FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

Connected Vehicle (CV) Infrastructure – Urban Bus Operational Safety Platform

MAY 2019

FTA Report No. 0133
Federal Transit Administration

PREPARED BY
Battelle Memorial Institute

U.S. Department of Transportation
Federal Transit Administration

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SPONSORED BY

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Office of Research, Demonstration and Innovation
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1200 New Jersey Avenue, SE
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Metric Conversion Table

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
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liter	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)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

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13. ABSTRACT

This document is the project report for the Connected Vehicle Infrastructure—Urban Bus Operational Safety Platform Project also known as the Enhanced Transit Safety Retrofit Package (E-TRP) project. The report describes the project's background and purpose, summarizes its activities and results, includes results from an independent evaluation, and provides insight into the lessons learned and experiences captured through the project.

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ABSTRACT

This document is the project report for the Connected Vehicle Infrastructure – Urban Bus Operational Safety Platform project also known as the Enhanced Transit Safety Retrofit Package (E-TRP) project. The report describes the project's background and purpose, summarizes its activities and results, includes results from an independent evaluation, and provides insight into the lessons learned and experiences captured through the project.

EXECUTIVE SUMMARY

A team led by Battelle Memorial Institute (hereafter Battelle), on behalf of the Federal Transit Administration (FTA), developed an enhanced version of the Transit Safety Retrofit Package (TRP) system that was originally part of the US Department of Transportation (USDOT) Safety Pilot Model Deployment, a large-scale Connected Vehicle (CV) deployment. The enhanced TRP (E-TRP) is based on experience gained and lessons learned from the earlier system, with the current focus on reducing pedestrian and vehicle conflicts with transit buses in the greater Cleveland, Ohio, metro area.

The E-TRP features enhanced versions of the Pedestrian in Crossing Warning (PCW) and Vehicle Turning Right in Front of Bus Warning (VTRW) CV applications. Key technologies deployed include Dedicated Short-Range Communications (DSRC) for vehicle-to-vehicle and vehicle-to-infrastructure communication, High-precision Global Navigation Satellite System (GNSS) for vehicle tracking, and Forward Looking Infrared (FLIR) cameras for enhanced pedestrian detection.

The E-TRP was installed on 24 Greater Cleveland Regional Transit Authority (GCRTA) transit buses for field testing at 3 locations—one signalized intersection, one non-signalized intersection, and one mid-block crossing. The buses operated in revenue service for a period of six months to collect data for evaluation of the performance of the system, safety impacts, return on investment, and driver acceptance. With the field test completed in August 2018, the evaluation results and lessons learned are presented in this project report. Table ES-1, E-TRP Evaluation Summary, provides a synopsis of the results which are further detailed in this report, along with lessons learned from the project.

Table ES-1

E-TRP Evaluation Summary

Evaluation Criteria	Performance Measures	Key Findings
System Performance	• False Alarm Rate	• 81% correct alerts (10% incorrect alerts and 9% false alarms).
Safety Impact	• Collision Reduction	• 16% increase in drivers' response (braking) to PCW warning situation. • 18% decrease in average drivers' reaction time (braking) to PCW warning situation.
Return on Investment	• Cost Savings	• 20 years[1] to recuperate investment cost in the form of E-TRP's safety impact of reducing risk of collision.
Driver Acceptance	• Usability • Perceived Safety Benefits • Unintended Consequences • Desirability	• Only 13 of 751 E-TRP drivers (less than 2%) participated in the survey. With this small sample size, conclusions drawn from the survey could not provide statistically meaningful findings for this criterion. For drivers that responded, results were mixed.

[1]Based on GCRTA transit collision data for a five-year period between April 2011 and May 2016, which included no fatalities. If one fatality over the five-year period was added to the Estimated Value of Preventing Injuries based on USDOT's VSL and MAIS Classification System, the return on investment period would drop from 20 to 5 years.

SECTION

1

Background

The Federal Transit Administration, together with the National Highway Traffic Safety Administration (NHTSA), Federal Highway Administration (FHWA), and the Intelligent Transportation Systems Joint Program Office (ITS JPO) have made significant investments in connected vehicle (CV)-based transit safety and mobility research (2). This research includes both vehicle-to-vehicle (V2V) and Vehicle-to-Infrastructure (V2I) safety applications, both unique to the transit environment, as well as those common to connected vehicles.

