requirements		description
Known non-functional situations		description
Additional discovered non-functionality		description
Additional subjective measures like ease of use, interpretability of warning, etc.	i.e., a human factors interface assessment	human factors response assessment

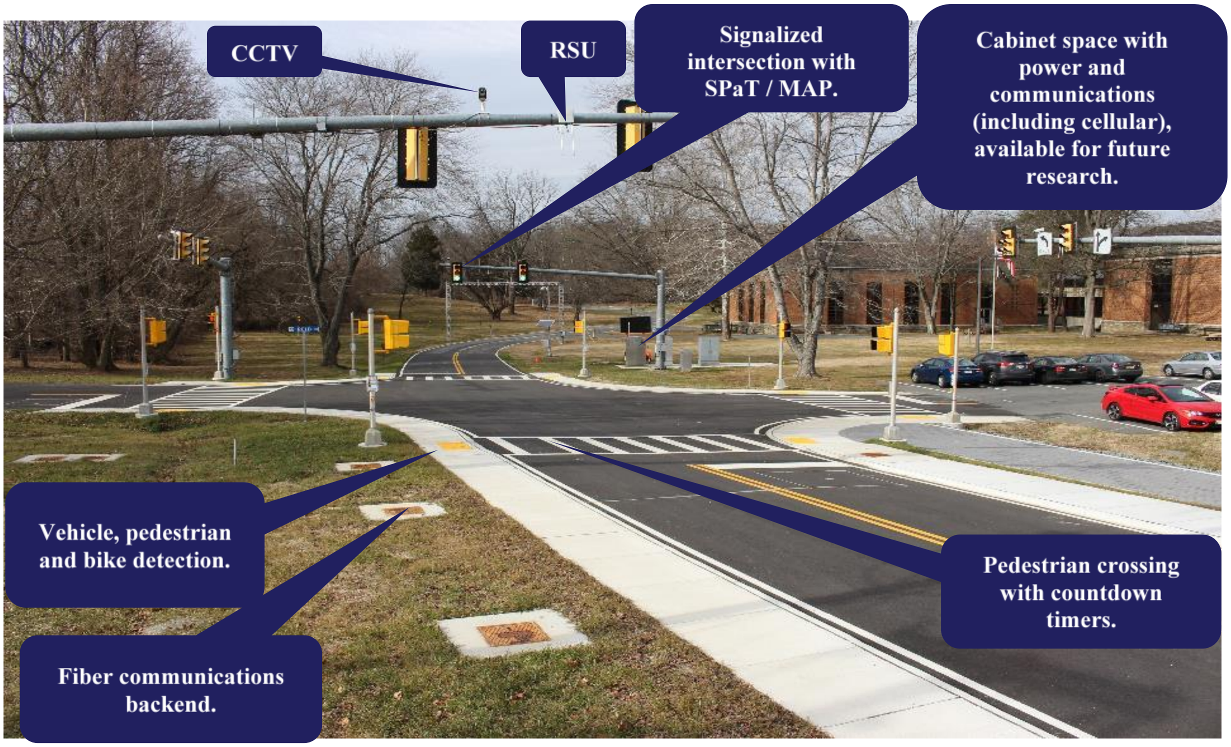
FHWA PEDESTRIAN TECHNOLOGY TEST BED

The Pedestrian Technology Test Bed (V2P Test Bed) was established using the already existing TFHRC Cooperative Vehicle-Highway Test Bed in McLean, Virginia, to implement the assessment plan with multiple market-ready V2P technologies. The Test Bed comprises two signalized intersections spaced approximately 600 feet apart and a midblock crossing. The signalized intersections are connected with sidewalks and feature pedestrian crossings, pedestrian call buttons, and signal heads (figure 4). This configuration offers the opportunity to test different V2P systems at both marked signalized intersections and marked midblock crossings (figure 3). It also offers several unique advantages for flexibly and adaptively testing a variety of systems, including changing the traffic signal timing plan (both timed and actuated) as needed. Due to its location within the grounds of the TFHRC, the Test Bed has the advantage of being able to control vehicular and pedestrian traffic while testing different technologies. This aspect has the potential to be very advantageous when testing with human subjects, particularly in the absence of signalized traffic control, such as in the case of a mid-block crossing. The intersection is also equipped with smart technologies that enable wireless communication with equipped vehicles and other devices, including dedicated short-range communication (DSRC) units, closed-circuit television (CCTV), and fiber communication. The Test Bed also gives researchers the flexibility to test different crash factors, including road characteristics, visibility, and light and weather conditions. The Test Bed was designed to accommodate rapid and diverse modifications as technology evolves. In the future, the features of the Test Bed can be further augmented with in-house expertise without the need for large-scale construction projects or long-term approval processes; for example, the installation of infrastructure-based pedestrian detection systems.

Original photo © 2018 Google®. (See acknowledgements section.)

Note: Arrows indicate direction of approach for testing of one market-ready technology.

Figure 3. Photo. Intersection and marked midblock locations at the Pedestrian Technology Test Bed.



Source: FHWA.

CCTV: Closed-circuit television; RSU: Roadside unit; SPaT: Signal phase and timing.

Figure 4. Photo. The signalized smart intersection at the FHWA Pedestrian Technology Test Bed.

The Test Bed has some limitations; for example, the road grade and curvature sometimes constrain vehicle sensor detection capabilities. However, these road features also provide the opportunity to test the effectiveness of a V2P system under a variety of road geometry scenarios. Also, being a two-lane roadway, the configuration does not support testing for multilane, high-speed roadway conditions. However, considering the features this Test Bed offers, including access to smart technologies, the traffic control cabinet, and its location, it has proven a useful site for testing different V2P technologies—an uncommon benefit for pedestrian safety evaluations.

PEDESTRIAN TECHNOLOGY TEST BED AND ASSESSMENT PLAN IMPLEMENTATION

The technical scan conducted under the initial phase of this V2P effort(4) summarized a wide variety of V2P technologies that are currently available or under development at the time of investigation.(5) Additional research was conducted to identify up-to-date systems that had the highest potential for quick and successful installation and assessment. After further discussion, it was clear that very few market-ready systems with comprehensive V2P capabilities were available. Market readiness and availability were given priority when selecting technologies for purchase and evaluation. Systems that are functional and require minimal programming or setup prior to use better reflect the performance of the system as employed by a typical consumer. Preference was given to systems that could be installed at the TFHRC Pedestrian Technology Test Bed, although technologies that are already installed in a customized testing environment were also considered for off-site assessment.

The technologies considered for testing were based on different types of sensors, including DSRC, radar, computer vision, cellular, and wireless/Cloud-based technology. All differed in the way they provided notification to the users.

The technologies acquired for testing fell into the following main categories:

- **Vehicle-Based:** These systems fall under the unilateral pedestrian detection and driver notification systems, which provide collision alerts only to the driver. Two different systems were tested under this category:
    - **System 1: Camera-Based Aftermarket Safety Device.** Equipment: Commercially available; installed in test vehicle.
    - **System 2: Camera- and Radar-Based Detection System.** Equipment: Original equipment manufacturer (OEM).

- **Smartphone-Based:** These can be categorized as unilateral vehicle detection and pedestrian notification systems, which provide collision alerts only to the pedestrian. The software used is in the early deployment stage, and the hardware was installed at the Pedestrian Technology Test Bed.
    - **System 3: Smartphone-Based Pedestrian-to-Infrastructure Application.** Equipment: Hardware, early-deployment software; installed at TFHRC.

- **Infrastructure-Based:** These technologies have the potential to serve as bilateral detection and notification systems, which will provide collision alerts to both drivers and pedestrians in parallel, if not only to the drivers at a minimum. No technology was acquired to test this category due to a lack of market readiness among those currently under development; however, comprehensive research was conducted to investigate its potential.
    - **Technology: Lidar-Based Pedestrian Detection.** Equipment: None.

A comprehensive discussion of the assessment of each of these technologies is presented in the next chapter.

CHAPTER 3. TECHNOLOGY ASSESSMENT

This chapter includes a detailed description of the methods by which each of the technologies described in the previous chapter were assessed using the Test Bed and assessment plan; and summarizes the findings.

VEHICLE-BASED TECHNOLOGY

Two of the technologies acquired for observation were designed to operate within a motor vehicle. These systems focused on detecting at-risk pedestrians and alerting the driver to intervene. Because the pedestrian and driver are not in direct communication, these vehicle-based systems function as passive pedestrian detection technologies rather than true V2P connected systems. However, the advanced sensors employed to detect the pedestrian and the communication technology used to alert the driver and, in one system, intervene to avoid a collision, are similar to those that can be applied to V2P technology.

Camera-based System

The first vehicle-based system tested is a commercially available aftermarket safety device consisting of a forward-looking camera-based system designed to monitor and inform the driver of potentially unsafe conditions in the surrounding environment, including at-risk pedestrian detection. The system used in this assessment consisted of an integrated visual camera and chipboard CPU connected to the vehicle's CAN bus systems, which monitor the vehicle's status (e.g., acceleration and braking). The alert display system mounted on the car's front windshield contained a front-facing, single-lens camera to detect objects in the path ahead. According to public materials provided by the vendor, the CPU applies proprietary computer vision algorithms to identify features and objects such as lane markings, vehicles, and pedestrians, as well as the distance between forward objects and the camera sensor. This visual "map" is in reference to the position of the vehicle and allows the system to detect lane departures and potential collisions and subsequently deploy alerts to warn the driver. The details of the input criteria and computations involved in this detection process are proprietary to the vendor and therefore unknown to the research team involved in this effort.

When the position and movement of the vehicle, combined with the location and movement of a detected pedestrian, indicate that a collision is likely if the vehicle and pedestrian remain on their observed course, the system deploys a visual or visual-audio warning through a driver interface device with a small display screen. In the test vehicle used for this project, the interface device was mounted on the driver's side next to the rearview mirror. This system provides two types of alerts when a pedestrian is detected in or near the path of the vehicle:

- Cautionary alert: A visual alert consisting of a small green walking pedestrian symbol is displayed at the top of the screen when a pedestrian is detected in an algorithm-defined "danger zone," but is not at imminent risk of collision. This alert is not accompanied by a sound but, once deployed, remains on the display until the pedestrian is no longer in the camera's view

- Emergency alert: If the speed of the vehicle and location of the pedestrian suggest a collision is imminent, the entire screen of the display is occupied by a large red pedestrian symbol that occupies the entire interface display. This sudden change in visual display is noticeable and easy to see. Simultaneously, two tones at approximately 2,700 Hz, each lasting approximately 0.5 s, are emitted via the device's audio system. The volume of this alert can be modified by the user, and was set at full volume during testing.

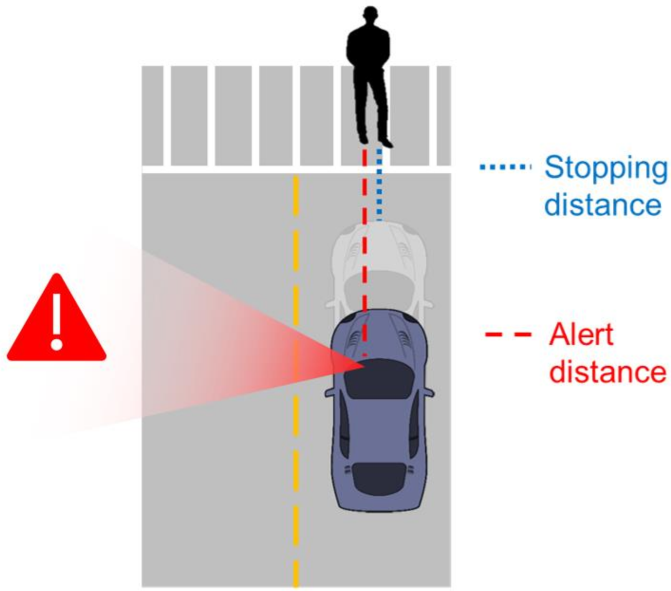
This aftermarket safety system warns the driver but is not capable of controlling vehicle functions, such as braking or steering. Therefore, appropriate driving responses depend upon the driver's reaction to the alert signal. The system possesses several other safety features, including headway from lead vehicle monitoring, forward collision warning, high beam monitoring, speed limit monitoring, and lane departure warnings. However, these features were not applicable to the current research scenario and were not assessed.