Under previous contract, as part the USDOT Safety Pilot Model Deployment, Battelle developed a suite of transit-focused applications called the Transit Safety Retrofit Package (TRP). The TRP application suite allowed transit vehicles to communicate using V2V and V2I technologies, with the goal of enhancing both transit vehicle and pedestrian safety. In 2013, the TRP technology, including the Pedestrian in Crossing Warning (PCW) and Vehicle Turning Right in Front of Bus Warning (VTRW) and applications,[2] was deployed on three University of Michigan transit vehicles for one year. The benefits of the applications in conjunction with Dedicated Short-Range Communications (DSRC) wireless technology were tested and evaluated. The TRP Project Report (16) and Evaluation Report (17) document the TRP project results.[3]

In 2015, as a part of the Innovative Safety, Resiliency, and All-Hazards Emergency Response and Recovery Research Demonstration (SRER) research program, FTA awarded Battelle Memorial Institute (Battelle) $2.74 million to conduct the Connected Vehicle Infrastructure – Urban Bus Operational Safety Platform project, more commonly referred to as the E-TRP project. The E-TRP project leveraged the foundational research and development performed under the earlier TRP project. The activities under the E-TRP project enhanced and refined the capabilities of the PCW and VTRW applications, customized them for the urban transit operating environment, and deployed them under real-world conditions (2). The enhancements addressed the need for increased safety within the urban transit operational environment and included:

- Improved pedestrian detection system
- Improved locational accuracy of the transit vehicle
- Improved interface for the transit vehicle driver (visual and audible)
- Newer DSRC radios
- On-board storage capabilities

[2]TRP also included three basic safety applications—Forward Collision Warning (FCW), Emergency Electronic Brake Lights (EEBL), and Curve Speed Warning (CSW).

[3]These documents may be obtained by request to FTA (steven.mortensen@dot.gov).

- Remote system management
- Enhanced PCW safety application
  - Use of turn signals to determine intended bus path (lane-level accuracy could not be met, so E-PCW required bus turn signal input)
  - Signalized AND un-signalized AND mid-block intersections
  - Operational for ALL intersection approaches, not just left and right turn
- Enhanced VTRW safety application
  - Activation: door open/close (signifying bus stop) with equipped vehicle approaching to activate application (vs. geo fence)

SECTION

2

Description andPurpose

Battelle partnered with the Greater Cleveland Regional Transit Authority (GCRTA) to deploy, test, and evaluate the E-TRP system at three intersections in Cleveland, Ohio. In total, 24 GCRTA transit vehicles of different makes and models that travel through the three intersections were equipped with the E-TRP system.

The E-TRP system leveraged the technologies and applications developed under TRP and included additional capabilities to enhance and improve transit vehicle and pedestrian safety in an operational context (1).The system relied heavily on technologies and approaches demonstrated in previous USDOT deployment projects and vehicles. The E-TRP System consisted of two physically-separate subsystems—an on-board, transit vehicle-based subsystem and an infrastructure-based subsystem—at each of the selected street intersections. Figure 2-1 shows the major components of the on-board subsystem, which was installed as a retrofit kit (like the TRP project) on each of the 24 transit vehicles. Figure 2-2 shows the major components of the infrastructure subsystem installed at each of the three street intersections. A summary of their requirements and design is included in Section 3.