Testing

Preliminary trials in test case 2 (vehicle turning right while a pedestrian crosses straight across the roadway) and test case 3 (vehicle turning left while a pedestrian crosses straight across the roadway) with the camera-based system yielded unreliable pedestrian alerts, despite attempts to optimize recognition by modifying crossing timing, simulated pedestrian characteristics, and vehicle approach. The lack of system response in these test cases resulted in the decision to evaluate the system's performance only in test case 1 (vehicle traveling straight while a pedestrian makes a perpendicular crossing). Additional trials with the simulated bicyclist were also conducted to provide a preliminary assessment of test case 4 (vehicle traveling straight while the pedestrian is traveling straight along the roadway). Trials were performed outdoors during daylight hours. Weather conditions were always clear but ranged from sunny to overcast. Vehicular and pedestrian traffic in the intersection was restricted during testing to maximize safety. The dummy wore standard clothing and a reflective safety vest.

The system's pedestrian detection capabilities are only active when the vehicle is traveling under 31 mph. Three speeds that fall into this range were selected for testing: 10, 15, and 20 mph. Although these speeds are less likely to be associated with pedestrian fatalities, faster speeds were not assessed due to concerns of the research team's safety and to minimize the risk of damage to testing equipment. Trials were performed at the signalized intersection and marked mid-block crossing locations at the TFHRC Pedestrian Technology Test Bed. Figure 3 shows a satellite image of the testing sites and vehicle approach directions.

During experimental trials, the vehicle accelerated toward the designated intersection while maintaining the assigned speed. When an emergency alert was received, the driver braked forcefully to bring the car to a stop. The distance from the front bumper to the center of the crosswalk was measured and recorded as the stopping distance from the target. The distances from the pedestrian at which the cautionary and emergency alerts were received were recorded. This procedure is illustrated in figure 5.



Source: FHWA.

Figure 5. Illustration. Measurement recording procedure during vehicle-based testing.

Results

Detection and Alerts

Table 2 summarizes the frequency of the cautionary and emergency alerts received over 10 trials at 3 speeds and 2 crossing locations.

Table 2. Frequency of alerts received over 10 pedestrian trials.

Pedestrian: Straight, perpendicular crossing	Vehicle: Straight		
Intersection (marked crosswalk)	**10 mph**	**15 mph**	**20 mph**
Cautionary alert (percent)	20	100	70
Emergency alert (percent)	90	100	40
Mid-block (marked crosswalk)	**10 mph**	**15 mph**	**20 mph**
Cautionary alert (percent)	100	30	0
Emergency alert (percent)	100	100	100

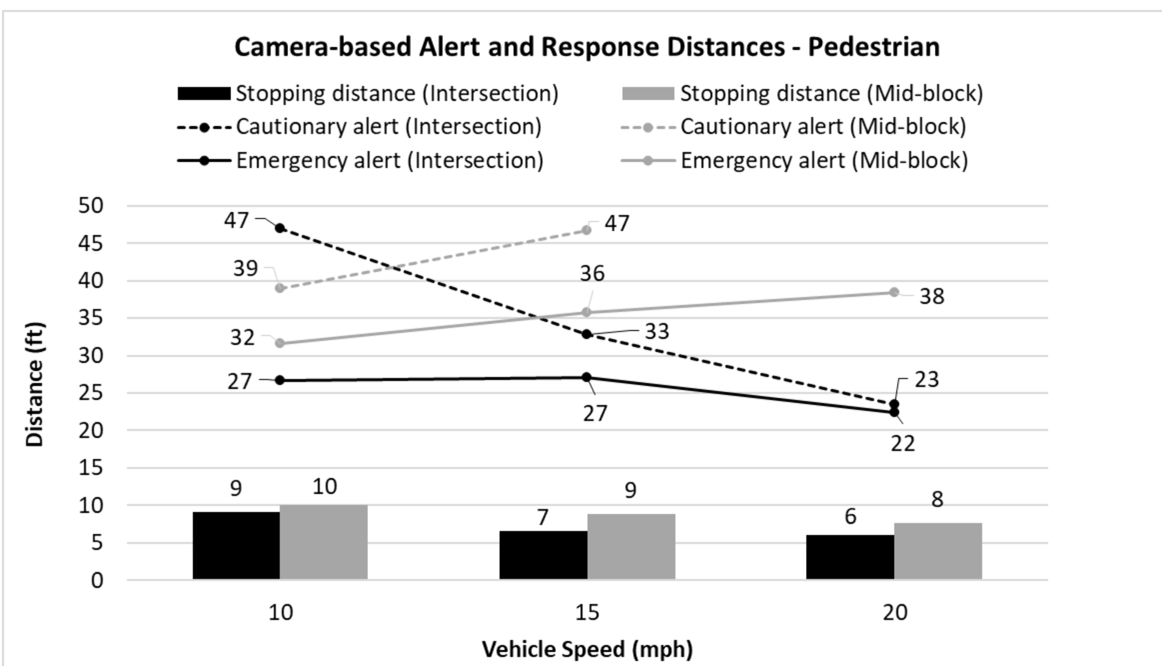
Overall, the deployment of the cautionary alert was inconsistent across both pedestrian trials and vehicle speeds for the pedestrian trials. Emergency alerts were slightly more reliable at lower speeds and at the mid-block crossing location. Although cautionary alerts did not present a discernible trend at the intersection location, the frequency of cautionary alerts received at mid-block appeared to decrease with increasing speed.

Table 3 provides the frequency of cautionary and emergency alerts when approaching the simulated bicyclist from behind.

Table 3. Frequency of alerts received over 5 bicyclist trials.

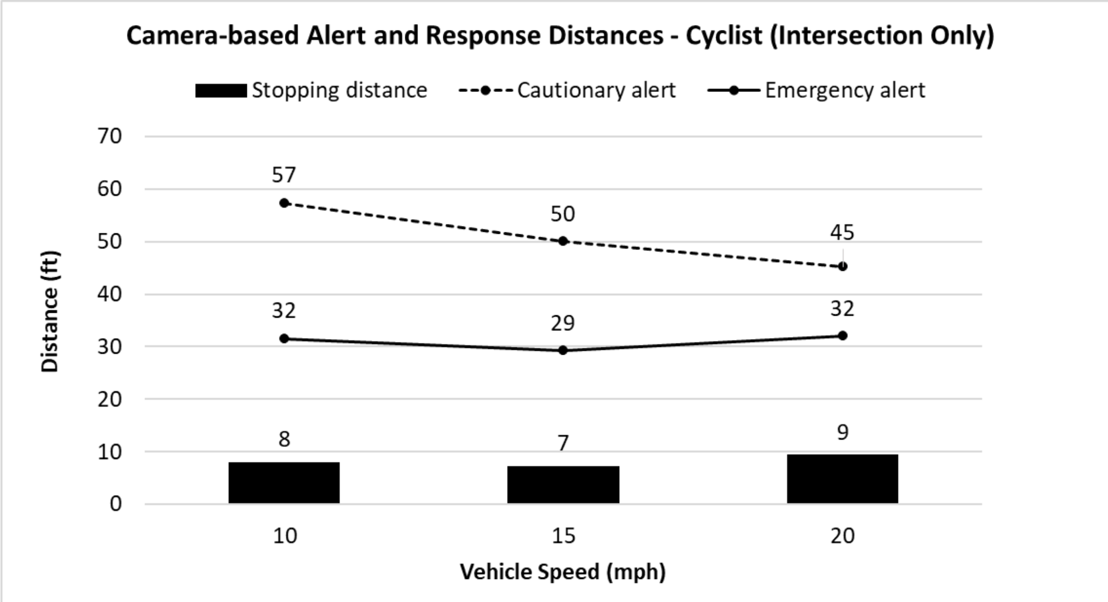
Cyclist: Straight along road, parallel with vehicle	Vehicle: Straight		
At intersection (marked crosswalk)	**10 mph**	**15 mph**	**20 mph**
Cautionary alert (percent)	60	80	100
Emergency alert (percent)	80	100	100

Figure 6 provides performance measurements averaged over the number of valid trials in each pedestrian scenario. Note that, since cautionary alerts were not received during 20 mph trials at the mid-block crossing, performance measures could not be calculated for that scenario. As shown in figure 7, the average stopping distance remained relatively consistent over various speeds and despite geographical variations between locations. Figure 7 also illustrates how, in general, emergency alert and stopping distances remained relatively consistent for the bicyclist, although the distance at which the cautionary alert was received decreased noticeably between 10 mph and 20 mph trials.



Source: FHWA.

Figure 6. Graph. Alert and response distances for pedestrian trials with the camera-based detection system.

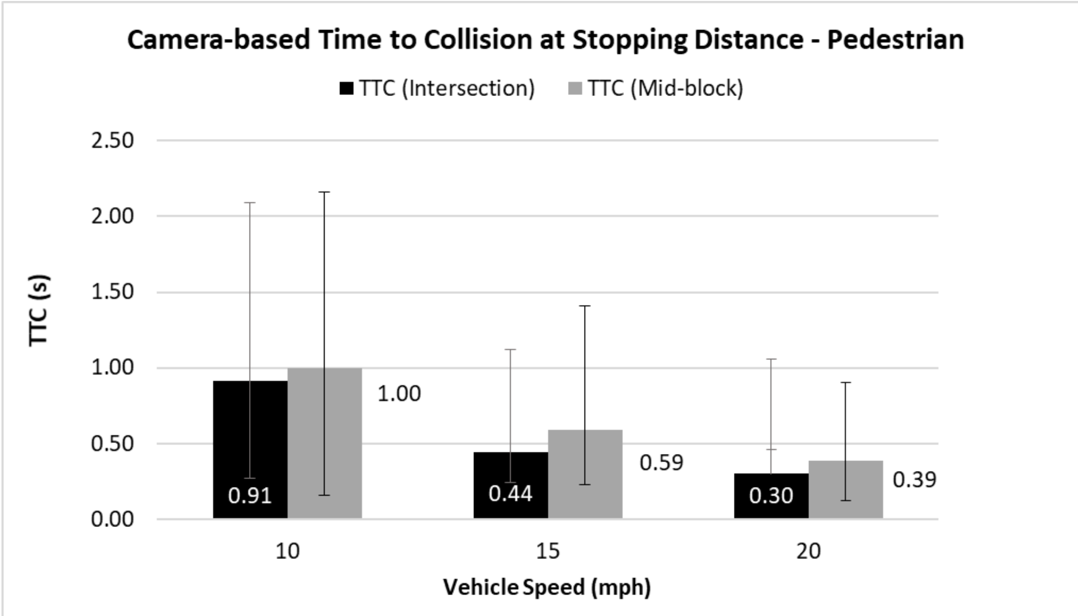


Source: FHWA.

Figure 7. Graph. Alert and response distances for bicyclist trials with the camera-based detection system.

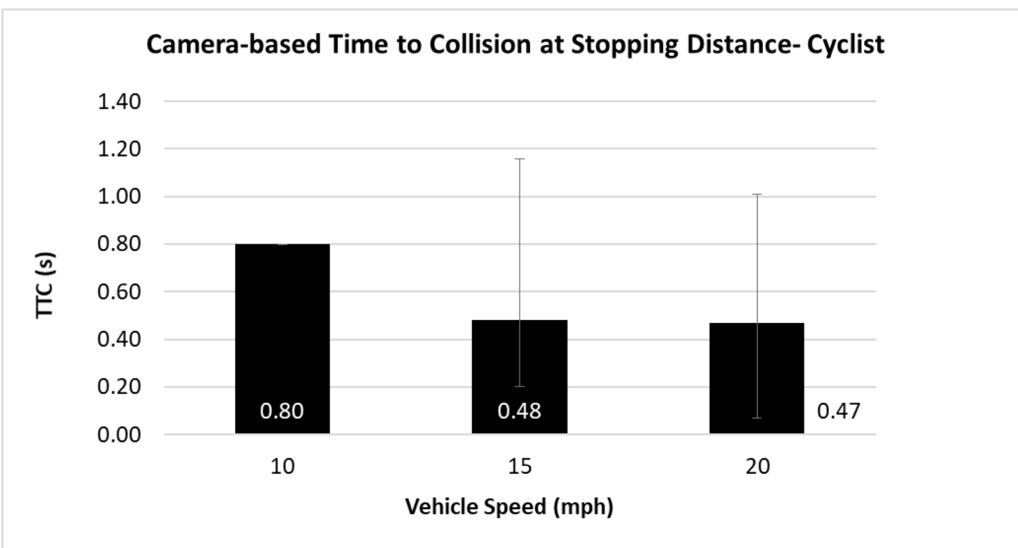
Figure 8 and figure 9 illustrate the variation in time to collision (TTC) for pedestrian and bicyclist trials, as calculated by the measured stopping distance divided by the assigned vehicle speed. As shown in figure 8, TTC decreased sharply with increasing speed in pedestrian trials. Variability in TTC (as indexed by standard deviations) increased slightly at the intersection location but remained relatively constant for mid-block TTC values. Unlike the pedestrian crossing trials, TTC did not appear to steadily decrease with increasing speed for bicyclist trials, as shown in figure 9.

The pedestrian detection system's human factors description, which considers the components essential for use by a driver, was also documented. These results are presented alongside those of the second vehicle-based system to facilitate comparison in the following section.



Error bars represent standard deviation of the means.
Source: FHWA.

Figure 8. Graph. Time to collision at stopping distance for pedestrian trials with the camera-based detection system.



Error bars represent standard deviation of the means.
Source: FHWA.

Figure 9. Graph. Time to collision at stopping distance for bicyclist trials with the camera-based detection system.

Discussion

The pedestrian detection and alert capabilities of the camera-based aftermarket safety device were assessed in two locations over three approach speeds. The results of the assessment showed that the system can detect both pedestrians and bicyclists and deployed a cautionary visual alert at a distance far enough upstream of the crosswalk (approximately 38 ft on average in pedestrian trials) to support collision avoidance. The cautionary alert was not always observed prior to an emergency alert, such as in the mid-block pedestrian trials at 20 mph, when no cautionary alerts were received. This may have been affected by the dummy's lack of limb articulation, the timing at which the dummy moved across the crosswalk, the slight variation in road grade across the two crossing locations, or some combination of the three. Similarly, trials in which the vehicle approached the bicyclist dummy at the intersection crossing revealed highly consistent readings over the three approach speeds. Stopping distance performance measures were, overall, similar to those for a crossing pedestrian. In all but one trial, the emergency alert was received in time to prevent a collision with the bicyclist. Even over half the number of trials as the pedestrian, the frequencies of cautionary and emergency alerts in response to the bicyclist remained consistent.

As would be expected in unassisted braking situations, higher vehicle speeds were associated with smaller TTCs overall. The range of TTC values for the static bicyclist was smaller than that of the pedestrian, and the minimum TTC for the bicyclist (0.47 s) was greater than that of the pedestrian (0.3 s). It is also notable that the TTC for the bicyclist at 15 mph was very similar to the TTC at 20 mph, while the standard deviation of TTC values decreased over the increase in speed. This pattern does not match the trend in TTC values observed in pedestrian trials.

During fast approaches, there may not have been enough time to detect the target and deploy a cautionary alert before an emergency alert was triggered, resulting in an immediate emergency warning. The limited time available in which to detect the target may have also affected the frequency of cautionary and emergency alerts. In mid-block pedestrian trials, the frequency of cautionary alerts appeared to steadily decrease with increasing speed. This was likely due to the crossing dummy occupying less time in the camera sensor's "cautionary zone." Although cautionary alerts were received less consistently, this is not considered to be a fault of the system as the goal of the task was to evaluate driver reactions to the emergency alert, which called for driver response.

In all cases in which it was received, the emergency alert was sufficient to brake in time to avoid a collision with the pedestrian target, despite changes in detection location and TTC prior to braking.

Testing indicated that the forward-looking camera-based safety device used in this experiment detected pedestrians and produced alerts with adequate timing and clarity to prevent collisions. Although the system failed to produce alerts in some trials, detection was adequate when achieved and provided advance notice to the driver to increase the time in which the driver could react to avoid a crash.

Camera- and Radar-Based Integrated Safety System

The second vehicle-based V2P technology tested was a vehicle with an OEM safety assistance system. The system combines sensor data from an optical camera and radar to detect objects in the driving environment, including vehicles, pedestrians, and bicyclists. The OEM system tested comes standard on a sizable selection of vehicles manufactured by a major automaker and was market ready and relatively accessible on the consumer market at the time of testing.

The vehicle's pedestrian pre-collision and avoidance/mitigation system is marketed as a safety system designed to detect and respond to pedestrians at risk of collision. The system is designed to either avoid or reduce the impact of a collision by producing alerts and, in some situations, directly reducing vehicle speed via brake control. The system has two component safety features:

- Visual/auditory alert: When a pedestrian is detected and the vehicle's computer system determines that a collision is imminent, the driver's instrument panel displays an alert instructing the driver to brake and simultaneously emits a short burst of nine brief tones (approximately 2,500 Hz; 2 s total duration).

- Automated braking: If the travel speed and distance to the pedestrian indicate that additional braking is necessary to avoid or mitigate the collision, the vehicle applies automated braking to further reduce vehicle speed (supplemental braking). The automatic braking system may also bring the vehicle to a complete stop (full automated braking), with or without the driver applying the brake. The system releases the brakes 2 s after the vehicle has come to a complete stop.

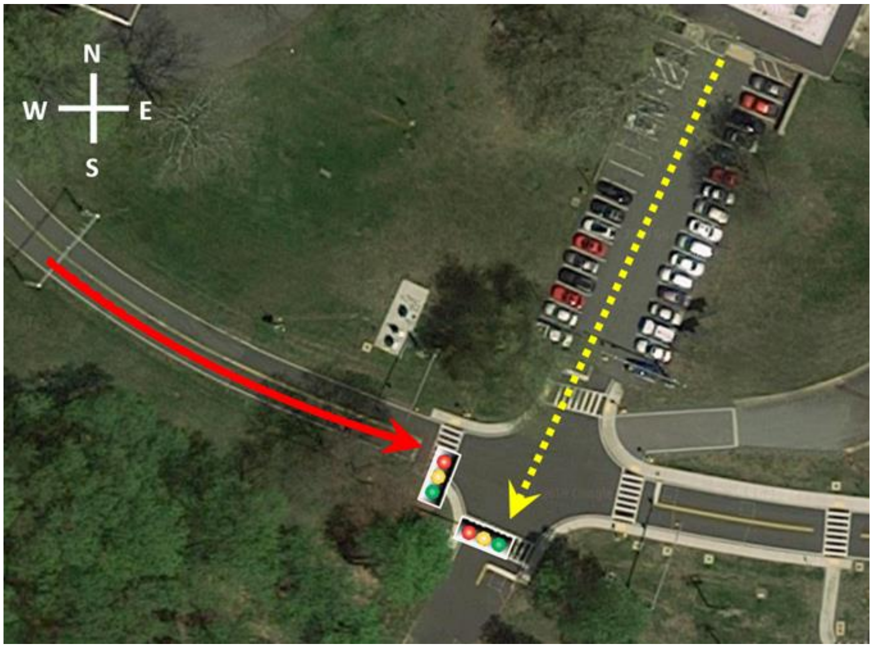
The visual/auditory alert occurs before automated braking is engaged. Automated braking is influenced by the driver's action, such that if the driver is pressing the brake pedal, the system may delay automated braking under the assumption that the driver is already aware of the situation and taking evasive action. The pedestrian detection and collision mitigation system operates at speeds between 7 and 50 mph.

In addition to being turned on or off, the vehicle collision avoidance system has three options adjusted for alert timing preference: near, medium, and far. The near setting delays alerts until the detected object is closer to the vehicle, thus reducing the amount of time that the driver has to detect and respond to potential collisions. The far setting allows alerts to be deployed earlier and farther away from the detected object, thus providing more time for the driver to respond. The exact distance corresponding to these settings is not provided by the manufacturer as it is proprietary. The following tests were performed with the medium sensitivity setting, which is the default setting for the system.

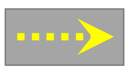
Testing

Preliminary testing revealed that the OEM system yielded inconsistent detection when turning around a curve and shortly afterward as well as on roads with vertical elevation; these limitations are noted in the vehicle manual. The limitations of the system prevented assessment of test case 1 (vehicle traveling straight while a pedestrian makes a perpendicular crossing), test case 2 (vehicle turning right while a pedestrian crosses straight across the roadway), and test case 3 (vehicle turning left while a pedestrian crosses straight across the roadway). Test case 4 (vehicle traveling straight while the pedestrian travels straight along the roadway) was assessed with both the simulated pedestrian and bicyclist. The intersection crossing location was chosen due to the even road grade and straight approaches. Based on the vehicle manual’s description of the system and the results of testing with the first vehicle-based system, detection was not expected to be influenced by the testing location. Testing was performed outdoors during daylight hours. Weather conditions were clear and sunny during pedestrian trials and clear and cloudy during bicyclist trials.

Trials were conducted at two marked intersection crossings at the Pedestrian Technology test bed. Figure 10 illustrates the vehicle approach for the test trials. Although the system performed relatively consistently with the bicyclist at the eastward approach intersection, preliminary testing with the pedestrian at this location produced sparse and unreliable alerts. Subsequent testing suggested that the curve of the eastward approach interfered with the recognition of the pedestrian (possibly related to the smaller size and narrow silhouette of the pedestrian relative to the bicyclist). As a result, pedestrian testing was conducted at a location with a longer, straight approach to optimize detection via the vehicle sensors (yellow arrow in figure 10).



Original photo © 2018 Google®. (See acknowledgements section.)

 = Approach during pedestrian trials.

 = Approach during bicyclist trials.

Figure 10. Photo. The test intersection and approach paths for pedestrian and bicyclist trials.

It should be noted that the short-range radar signature of the test dummies was not verified to mimic that of a human. However, it was thought that the clothing and standard reflective safety vest worn by the dummy would be sufficient for the camera and radar sensor fusion used in this OEM system.

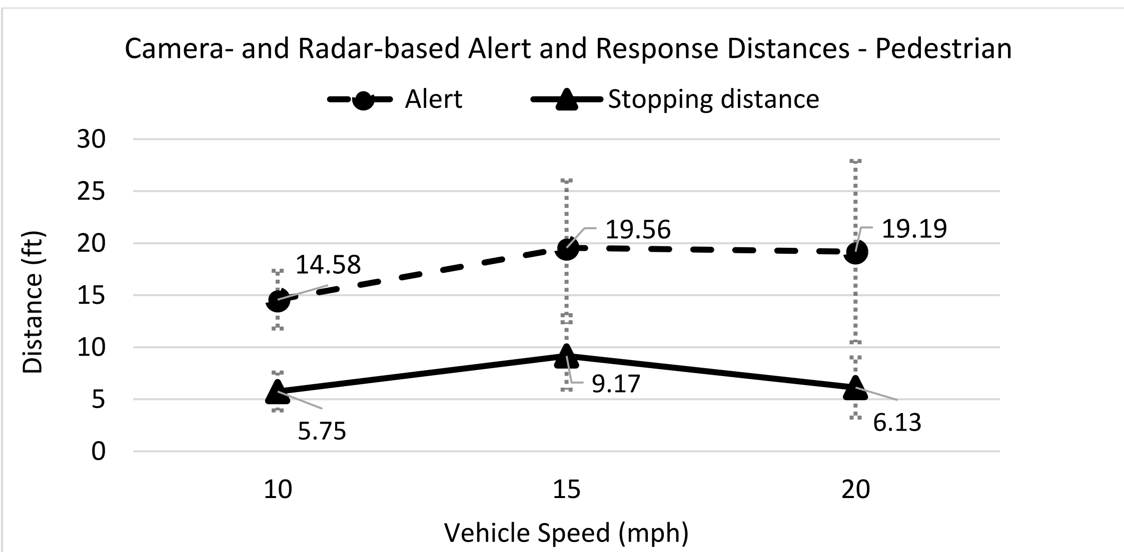
Trials for the OEM system were performed in the same manner as those of the camera-based aftermarket safety device and consisted of 10 trials each with the pedestrian and bicyclist dummy at the same 3 approach speeds of 10, 15, and 20 mph. Driver reaction to the alert and the distance from the crosswalk at the time of the alert and after the vehicle came to a complete stop were again measured. Additionally, the engagement of the supplemental and/or automated braking system was recorded based on driver perception. Because the test vehicle was commercial rather than research-dedicated, it was not possible to access its CAN bus system to objectively determine whether the braking system was activated. However, the driver could monitor the depression of the brake pedal when the system applied additional force.

Results

The system issued alerts in all but one of the 30 trials performed with the pedestrian dummy (the single failure occurred during 15 mph testing; see table 4). The visual/auditory alert was clear and attention-capturing; it provided direct textual instructions to apply brakes immediately. The frequency of supplemental and full automated braking observed is shown in table 4 and table 5. Figure 11 summarizes the average alert and stopping distances observed at the three testing speeds Stopping distances include both manual, supplemented, and full automated stops.

Table 4. Frequency of automated braking with integrated collision avoidance system during pedestrian trials.