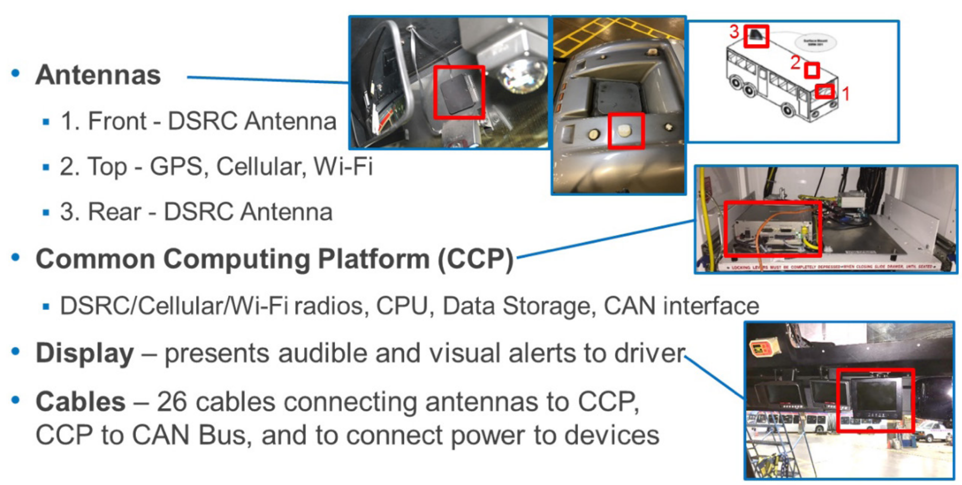

Figure 2-1

On-board subsystem equipment

Figure 2-2

Infrastructure subsystem equipment

Table 2-1 and Figure 2-3 show the location and type of deployed intersections. Each of these intersections was equipped with Forward-Looking Infrared (FLIR®) cameras and other equipment to detect pedestrians and transmit messages to the equipped transit vehicles to generate E-PCW alerts when appropriate. Figures 2-4, 2-5, and 2-6 show the layout of equipment at each of the deployed intersections.

Table 2-1

Intersections with E-TRP Technology Deployed

Site ID	Intersection	Intersection Type
1	E 12th St and Superior Ave	Signalized intersection
2	E Roadway and Rockwell Ave	Non-signalized intersection
3	E 19th St and Euclid Ave	Mid-block crossing

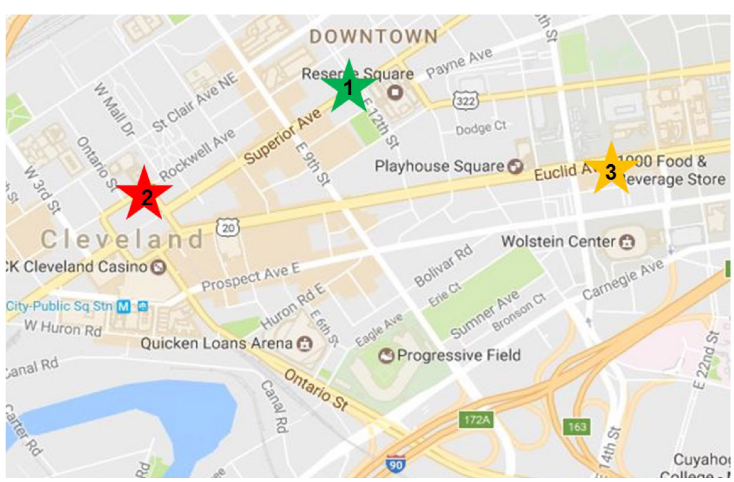

Figure 2-3

Map of intersections with E-TRP technology deployed

Figure 2-4

E 12th Street and Superior Avenue equipment layout

Figure 2-5

E Roadway and Rockwell Avenue equipment layout

Figure 2-6

E 19th Street and Euclid Avenue equipment layout

Table 2-2 provides a list of the types and number of transit vehicles that were equipped with the E-TRP onboard system as well as a mapping of each equipped vehicle type to each equipped intersection it traversed. For each mapping, the relevant bus routes are shown.

Table 2-2

Summary of E-TRP Transit Vehicles Mapped to Intersections by Route

Transit Vehicles	E 12th St and Superior Ave	E Roadway and Rockwell Ave	E 19th St and Euclid Ave
New Flyer Hybrid Articulated – HealthLine branding (4 vehicles)		Health Line	Health Line
New Flyer Diesel Articulated (8 vehicles)	Routes 22, 26		
New Flyer Diesel Articulated – CSU branding (4 vehicles)	Route 55	Route 55	
Gillig Trolley (8 vehicles)	B-Line, C-Line	E-Line	E-Line

The E-TRP system deployed E-PCW and E-VTRW safety applications. E-PCW was a V2I application that alerted transit operators driving E-TRP-equipped buses when pedestrians were detected in equipped roadway crossings and curbsides in the potential path of the vehicle. "Inform" alerts were generated for pedestrians on the curb in the potential path of the bus, and "Warning" alerts were generated for pedestrians in the crosswalk in the path of the bus. Alerts were generated only if the pedestrian was not "protected" by a traffic signal red light.