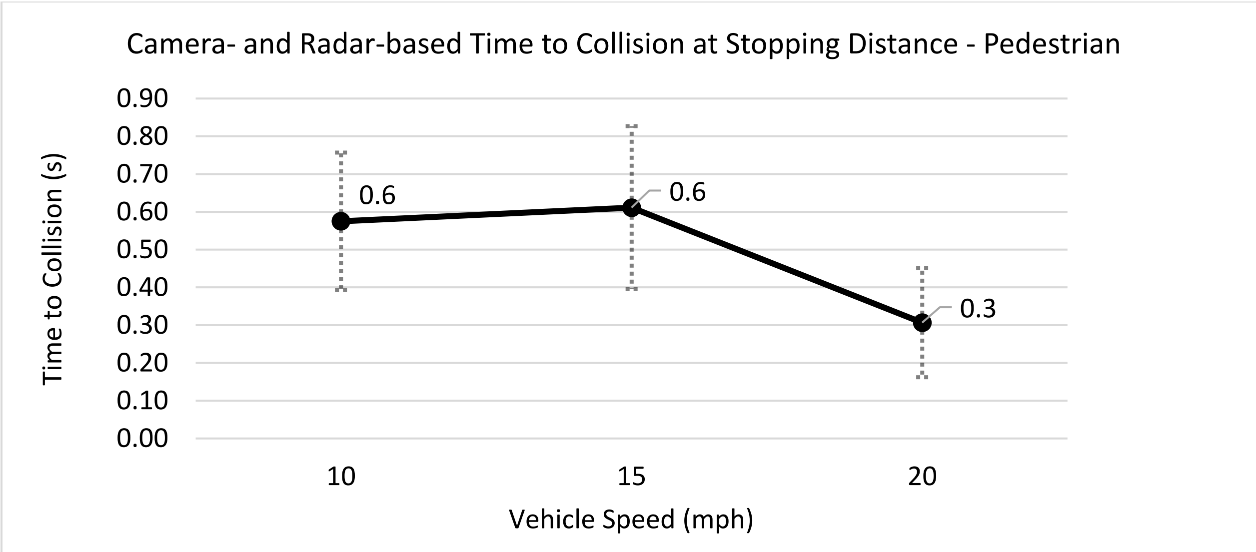
Pedestrian: Straight along road, parallel with vehicle	Vehicle: Straight		
Intersection (marked crosswalk)	**10 mph**	**15 mph**	**20 mph**
Number of successful alert trials	10	9	10
Frequency of supplemental braking (percent)	50	0	80
Frequency of full braking (percent)	50	11	30



Source: FHWA.

Error bars represent standard deviations of the means.

Figure 11. Graph. Alert and stopping distances in pedestrian trials with the integrated collision avoidance system.



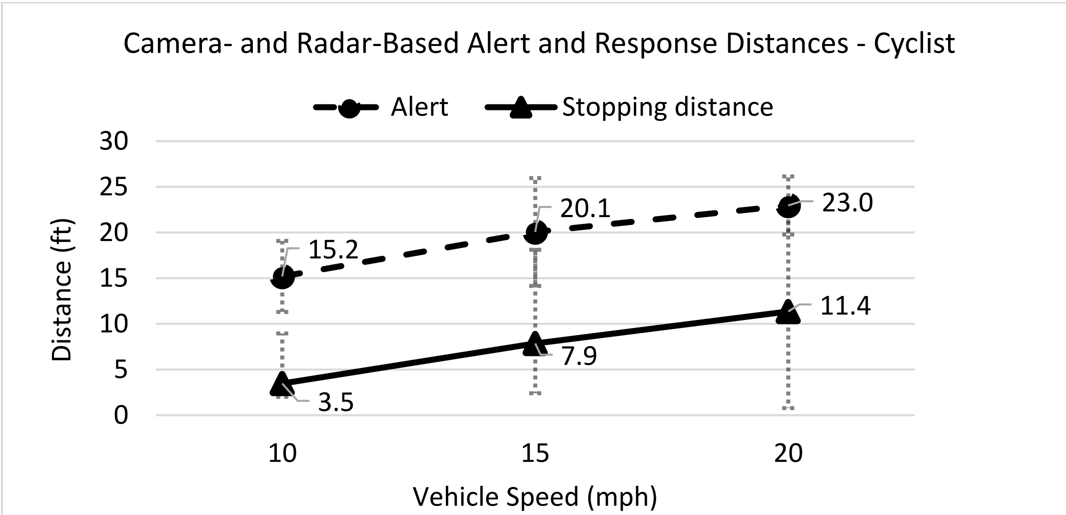
Source: FHWA.
Error bars represent standard deviations of the means.

Figure 12. Graph. Time to collision in pedestrian trials with the integrated collision avoidance system.

The system issued alerts in 63 percent of bicyclist trials. Eleven trials (37 percent) did not produce an alert, with the majority of these failures (55 percent) occurring during 20 mph trials. The number of valid trials within each speed category is shown in table 5, along with the frequency of automated braking during valid bicyclist trials. Figure 13 and figure 14 provide a summary of alert, stopping, and TTC measures during bicyclist trials in which an alert was received.

Table 5. Frequency of automated braking with integrated collision avoidance system during bicyclist trials.

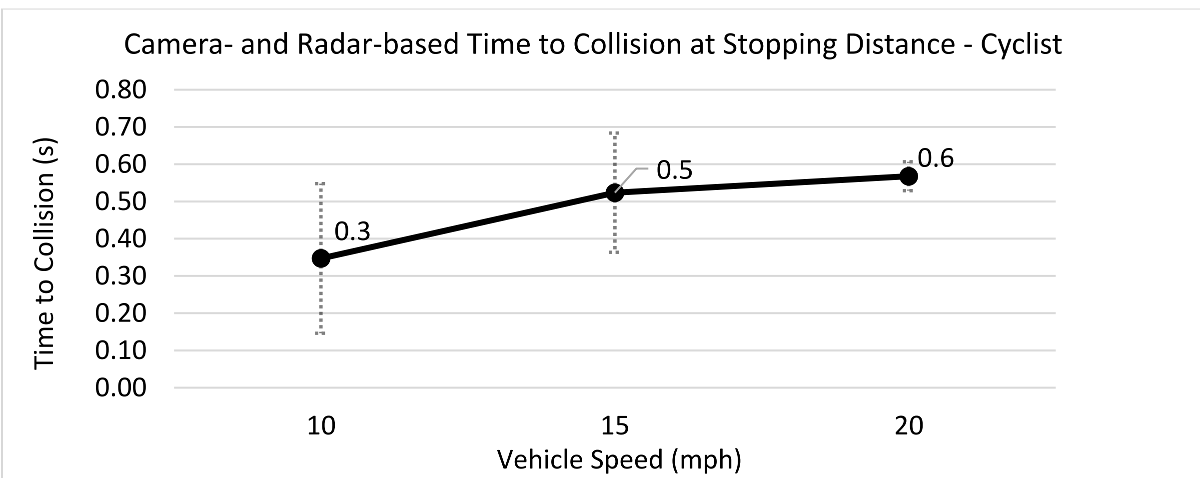
Bicyclist: Parallel	Vehicle: Straight		
Intersection (marked crosswalk)	**10 mph**	**15 mph**	**20 mph**
Number of successful alert trials	7	8	4
Frequency of supplemental braking (percent)	50	0	80
Frequency of full braking (percent)	50	11	30



Source: FHWA.

Error bars represent standard deviations of the means.

Figure 13. Graph. Alert and stopping distances in bicyclist trials with the integrated collision avoidance system.



Source: FHWA.

Error bars represent standard deviations of the means.

Figure 14. Graph. Time to collision in bicyclist trials with the integrated collision avoidance system.

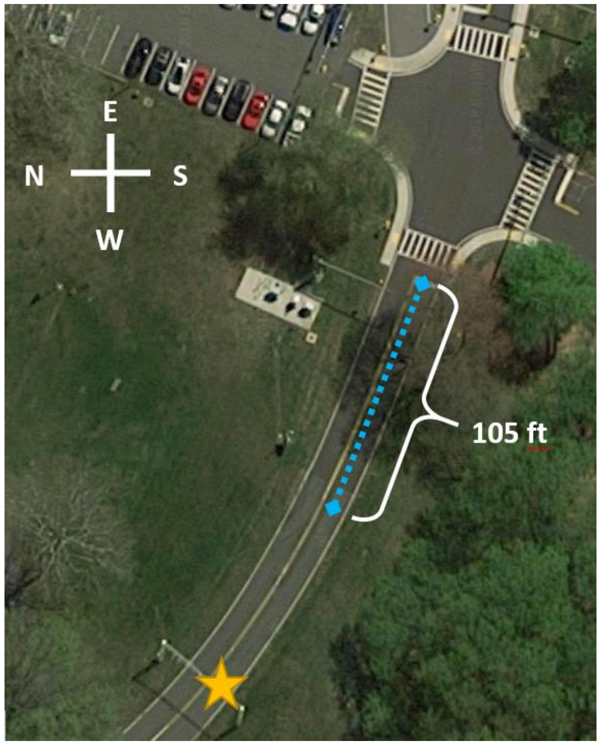
The braking intervention is perceived to be effective and intuitive. Supplemental braking could be detected by the additional depression of the brake pedal, but was often subtle. The sudden stop caused by full automated braking was jarring at times and could be uncomfortable for unprepared drivers. The seatbelt appeared to play an important role in minimizing the effect of the sudden braking; occupants without seatbelts might find themselves falling out of their seat and could risk injury. The deployment and force of full automated braking was found difficult to predict. For example, at times, the system engaged full braking nearly 6 ft ahead of the target, which did not appear to present an immediate threat. In other trials within the same speed category, the braking system engaged later or not at all. In addition, the force of automated braking varied greatly even at similar speeds and stopping distances.

Discussion

During trials in which no alert was received, a crash would have presumably occurred if the driver did not manually intervene. Because the testing location varied between bicyclist and pedestrian testing, it is uncertain whether detection of the bicyclist would have been different at the straight intersection approach used for pedestrian testing.

Average alert distances were similar across both pedestrian and bicyclist scenarios and speeds (average difference of 1.6 ft). Stopping distances varied slightly at 10 and 15 mph, with greater stopping distances observed for the simulated pedestrian. As noted earlier, bicyclist distance measures were taken from the edge of the bicycle’s front tire, thus adding approximately 1.5 ft to the footprint of the mannequin. At 20 mph, the variability in stopping distance increased, and the mean decreased for the pedestrian but increased for the bicyclist. This may indicate that, when the sensors had ample time and appropriate angle to detect the bicyclist, the system could identify the bicyclist from a greater distance than the pedestrian, possibly due to the larger silhouette of the dummy and the bicycle. However, the four trials that produced alerts during the bicyclist testing at 20 mph are not a fully representative sample.

It is possible that the relatively high rate of detection failure at 20 mph was influenced by the vehicle’s approach path. Due to the slight curvature of the road preceding the approximately 105 ft of direct approach (see figure 15), the amount of time during which the vehicle has a straight, direct view of the target object is shorter at 20 mph than at lower speeds. At 20 mph, it would take approximately 3.4 s to travel the 105 ft of straight road leading up to the target. At 15 mph, this distance is traveled in approximately 4.5 s, and 6.8 s at 10 mph. However, the slightly greater number of failures (30 percent) observed at 10 mph compared to 15 mph (20 percent) may call this hypothesis into question, although statistical evidence is needed to draw stronger conclusions. Given that such variations in road grade and curvature are not uncommon or severe, the possible influence of subtle variations in road grade and curvature observed in testing may also indicate that system performance could be further reduced on complex roadways or when more obstacles are present. Additional testing would be required to investigate this possibility.



Original photo © 2018 Google®. (See acknowledgments section.)
= Length of straight approach.
= Approach start point.
Figure 15. Photo. Intersection used for bicyclist testing.

Across both scenarios (pedestrian and bicyclist), alerts were deployed earlier at 15 mph compared to 10 mph. As a result, the driver stopped the vehicle farther ahead, indicating the system offers a potential safety benefit, particularly at 15 mph. This finding also demonstrated that the system took the increased speed into account and deployed an earlier warning, thus providing the driver more time in which to respond. It is likely that the system does not consider the risk of collision or injury at 10 mph to be immediate, and it instead delays response in favor of allowing the driver to respond. This may be the reason that alerts at 10 mph were deployed roughly 5 ft closer to the pedestrian than the alerts deployed at 15 mph in both scenarios.

Data from 2010-2015 indicate that pedestrian fatalities are more common at speeds of 45 mph.(7) Current testing suggests potential safety benefits for low speed zones, such as parking lots and residential areas. More thorough testing should evaluate performance at higher speeds and in conditions that mimic those of high-speed roads.

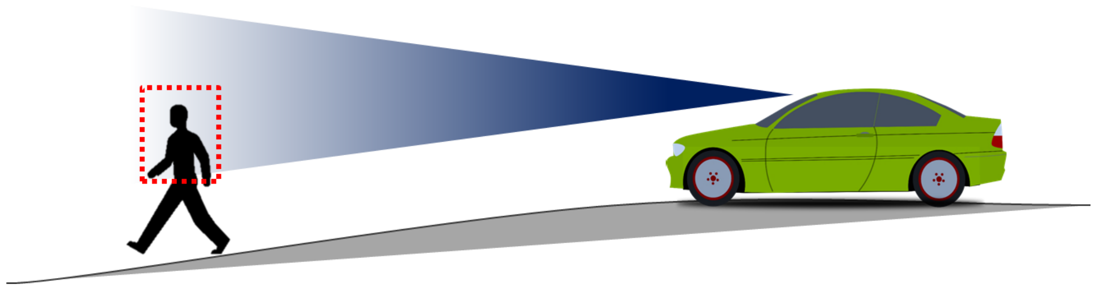
Vehicle-based Technology: Overall Assessment

Testing conducted with two vehicle-based pedestrian safety systems at the TFHRC Pedestrian Technology Test Bed revealed slightly different capabilities, strengths, and weaknesses for detecting and responding to pedestrians and bicyclists at risk of collision. The systems varied in their sensor technology; although both included single-lens, forward facing cameras, the second system combined sensor data from a forward-facing short-range radar to identify potential collisions. Both systems deployed unilateral alerts to the driver, but the OEM system was also capable of actively mitigating the crash by slowly or stopping the vehicle via supplemental or full braking. By comparing the design, characteristics, and performance of the two systems, which underwent similar testing in the same Test Bed, it is possible to gain insight on their respective strengths and weaknesses for pedestrian safety and the implications for effective advanced technologies.

Safety Effectiveness

The results of these tests provide evidence for a potential safety benefit offered by the two vehicle-based systems. However, reliable and early alerts and mitigation appeared to depend upon clear and direct sightlines to the pedestrian or bicyclist, which greatly limits the systems' ability to enhance the safety of vulnerable road users. As noted earlier, pedestrians and bicyclists are more likely to be involved in a fatal crash when they are not seen by the driver, as in cases of low light or poor visibility. If it is indeed the case that the two tested systems are best suited to detect obstacles that are in clear view of the driver, the effectiveness of the system is reduced to situations in which the pedestrian unexpectedly enters the roadway or when a driver is distracted or otherwise not looking at the road ahead when the pedestrian appears. Neither system performed in the turning test case scenarios common to pedestrian-vehicle and bicyclist-vehicle collisions. Although this result may be specific to the testing environment and strategy used in this project, the ability to reliably detect and respond to pedestrians in the roadway after turning a corner or at the end of a curve would provide a valuable benefit beyond the common abilities of an otherwise alert and aware driver.

Trials conducted with both systems suggest that road geometry and grade influenced the reliability of pedestrian detection and subsequent alerts. The effect of road grade on detection accuracy may be due to the limitation of the sensors' ability to capture enough information to reliably identify a pedestrian, as illustrated in figure 19. Subtle variations in road characteristics are likely to be encountered during typical driving. Therefore, it is important to further investigate the effects of these features on system effectiveness. Additional testing in a wide range of road geometries and geographies could more thoroughly test the functionality of sensor-based pedestrian detection systems. However, the flexibility offered by the infrastructure at TFHRC proved to be suitable for initial testing and the identification of key non-functional scenarios.



Source: FHWA.

Figure 16. Illustration. Example of how the ability of a sensor to detect a pedestrian may be affected by road grade.

Accessibility and Usability

One of the goals of this project was to holistically evaluate the potential for V2P technologies to effectively improve pedestrian safety by considering the usability and accessibility of the product for typical users. These technologies depend upon consistent, accurate, and reliable use to reduce collision frequency and severity. Table 6 presents key human factors components for the two vehicle-based systems to illustrate variations in each category.

As shown in table 6, both vehicle-based systems are highly accessible as they are fully market-ready and designed for intuitive, passive use. A major advantage of the camera-based technology is that it was one of only a few aftermarket safety devices that was market ready, commercially available, and reasonably priced. The system can be installed in a wide variety of cars, trucks, and fleet vehicles, making the device appealing and accessible to the average consumer. In addition, an increasing number of vehicles are being manufactured with this or similar camera-vision sensing technology integrated into their safety systems by the OEM. The vehicle OEM has the added advantage of not requiring additional installation and further improves usability and effectiveness with direct control of the vehicle's braking system. An integrated vehicle system also operates at a greater range of speeds, up to 50 mph compared to the camera-based system's 31 mph, giving the integrated system a greater likelihood of mitigating crashes associated with a greater number of pedestrian fatalities. Unlike the camera-based system, the integrated pedestrian detection system does not operate below 7 mph.

Table 6. Human factors assessment of vehicle-based technologies.

Measure	Camera-based Detection System	Camera- and Radar-based Collision Mitigation System
Alert clarity	• Clear, easy to understand visual and audio alerts	• Clear, direct, easy to understand visual and audio alerts
User access to technology	• On the market, available for installation at multiple locations • Affordable at less than $1,500 for purchase and installation • Aftermarket safety device not widely advertised	• On the market, available for consumer purchase or rental • No additional cost in multiple economy-class vehicles • Detailed explanation of system functionality provided only in vehicle manual

Table 6. Human factors assessment of vehicle-based technologies. (continued)

Measure	Camera-based Detection System	Camera- and Radar-based Collision Mitigation System
Market availability	• Available on consumer market	• Available on consumer market
Institutional and infrastructure requirements	• No additional infrastructure required for pedestrian detection	• No additional infrastructure required for pedestrian detection
Known non-functional situations	• Low-light or night time • Low visibility (e.g., heavy rain, fog) • Vehicle traveling over 31 mph • Direct sunlight into camera • Camera obscured by dust, dirt, or grime • Cyclist traveling perpendicular to vehicle • Pedestrian obscured	• Low-light or night time • Low visibility (e.g., heavy rain, fog) • Uneven roadway elevation • Vehicle traveling under 7 mph or over 50 mph • Relative speed between vehicle and pedestrian approx. 7 mph or more • During left/right turn and for a few seconds after making a turn; also applies to curves • Blocked camera or radar • Pedestrian obscured • Pedestrian wearing white or bright clothing
Additional discovered non-functionality	• During turns* • Uneven road grade	• Pedestrian or bicyclist facing perpendicular to the vehicle* • Uneven road grade • Significant road curvature
Human factors assessment	• Clear warning prompts appropriate action • Easy to interpret symbols and audio • Straightforward operation and use • Cautionary alert may be confusing without proper knowledge • Drivers must be properly informed of performance limitations	• Clear warning directly prompts appropriate action • Easy to interpret symbols and audio • Straightforward operation and use • Adjustable timing preference improves likelihood of acceptance and proper use • Performance limitations described in vehicle manual and unlikely to be well-known to drivers

* Results are specific to this testing effort and may not apply to other scenarios.

The engagement of fully automated braking was intuitive and was effective for collision avoidance, but the unexpected and forceful jerk that results could be uncomfortable and reduce acceptance of the system among unprepared drivers. These effects on the driver also emphasize the importance of accurately deploying the automated braking system, as users are likely to mistrust or deactivate the system if it engages unnecessarily.

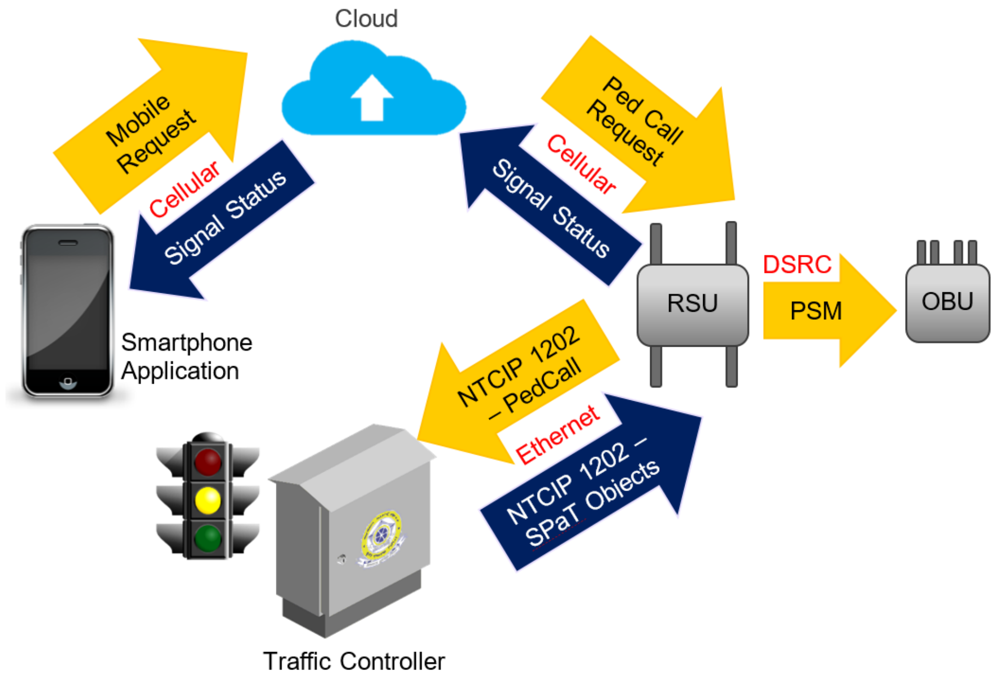
One of the drawbacks noted during this evaluation is the large number of edge-cases or non-functional scenarios identified by the manufacturer of the integrated vehicle system. The vehicle manual lists scenarios such as partial obscuration by bicycles, people, vehicles, heavy objects, and large, bulky clothing as factors that can reduce the system’s detection accuracy. In addition, scenarios such as coming around a curve are explicitly mentioned as potential non-functional situations. It is unlikely that drivers will consult this resource thoroughly prior to using the system; therefore, they may be unaware of its many limitations (e.g., low light, fog, turning around corners, etc.) and misuse the system. Limitations may also be forgotten with continued use. This could lead to abuse and/or excess trust or distrust in the system, which could affect usability over time. One way to improve driver knowledge may be to provide in-vehicle instructions, warnings, or reminders in addition to the existing vehicle manual.

SMARTPHONE-BASED TECHNOLOGY

Pedestrian Assistance Smartphone Application

In addition to vehicle-based safety technology, systems that communicate directly with existing infrastructure are being explored to improve pedestrian safety. These systems allow a greater degree of flexibility in the users alerted as well as the characteristics and format of the alert. For this project, a smartphone-based application that allows pedestrians to communicate with existing pedestrian infrastructure at signalized intersections was acquired for testing. Although the system was available for free download on Android and iOS devices, the necessary supporting infrastructure had only been installed in a few select locations at the time of testing. Therefore, the system was considered to be in late-term stages of market readiness at the time of evaluation.

Typically, users at an intersection equipped with pedestrian signal heads are required to activate a physical call button to request a crossing phase. However, at enabled intersections, the application allows users to request a crossing phase via their smartphone. This prevents users from having to locate and activate the call button and provides more direct access to the state of the crossing signals. The full system consisted of the smartphone application as well as proprietary software that operated via a wireless roadside unit (RSU). When the crossing request is activated in the application, the smartphone uses cellular connection to send the data to a Cloud-based server, which then relays information to the RSU. The RSU then communicates the request to the traffic controller via Ethernet to initiate a crossing signal. At the same time, information regarding the status of the pedestrian crossing signal is sent back to the smartphone to notify the user of when the crossing cycle began, the status of the countdown, and when the crossing cycle ends. The system’s communication architecture is illustrated in figure 17.



Source: FHWA.

PSM: Personal safety message; OBU: Onboard unit.

Figure 17. Illustration. Communication architecture of the smartphone pedestrian assistance application.

Because the application facilitates communication between the pedestrian and the crossing signal head, it is classified as a pedestrian-to-infrastructure (P2I) system. Drivers are expected to respond to the traffic and pedestrian signals as they normally would; in the system version tested, naïve drivers would not be alerted to the operation or presence of the system. However, an additional feature that was not tested in this effort allows the RSU to send personal safety messages (PSMs) to wireless onboard units (OBUs) installed in vehicles. With this feature, nearby vehicles equipped with direct communication technology would be alerted when a pedestrian using the application was in an enabled intersection. However, this functionality was not tested in the current study as it was not yet fully developed at the time of testing.

The application used the smartphone's GPS and heading measurements to detect when the user had entered a specified geofenced region close to the intersection or crosswalk. Once in these areas and facing a crosswalk, the pedestrian could request a crossing signal. The application then provided haptic (vibration), visual (symbol and text), and auditory (speech) alerts to the pedestrian to reflect the "Don't Walk" and "Walk" phases, as well as the time countdown. Text and speech features could be turned on or off by the user, along with a verbal response option to request a crossing using voice rather than button press.