E-VTRW was a V2V application that alerted transit operators driving E-TRP equipped buses of other CV-equipped vehicles making an illegal right turn in front of the bus as it departs from a near-side bus stop. "Inform" alerts were generated as the other vehicle moved from behind to beside the bus, and "Warning" alerts were generated as the other vehicle started to turn right in front of the bus. Alerts were generated only after the bus doors had been cycled open then closed and the bus was in forward gear without the foot braked applied.

Table 2-3 summarizes the E-PCW and E-VTRW functionality with respect to the application's input, processing, and output.

Table 2-3

Summary of E-TRP Application Inputs, Processing, and Outputs

Functionality	Applications	
	E-PCW	E-VTRW
Application Input	• Obtains position and time information for the transit vehicle (Latitude, Longitude, Timestamp, Heading, Speed, Elevation) • Receives geometric intersection information (Map Data Message [MAP]) and Signal Phase and Timing (SPAT) information (SPaT Message) from the roadside infrastructure DSRC broadcast • Receives status of crosswalks (pedestrians detected, zones affected, etc.) from infrastructure DSRC broadcast (part of SPaT message) • Obtains vehicle information (CAN Bus) (turn signal status)	• Obtains position and time information for the transit vehicle (Latitude, Longitude, Timestamp, Heading, Speed, Elevation) • Receives notification of triggering event (i.e., Basic Safety Message (BSM)) from DSRC-equipped vehicles • Obtains vehicle information (CAN Bus) (door status, gear position, brake status)
Processing	• Determine if transit vehicle movement, signal phase, and pedestrian activity warrant inform or warn alert. • Determine if heading and position warrants inform or warn alerts to be issued.	• Determine the position of the transit vehicle relative to other vehicle traffic via the BSM received from DSRC. • Determine if heading and position warrants inform or warn alerts to be issued.
Application Output	• Provide real-time situational awareness to driver	• Provide real-time situational awareness to driver

Figure 2-7 shows a real-world E-PCW warning displayed to a driver along with the pedestrian triggering the warning.

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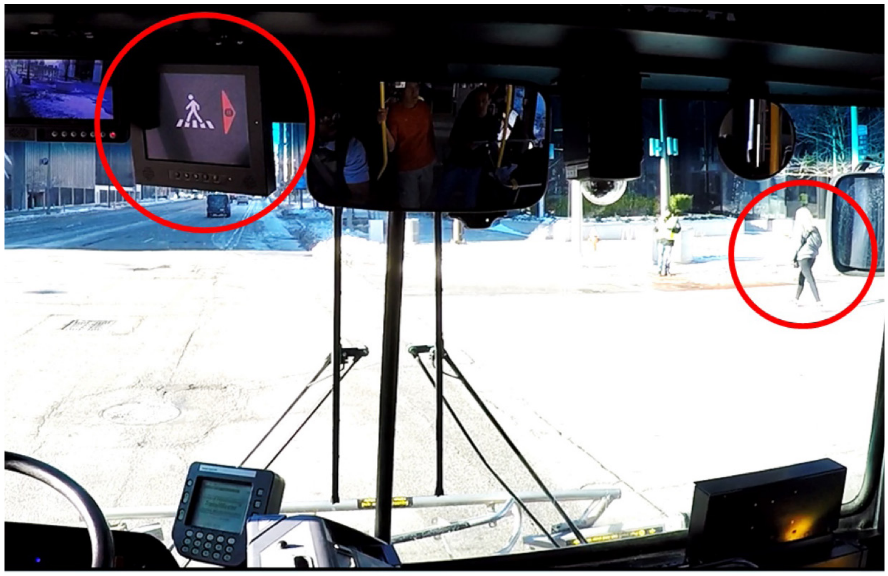

Figure 2-7

E-TRP in transit vehicle, E-PCW warning

Figure 2-8 shows an E-VTRW warning displayed to a driver in a closed-loop test environment, where the warning image is overlaid so that both the remote vehicle and the warning can be seen. E-VTRW was tested in the closed-loop environment but was not part of the evaluation, as there were no other vehicles (e.g., light vehicles) equipped with DSRC other than the 24 buses. Thus, E-VTRW alerts were not seen in the field, other than a rare occurrence of a DSRC-equipped bus turning in front of another DSRC-equipped bus that was departing from a near-side bus stop.

Figure 2-8

E-TRP in transit vehicle, E-VTRW warning

SECTION

3

Project Activities Summary

The subsections discussed in Section 3 sequentially describe the project activities that were performed under the E-TRP project, from kickoff to the end of the period of performance.