The application was designed to help pedestrians with visual impairment navigate by eliminating reliance on the physical pedestrian call button and by guiding users to and through the crosswalk. To support safe crosswalk navigation, the application provided haptic feedback if it detected that the user was drifting away from the middle of the crosswalk. The users involved in this evaluation did not have mobility or vision impairments.

Testing

The application was tested at four marked, signalized crosswalks at the Pedestrian Technology Test Bed. Five trials in each crossing direction were conducted at each crosswalk. Figure 18 illustrates the four crossings used during the assessment. The length of the crosswalks ranged from approximately 21–32 ft, with a mean length of 24.5 ft. All crosswalks were between 10 and 11 ft in width. The application's performance was evaluated by measuring the following performance criteria, which reflect the feedback and steps performed it performs before, during, and after a crossing:

- The application recognized that the user was in an enabled intersection.
- The application recognized when a user was near a crosswalk but was not facing it.
- The application recognized when a user was facing a crosswalk.
- The application allowed the user to request a crossing.
- The application successfully transmitted the request to the traffic controller/signal head, resulting in a crossing sign at the intersection.
- The application sent the request to cross to the correct crosswalk intersection.
- The application reflected the "Don't Walk" phase prior to the start of the crossing cycle.
- The application's walk time countdown was synchronous with that of the signal head.
- The application communicated when the walk phase had ended or when the user had reached the other side of the intersection.

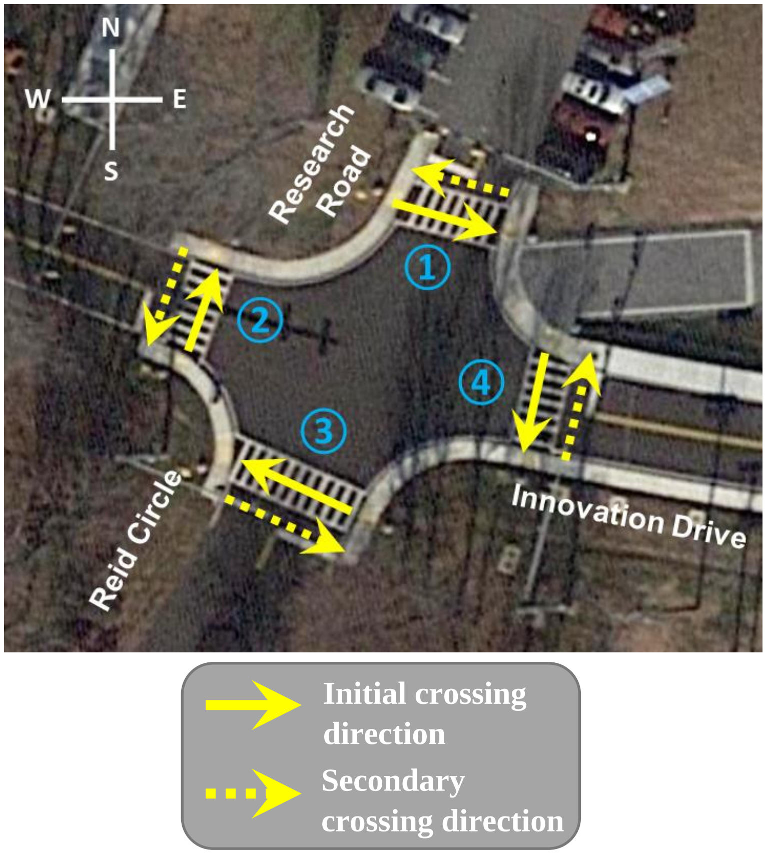


Figure 18. Photo. The test intersection with experimental approaches labeled.

The smartphone application was applicable to test case 1 (vehicle traveling straight while a pedestrian makes a perpendicular crossing), test case 2 (vehicle turning right while a pedestrian crosses straight across the roadway), and test case 3 (vehicle turning left while a pedestrian crosses straight across the roadway) from the test plan. The reliance on intersection infrastructure excluded test case 4 (vehicle traveling straight while the pedestrian travels straight along the roadway), as signalized crosswalks would not position pedestrians in a parallel direction with traffic. Because the application did not require vehicle interaction to function, the evaluation focused on pedestrian crossing functionality, behavior, and human factors. When functioning as intended, drivers are expected to comply with infrastructure signals that prevent vehicle traffic while the pedestrian crosses. The only exceptions to this are “right turn on red” or “left turn yield on green” scenarios during a crossing cycle. However, because the application did not alter the signals provided to drivers from those that are typically provided by the infrastructure, drivers would be expected to yield as they would in any non-V2P interaction. Therefore, a vehicle was not used for this evaluation. It was decided that potential conflicts in turning test cases could be extrapolated from the number of instances in which a pedestrian was unable to finish the crossing before the countdown completed or when the timing of the application status deviated significantly from that of the signal head.

Two phones were tested to evaluate the application's compatibility and performance across different operating systems. An Android phone running Android version 7.0 was assessed at all four crosswalks in both directions. For comparison, an iPhone running iOS version 12.0.1 was evaluated at two intersections with the longest and shortest crosswalks. Cellular service for each phone was provided by different carriers, both of which offer full coverage at the test site. No notable differences in signal quality were observed. Trials were conducted with the application's text and audio mode, in which written messages appear on the screen and are automatically converted to speech using the phone's native text-to-speech software. In this mode, the user requested to cross the intersection by swiping right on the screen. Five additional trials were completed in one direction at the longest crosswalk using the Android application's speech-recognition software, in which the user responded verbally to the option to request a crossing signal. This test was conducted on the Android phone and used the phone's native speech recognition software.

All trials were conducted with the traffic controller in actuated signal timing mode. After first starting up, the application often provided a message stating that GPS positioning was insufficient to provide accurate location data. The user was then instructed to calibrate the phone's heading by rotating the phone on its three axes several times. This orienting process was performed at the start of testing and whenever the application timed out due to inactivity.

Results

Android trials were conducted at all four intersection approaches/crossings in both directions. Trials were conducted with users who had typical sight and mobility functions. The weather was clear and sunny during Android trials. The Android application recognized the enabled intersection and when the user was near and facing a crosswalk in all 40 trials. The application indicated that the phone's GPS precision was 10 m (32.8 ft) on all trials. A successful crossing signal was transmitted and processed by the traffic controller in all but two trials (95 percent success rate). On the two trials in which the pedestrian call was lost, a vehicle approaching or near the intersection appeared to cause a conflict, resulting in the actuated traffic controller responding to the vehicle trigger and failing to queue and respond to the pedestrian call. Haptic feedback indicating that the user was drifting out of the crosswalk was not observed during any of these Android trials, as expected since users maintained a heading aligned with the crosswalk throughout the crossing.

Successful pedestrian calls always began with a "Don't Walk" on-screen and audio message, although this message was observed to be cut-off abruptly when the crossing cycle was immediately activated at the intersection after receiving the request. During the crossing phase, the signal head and application countdown were judged to be synchronized approximately 92 percent of the time (table 7). In the three trials (8 percent) which were perceived to be asynchronous, the application appeared to lag behind the signal head by approximately 0.5–2 s. In some trials, the application countdown lagged by about 1 s, but would then compensate to match the signal head timing by skipping one count. This resulted in the last several seconds of the crossing being synchronized, so these trials were categorized as synchronous.

Based on the application's ability to track the user's movement and location precisely, the system provided one of two messages at the end of the crossing signal phase. If the system detected that the user had reached the other end of the intersection, it provided the message, "You have reached the other side of the crosswalk." This message would interrupt a countdown in progress and prevented further messages regarding the pedestrian signal state from appearing in the application. The system sent this message in 53 percent of trials. If the application detected that the user had moved but could not confirm that the user had reached the other end of the intersection, it continued to count down until the timer reaches 0, followed by the message, "The light changed to red." The system sent this message in 39 percent of trials.

If the application did not detect that the user had moved into the crosswalk by a certain time relative to the countdown, the application provided the message, "Don't walk, it is too late to cross." This message was intended to prevent a user from entering the crosswalk during the flashing "Don't Walk" signal near the end of the countdown. In three trials (8 percent), the application sent this message when 4–5 s remained in the countdown. Given that the maximum time to cross the test intersections was 10 s (6 s pedestrian crossing time and 4 s clearance), the user was in the crosswalk, often halfway or two-thirds of the way to the opposite side of the intersection, when the message was received. Two of the three trials in which this occurred were observed at crossing 4 in figure 18, which was a shorter crosswalk with an immediate walk sign if no conflicts are present.

Table 7. Summary of Android testing metrics in visual/audio mode.

Android - Visual/text mode	**Percentage of valid trials**
Initial "Don't walk" message	100
"Don't walk, it is too late to cross"	8
Signal and application countdown in sync	92
"The light changed to red"	39
"You have reached the other side of the crosswalk"	53
Cross request signal lost/sent to wrong crosswalk	5
Total valid trials	**38**

To draw comparisons for system compatibility, the research team evaluated the iOS version of the application at two intersection approaches/crossings in both directions. The crosswalks (crosswalks 2 and 3 in figure 18) were adjacent to one another and represented the shortest and longest crosswalks at the test intersections. The application was tested in the default visual, text, and audio mode. The weather was clear and cloudy during testing.

The iOS application successfully detected the intersection, crosswalk proximity, and crosswalk heading, and sent requests to the correct crosswalk in all 20 trials. The application reported a GPS accuracy of 5 m (16.4 ft) throughout testing. After sending a request, the application provided a “Don’t walk” visual-audio message prior to the appearance of the cross signal in 100 percent of trials (table 8). No trials resulted in a “Don't walk, it is too late to cross” message. In 75 percent of trials, the application lagged approximately 1–2 s behind the signal head. This occurred more frequently in early trials. The application accurately detected that the user reached the other side of the intersection in 10 percent of trials, resulting in a “You have reached the other side of the crosswalk” message. “The light changed to red” message was received in 85 percent of trials. In one trial, a low battery warning appeared and prevented the end-of-walk-phase message from playing. In another trial, the application sent erroneous haptic feedback (2–3 vibrations) near the end of the crossing, while the researcher’s heading remained aligned with the end of the crosswalk. It is unclear why this feedback was received.

Table 8. Summary of iOS testing metrics

iOS - Visual/text mode	**Percentage of valid trials**
Initial “Don't walk” message	100
“Don't walk, it is too late to cross”	0
Signal and application countdown in sync	75
“The light changed to red”	85
“You have reached the other side of the crosswalk”	10
Cross request signal lost/sent to wrong crosswalk	0
Total valid trials	**20**

Speech Recognition

In addition to visual and text-to-speech modalities, the application could use the phone’s microphone and speech recognition software to record and process speech responses. The speech recognition feature was tested on the Android system in five trials conducted at the longest intersection in one crossing direction (crosswalk 3). Weather conditions were cloudy, but this was not expected to influence system performance as signal strength and connectivity were not affected. During these tests, the application functioned much like the other Android trials; proximity to the intersection and crosswalk and heading facing toward the crosswalk were all consistently detected, and the GPS precision was reported as 10 m (32.8 ft). In speech recognition mode, when the user faced a crosswalk, they received the message, “If you want to cross, say yes. If not, say no.” Default system tones indicated when the system was “listening”, when input had been received, and when the recording period ended. The researcher responded “Yes” to these messages to send the cross request to the network controller.

The application sent crossing requests to the correct signal head in four of the five trials; in one trial, it sent the request to an adjacent crosswalk. The researchers suspect that this was due to the relative amount of time needed for the application to play the “If you want to cross, say yes. If not, say no” message. In this case, it appeared that the researcher briefly oriented toward the other intersection, triggering the crossing message, which did not finish playing until the researcher was oriented toward the target intersection. This resulted in the researcher requesting a crossing when facing the desired intersection, while the application was still processing a trigger related to the adjacent intersection.

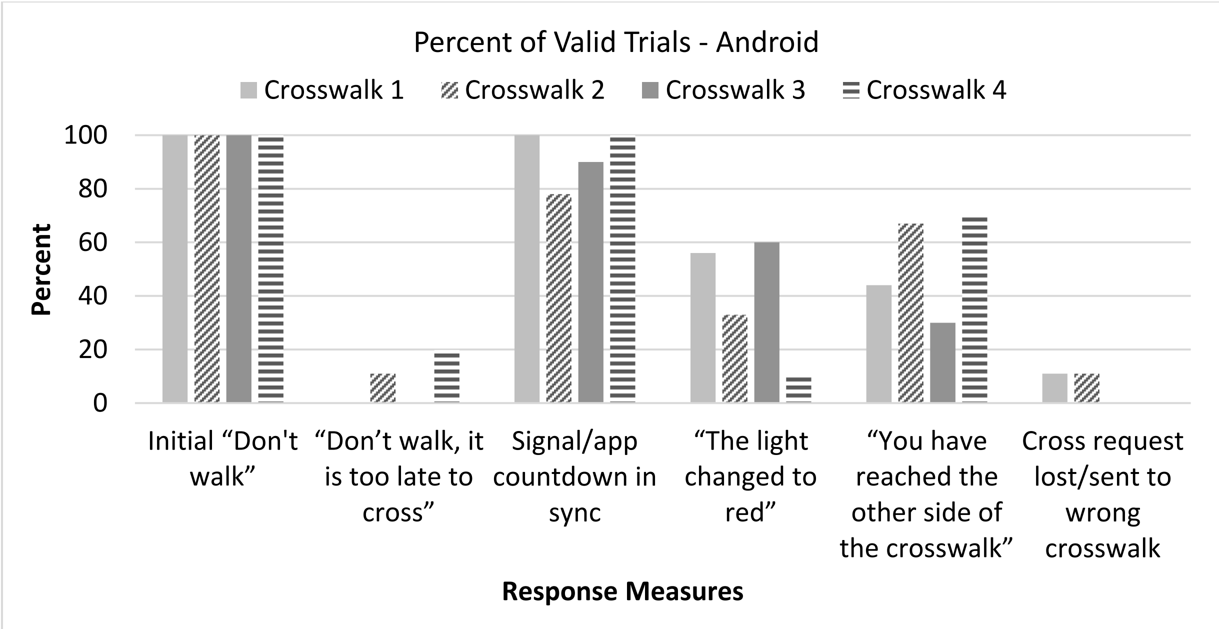
In the four remaining trials, the signal and application countdowns were synchronous, and the user received no erroneous haptic feedback while crossing the intersection. The application detected that the user reached the other end of the crosswalk half of the time (50 percent) and announced that the light changed to red on the other half of the trials. Table 9 provides a summary of speech recognition metrics.

Table 9. Summary of Android testing metrics in speech recognition mode

Android – Speech recognition mode	**Percentage of valid trials**
Initial “Don't walk” message	100
“Don't walk, it is too late to cross”	0
Signal and application countdown in sync	100
“The light changed to red”	50
“You have reached the other side of the crosswalk”	50
Cross request signal lost/sent to wrong crosswalk	1
Total valid trials	**4**

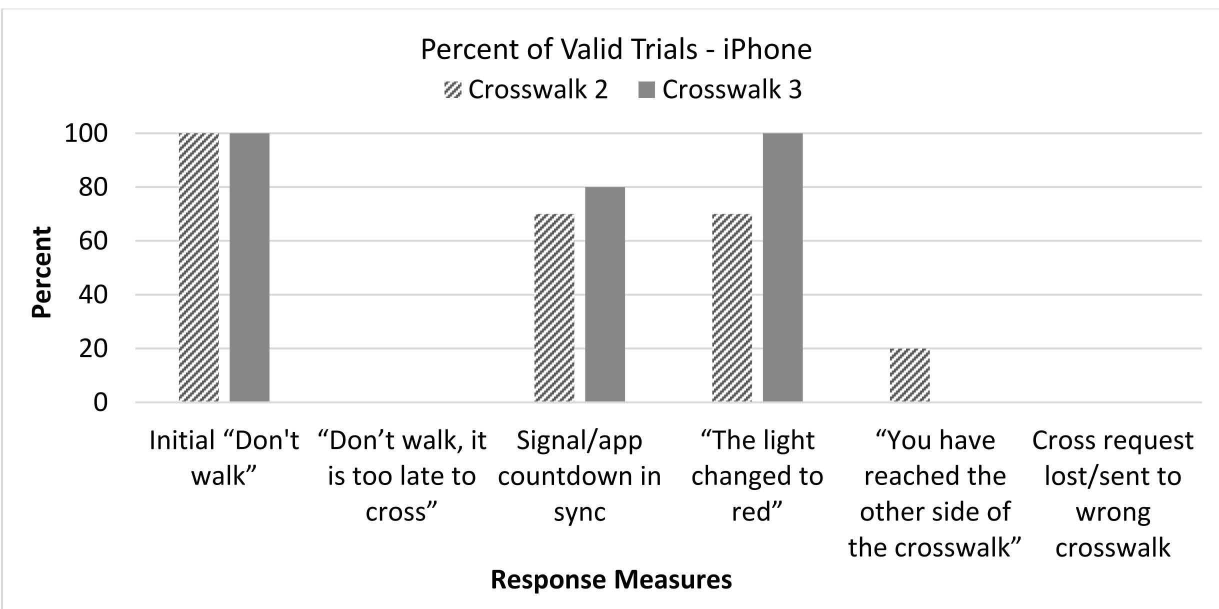
To investigate the potential effect of crosswalk length and geometry on application performance, performance metrics were separated by intersection as well as the type of test (i.e., Android, iOS, speech recognition). Figure 19 provides data for Android trials and figure 20 provides data for iOS trials. Metrics were combined over the two different crossing directions for each crosswalk and the crosswalk labels refer to the crosswalks shown in figure 18. This comparison allows for general comments on the behavior of the application under different conditions.

Performance between Android and iOS applications was generally comparable within a crosswalk location. However, Android testing resulted in three instances of “Don’t walk, it is too late to cross” messages, whereas the iOS version of the application provided none. These messages were most frequent in crosswalk 4. In addition, although the iOS application reported a finer GPS accuracy than the Android, the iOS application rarely detected that the user had reached the other side of the crosswalk. The iOS version also suffered from poorer countdown synchronization with the pedestrian signal head. Performance was fairly successful for tests conducted in crosswalk 3, which had the longest crosswalk, regardless of phone operating system. This may indicate that the longer distance improves system functionality by providing greater variability in location, which is easier for the system to detect properly.



Source: FHWA.

Figure 19. Graph. Distribution of response measures across four crosswalks with the Android version of the pedestrian assistance application.



Source: FHWA.

Figure 20. Graph. Distribution of response measures across two crosswalks with the iOS version of the pedestrian assistance application.

Taken across all three types (Android, iOS, and speech recognition), the application successfully initiated a crossing phase at the desired intersection in the majority (approximately 95 percent) of trials. The redundancy between graphics, on-screen text, and text-to-speech audio information improves message clarity and usability. However, on-screen text was observed to disappear randomly and would not reappear for several trials. During Android visual/audio testing, text information was lost in nearly 43 percent of trials.

Market Availability and Accessibility

The availability of the application in both Android and iOS devices at no cost to end users offers a larger group of users the opportunity to use the application. The research team found no major difference in application performance or usability between these two operating systems. The application interface was straightforward and required minimal user experience to operate.

One of the major concerns for usability in the current version of the application was the lack of feedback to the user regarding their actions. In the version tested, the system provided no feedback for a crossing request sent either through swiping or through voice command. A visual and audio confirmation could be helpful for the user to understand that the system has accepted their request. In addition, the application was observed to allow the cross request to be sent from a significant distance away from the crosswalk, as well when the user was heading diagonally toward the direction of the crosswalk. Some indication of the user's position on a map relative to the crosswalk or intersection may help them understand where the system "thinks" they are and could improve trust in and accurate use of the system. Table 10 provides an assessment of several usability factors related to the performance and usability of the pedestrian assistance application.

Table 10. Human factors assessment of the pedestrian assistance smartphone application.

Measure	Result
Alert clarity	• Clear, easy to understand visual/audio alerts directly reflect signal head messages • Redundant graphic, text, and audio messages improve clarity, accessibility
User access to technology	• Requires smartphone with network/data plan • Standard download on Android and iOS devices • No additional cost to user • Customization options improve accessibility for users with impairments or specific needs
Readiness	• App is in final stages of development; nearing market deployment • Few intersections equipped with necessary equipment*
Institutional and infrastructure requirements	• Signalized intersection • RSU equipped with proprietary plug-and-play software* • Smartphone application with network/data connection • Equipped intersections only identified within application • Vehicle warning component requires additional OBU

Table 10. Human factors assessment of the pedestrian assistance smartphone application. (continued)

Measure	Result
Examples of known non-functional situations	• Unequipped intersection • Poor or lost smartphone GPS signal • Cloud sever interruption due to weather or network connectivity
Additional discovered non-functionality	• Cross requests sent to wrong locations • Heading and physical crosswalk sometimes misaligned • Pedestrian crossing request lost when vehicle or other pedestrian call creates signal trigger conflict
Human factors assessment	• Operation requires some learning/experience • Lack of feedback regarding system actions may hinder user understanding and trust • Multi-modal and customizable interface improves accessibility and usability

* Alternative hardware is available to allow P2I communication without an RSU.

This pedestrian assistance application was primarily designed to support the safety and mobility of pedestrians with vision impairments. The redundancy between visual, audio, and haptic signals to communicate with the user supports accessibility and customization for a variety of users. Although the time needed to play the text-to-speech and speech recognition messages can be lengthy, users can modify playback speed using their phone's device settings. These features may also benefit users with slower average crossing speeds or hearing impairments. However, the human factors evaluation did not investigate specific population needs, which would be helpful for improving usability for desired target groups.

The message "Don't walk, it is too late to cross" received during in-progress crossings was found to be inaccurate and a hindrance to safe crossing. In addition to causing confusion for the user, the message stopped counting down the remaining few seconds of the walk phase. This feature could be removed or the threshold for time needed to complete the crossing could be made relative to the length of the crosswalk. However, the feature remains susceptible to poor GPS positioning, which could result in frequently inaccurate messages. Alternatively, simply communicating the state of the crossing may allow users to determine what is sufficient for them based on their needs. This or similar technology could be made even more useful if it allowed a user to request a longer cross phase, or to temporarily extend an existing one.

Discussion

Results suggest that the application has the potential to improve the safety and accessibility of requesting a crossing signal and remaining aware of the crossing cycle status throughout the crossing, both of which can be particularly challenging for mobility- or vision-impaired individuals at unfamiliar intersections. Detailed GPS positioning employed by this system also facilitates independence and safety for these individuals. The application's redundancy between visual, audio, and haptic feedback improve accessibility for a diverse range of users, thus potentially improving user safety through real-time and personalized services. These features support the potential benefits for safety and accessibility afforded by the application.

The results of both the Android and iOS assessments showed that the application successfully identified the intersection and crosswalk. The system also detected the correct crosswalk approach provided users were within the geofenced area and oriented the application towards the crosswalk. Users successfully requested the crossing signal in all trials when facing towards the crosswalk in the first attempt, although one request was sent to an incorrect crosswalk. In most of the Android trials (95 percent), the requested crossing signal was successfully transmitted to the controller and the pedestrian received the green signal to cross. In most of the walking signal phases (92 percent of Android trials), the signal head and application countdown were perceived to be synchronized during the countdown. Together, these results indicate the proper functionality and usability of the application.

The application was designed to provide haptic feedback when the user deviated from the middle of the crosswalk. However, the boundaries of the crosswalk appeared to be relative to initial heading rather than the physical crosswalk markings. Although this feature could be helpful to alert the user and encourage them to stay within the crosswalk boundaries, receiving unexplained and inaccurate vibrations may be confusing for the user.

The application informed the user of a successful crossing with the message, "You have reached the other side of the crosswalk," based on their movement and location. This feature could be particularly helpful for pedestrians with visual impairments. However, this message was received in only 53 percent of Android trials in audio and text mode. In the remaining trials, the user received the message that "The light changed to red," which the application provided when it could not confirm that the user had reached the other end of the intersection at the end of the walk phase.

Users were directed not to start crossing during the flashing "Don't Walk" phase with the message, "Don't walk, it is too late to cross." Although this message was intended to warn pedestrians who have not yet entered the crosswalk, users in this testing received this message in 8 percent of the trials well after they began crossing. Each time the system sent the message, 4–5 s remained in the countdown. This confused the user and could have potential safety implications for users in unfamiliar intersections.

Limitations in the application's effectiveness included reliance on GPS, which requires time to "warm up" to gain precision. There was also a lack of feedback regarding user actions and the status of the crossing request. Finally, the requirement for an RSU equipped with vendor-specific software could limit use of the application, as this equipment is not currently common at intersections. However, the vendor offers an alternative method for connecting the traffic controller and Cloud server that does not require wireless communications on a specific frequency band. With the deployment of more connected vehicle applications, the usability of this application can be expected to increase.

This application was one of only a few known systems that operated as a P2I system to allow pedestrians to cross an intersection using existing infrastructure. It was unique in that it communicated directly with the pedestrian and leveraged existing infrastructure to indirectly communicate with drivers. However, the infrastructure and technology required to enable the system are less likely to be found in rural or remote intersections. Although the application shows early promise for pedestrian safety and assistance for people with vision impairments, it remains in the final stages of development and requires further testing with members of the target audience to further identify benefits and areas of improvement.

Notably, the P2I application represents a step toward interconnected roadways that facilitate communication and safer behavior between vehicles and pedestrians. In the future, the components of this system can be leveraged toward vehicles to notify drivers of crossing pedestrians, which could potentially reduce incidences in common conflict scenarios, such as vehicles turning right on a red signal while a pedestrian crosses the intersection.

INFRASTRUCTURE-BASED TECHNOLOGY

Lidar Applications

Light detection and ranging (Lidar) technology has become increasingly popular and has developed rapidly in recent years. Lidar's ability to detect and track complex objects could be applied to identifying pedestrians at risk of collision. Although currently used in some autonomous vehicles and explored as applications for traffic management and enforcement at intersections, fully mature systems have yet to be deployed on the commercial market. Despite this, the high potential for this type of system to be applied to pedestrian safety, and the maturity of the component sensor technology, makes Lidar a likely candidate for use in future V2P systems, and therefore pertinent to the current discussion.

As a sensor technology, Lidar has several advantages over other sensors, including longer sensor range than typical radar, ability to acquire three-dimensional data, and the ability to constantly scan and update the "picture" of the physical environment. High-resolution, three-dimensional point clouds can then be used to identify and track objects in the environment with a fair degree of precision.(8) However, Lidar is also susceptible to obstruction and shadows caused by objects in the path of the sensor. Therefore, multiple Lidar units are required to provide full coverage of an area and improve detection and tracking reliability. Although these limitations are not unlike those that apply to radar or camera sensors, the cost of a single high-performance Lidar unit can reach as high as $75,000 USD, making multiple units difficult to manage financially. In recent years, however, the cost of Lidar has dropped dramatically and continues to do so, with some units available for as little as $5,000 USD.

Lidar sensors have been applied successfully for collision detection and mitigation purposes in some automated vehicle models. These systems generally function in a manner similar to that of the radar- and camera-based technologies reported earlier, with the addition or replacement of Lidar sensor data to improve the accuracy and precision of detection. However, the long and high-resolution sensor range of Lidar is also well-suited to infrastructure applications. This use offers the potential for improving pedestrian safety through permanent Lidar installations at locations where pedestrians are at high risk of collision. In such situations, pedestrians may be identified and tracked at crossings; this data could then be relayed to traffic controllers, pedestrian crossing infrastructure, or wireless equipment such as RSUs to automatically activate signals or wireless alerts to prevent collisions. Lidar sensors could augment or replace similar existing systems that have been implemented with short-range radar devices, which are less precise and less reliable. In addition, Lidar's ability to actively track 3D objects in space at a high level of precision offers the opportunity to tailor specific alert responses for individual instances of pedestrians and vehicles that are at risk of collision.

A Lidar-based pedestrian safety system incorporated into the infrastructure could also provide benefits that are not possible with the three types of systems investigated in this effort. First, a Lidar sensor system installed at a crosswalk or intersection would be passive and would not require the users to "opt-into" the system by installing or activating hardware or software. In addition, the burden of acquiring, maintaining, and operating the system would fall upon a government entity rather than individual users. Finally, a permanent installation allows all users in range of the sensor to benefit equally from the technology: Whereas vehicle-based systems benefit pedestrians encountered by equipped vehicles and smartphone-based systems only benefit pedestrians who have downloaded the application onto a compatible smartphone and activated it at an equipped location, a passive infrastructure-based technology could potentially target all pedestrians and vehicles within the covered area, regardless of equipment. These features could greatly improve the reliability, accessibility, and effectiveness of an infrastructure-based pedestrian safety system.

As Lidar technology continues to be refined and its costs made more accessible, many viable applications for improving pedestrian safety may result. The possibilities discussed here are only some of many potential options, illustrating that the technology in general holds meaningful promise for improving pedestrian safety through direct or indirect V2P communication.

CHAPTER 4. CONCLUSION

This project demonstrated the development of a standardized, holistic, and flexible assessment plan strategy and established a Pedestrian Technology Test Bed to assess the pedestrian safety benefits offered by emerging safety systems. The assessment plan was successfully applied to the investigation of three pedestrian safety systems with V2P components, which differed in the sensors employed, alert type and characteristics, intervention implemented, and types of users targeted for alert reception and response. The research team evaluated these systems in a Test Bed located at the U.S. Department of Transportation Turner Fairbank Highway Research Center, which allowed for customizable installation, operation, and performance measurement of each system. Together, the results of this effort can be applied to common scenarios observed in pedestrian and bicyclist collisions to better understand the strengths and weaknesses of each technology in terms of improving vulnerable road user safety.

The camera-based system is fairly accessible because it is low-cost and available for installation on most vehicle models. The system's ability to detect and warn drivers of at-risk pedestrians could be useful for reducing crashes in a variety of scenarios, such as in cases where pedestrians may behave unexpectedly or are difficult to see, when the driver is distracted from the roadway, and in crowded urban settings. However, the system's functionality is limited to low speeds (less than 31 mph), and reliable performance is limited to clear visibility conditions and even road grades. As explained in the system's operational manuals, adverse weather, low light, and roadway variability can reduce the reliability of detection. This system may therefore be most beneficial for reducing daytime crashes on roads where speeds are 31 mph or lower, which encompasses some, but not the majority of, fatal crash scenarios.

The camera- and radar-based system is slightly less susceptible to visibility issues due to the addition of short-range radar. The integrated detection, alert, and mitigation system is also becoming increasingly common as a standard feature in newer model vehicles, which suggests accessibility will continue to improve in the near future. Due to its use of similar sensor technology, the system's effectiveness is comparable to that of the camera-based system alone, but with limited additional functionality under low light conditions, which could aid in reducing some nighttime crashes. In addition, the overall effectiveness of the integrated vehicle system is improved by the active mitigation system provided by automated braking. This system operates within a wider range of speeds than the camera-based technology alone, but still only functions up to 50 mph and is affected by environmental conditions such as adverse weather, road grade and curvature, and pedestrian obstruction. The short-range radar is also affected by extremely hot or cold temperatures.

The smartphone-based P2I application was also highly accessible as a free download for wireless devices, which many pedestrians already own. The system's compatibility and comparable performance with both Android and iOS devices also improves its usability. Additionally, the application is designed to support the safety and independence of road users with vision impairments that could make them particularly vulnerable in roadway settings. Direct access to the state of the crossing signal on one's personal device could have benefits for sighted users as well. Because the technology is not reliant on external sensors, its functionality is independent of light conditions, roadway grade or curvature, and pedestrian density. However, the system does rely on fast, consistent data, a cellular network, and a Cloud server connection to operate reliably and efficiently. In addition, this particular application requires physical pedestrian signal heads. Pedestrian signal heads are most often found at marked intersection crossings, and these locations tend to have lower rates of pedestrian fatalities than, say, mid-block crossings. Because of this, the additional safety benefits to be gained by this implementation of a smartphone application may be greater for users with impairments but minimal for others. Nonetheless, the structure and concept for the P2I implementation illustrate the potential for pedestrian communication with infrastructure, and/or vehicles as a viable path for future pedestrian safety systems.

Finally, although market-ready, infrastructure-based V2P technologies using Lidar sensors could not be identified, future applications using Lidar have the potential to be highly accessible if they are passive and permanent installations. The limitations of Lidar as a sensor technology are generally well-known, such as limited visibility due to physical obstruction and Lidar shadow. Potential reliance on connected roadway infrastructure to facilitate communication with road users may also present challenges for safety applications using Lidar. However, the scenarios that benefit most from an infrastructure-based system would depend upon the specific implementation of Lidar technology, and further speculation on system effectiveness is not warranted until further development and testing are conducted.

The findings from this testing can be applied to identify the scenarios in which different systems may be more effective at improving vulnerable road user safety. Table 11 summarizes three key elements that influence the potential to yield real-world safety benefits: accessibility, system effectiveness, and system limitations. The summary provided in table 11 is specific to the technologies tested in the current effort and do not necessarily apply to other systems.

Table 11. Summary of technology effectiveness

System	Accessibility	Limitations	Effectiveness
Camera-Based	• Inexpensive • Aftermarket installation • Acquired through certified vendors • Compatible with most vehicle models	• Speed under 31 mph • Direct or low light • Adverse weather • Road grade • Road curvature	• Older/intoxicated pedestrian • Distracted driver • Crowded urban settings
Camera- and Radar-Based	• Increasingly common in newer models • Often no additional cost • Intuitive • Integrated with vehicle systems	• Speed 7–50 mph • Adverse weather • Road grade • Road curvature • Temperature	• Older/intoxicated pedestrian • Distracted driver • Crowded urban settings

	• Customizable settings		• Low light (limited)

Table 11. Summary of technology effectiveness. (continued)

System	Accessibility	Limitations	Effectiveness
Smartphone-Based	• Free download and installation • Compatible with Android and iOS devices • Customizable features • Tailored toward special populations	• Smartphone • Network/data connection • Pedestrian crossing infrastructure • RSU (potentially)	• Low light • Road grade • Road curvature • Crowded urban settings • Mobility-impaired pedestrians
Infrastructure-Based	• All users at equipped location • Independent of pedestrian state/action • Communication with equipped vehicles (potentially)	• Multiple units for full coverage • Potentially expensive • Connected infrastructure/ vehicle (potentially)	• Requires additional testing

LOOKING AHEAD

The results of this effort represent an important step in evaluating the strengths and weaknesses of highly diverse pedestrian safety and V2P implementations. Framing the safety effectiveness of technologies within a common perspective of accessibility, functionality, and applicability to known high-risk scenarios enables researchers to advance the development and effectiveness of safety technology for vulnerable road users.

As automated vehicle and assistive driving technologies continue to grow in complexity and market accessibility, new opportunities for pedestrian and bicyclist safety will undoubtedly emerge. For example, with the increasing reliability of connected vehicle technology and a rising number of vehicles equipped with wireless communication equipment, vehicles may collect more accurate spatiotemporal data related to pedestrian movement via constant V2P or V2I communication. A connected network would improve the accessibility, equitability, and range of scenarios in which pedestrian safety technologies could efficiently operate. For example, a vehicle-based collision detection and mitigation system supplemented by infrastructure data regarding the crossing signal cycle and detailed location data from a pedestrian sensor or device would likely be capable of more reliably and efficiently preventing collisions. In addition, pedestrians may be able to take more active control of their safety with devices that communicate directly with vehicles via wireless signals. Such devices could circumvent the fiscal and logistical challenges posed by a reliance on permanent physical infrastructure, as well as the lag associated with multi-point pedestrian-to-Cloud-to-infrastructure communication. However, a system that puts the onus of broadcasting a safety message on vulnerable road users themselves may cause the system to be ineffective when a pedestrian does not possess the necessary equipment or fails to activate it appropriately. However, implementing pedestrian-based systems in conjunction with permanent and physical infrastructure may provide the utmost safety benefit and improve efficiency. More testing would be necessary to evaluate this prediction.

Pedestrians with accessibility needs may benefit from using devices that broadcast safety messages through connected networks. As opposed to routing messages through a server, direct communication with nearby vehicles, infrastructure, and other transportation users could provide seamless connectivity from trip origin to destination. Future advancements in sensors and communication methods may incorporate new wireless technologies for the transfer of safety information within the system. However, many uncertainties will have to be addressed before implementing these emerging communication technologies, including message security, data loss, and latency of message transfer.

This assessment plan will be further enhanced as more commercial V2P technologies become available for testing. In the meantime, there will be a continuing effort to increase the capabilities of the FHWA Test Bed to improve its reliability and capability to test more advanced V2P technologies. Immediate steps include attempts to acquire infrastructure-based pedestrian detectors and/or Lidar units for installation at the intersection.

ACKNOWLEDGEMENTS

The original map in figure 10 is the copyright property of Google® Earth™ and can be accessed from https://www.google.com/earth.[9] The map overlays comprise a set of arrows indicating the direction of vehicle approach in the test scenario.

The original map in figure 10 is the copyright property of Google® Earth™ and can be accessed from https://www.google.com/earth.[9] The map overlays comprise a yellow arrow and a red arrow, with the yellow arrow indicating the direction of the vehicle's approach during pedestrian trials and the red arrows indicating the vehicle's approach during bicyclist trials.

The original map in figure 15 is the copyright property of Google® Earth™ and can be accessed from https://www.google.com/earth.(9) The map overlays comprise a dashed line representing the approximately 105 ft of length on the direct approach and a gold start indicating the approach start point.

The original map in figure 18 is the copyright property of Google® Earth™ and can be accessed from https://www.google.com/earth.[9] The map overlays comprise a solid line with an arrow representing the initial crossing direction and a dashed line with an arrow representing the secondary crossing direction. In addition, the crossings are labeled 1 through 4, the cardinal directions are indicated, and the names of the roads that intersect are labeled.

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