User Needs and System Requirements

As discussed in the Sections 1 and 2, the E-TRP system design leveraged Battelle's TRP system design developed in 2013. The purpose of the E-TRP project was to continue making improvements to the system and reflecting lessons learned from the TRP project into the design of the E-TRP system. During the kickoff phase of the E-TRP project, the Battelle Team met with the Federal Transit Administration (FTA) and GCRTA to discuss and identify the needs of the system. Once all system needs were agreed upon, the needs were analyzed and converted into the Concepts of Operations (ConOps),[4] (9) which described the current state of operations with respect to the CV technology in transit vehicles, established the reasons for change, and discussed the E-TRP system in terms of its features and operations. The ConOps was then transformed into a set of system requirements written by the Battelle[5] (5). The system requirements were written to convert the needs of the stakeholders into a technical view of a solution that met the operational needs of the user that could be verified and validated through inspection, demonstration, testing, or analysis (6).

Table 3-1 summarizes the E-TRP enhancements desired by the stakeholders and the resolutions put into action to improve the overall operations of the system.

Table 3-1

Summary of E-TRP Enhancements and Resolutions to Improve System Design

E-TRP Enhancements	Resolutions
Integration of improved pedestrian detection system (E-PCW only)	• Vigorous pedestrian detection system testing and evaluation in Battelle transportation laboratory and live-test intersection environment. • Decision to use FLIR thermal vision pedestrian detection technology. • Technology can discern between pedestrians and vehicles. • Thermal cameras have a wide operating environment, including below freezing, at night, and in rain and snow. • Multiple pedestrians can be detected in different locations at the same time. • Detections can differentiate between pedestrians at the curbside and in the crosswalk. • Low false-positive detection rate.

[4]This document may be obtained by request to FTA (steven.mortensen@dot.gov).
[5]This document may be obtained by request to FTA (steven.mortensen@dot.gov).

Table 3-1 (cont.)

Summary of E-TRP Enhancements and Resolutions to Improve System Design

E-TRP Enhancements	Resolutions
Improvement of transit vehicle locational accuracy	• High-precision Global Navigation Satellite System (GNSS) receives chip integrated into CCP. • Newer model of GPS antenna used on transit vehicle
Improvement of transit vehicle driver interface	• Improved Transit Vehicle Operator (TVO) display with reduced glare and higher volume capability. • Display installed near other pre-existing displays rather than near the bottom of the windshield. • Integration of display with pre-existing rear backup camera. • New visual alert and warning graphics developed with Battelle's Human Factor's consultation with GCRTA. • New audio alerts and warnings developed with Battelle's Human Factor's consultation with GCRTA.
Integration of newer DSRC radios	• Newer in-vehicle and roadside DSRC radios used in system design (RSU 4.0 specification and J2735-2015).
On-board storage capabilities	• Common Computing device (CCP) designed and developed for computer processing and on-board storage.
Remote system management design	• Development of cloud-based management system for remote data storage and remote fleet monitoring and management. • Integration of cellular connectivity into the CCPs inside the transit vehicles and at the roadside for remote system monitoring and management. • Integration of remote reboot hardware inside the transit vehicles and at the roadside.
Improvements made to E-PCW and VTRW applications	• More accurate and timely alert and warning notifications.

System Design

The E-TRP system was made up of two main hardware subsystems as shown in Figure 3-2—the In-Vehicle Subsystem (IVS), a transit vehicle-based subsystem, and a Roadside Subsystem (RS) at each of the selected street intersections, as documented in the E-TRP Architecture and Design document[6] (1). Both subsystems shared some common hardware and software subsystems and have a subsystem unique to themselves.

The IVS included the CCP hardware complete with Cellular and DSRC communications links and integrated GNSS and CAN, in addition to the Human Interface Subsystem (HIS) and software application components installed within the transit vehicle. The incoming DSRC messages, along with the GNSS and

[6]This document may be obtained by request to FTA (steven.mortensen@dot.gov).

CAN data served as input to the software applications running on the in-vehicle CCP, which processed the data and initiated alerts on the display inside the bus. Those changes and the messages that triggered them were uploaded to the Cloud Data Management Subsystem (CDMS) via the Cellular interface. Likewise, active monitoring of the CCP and the software applications occurred remotely over Cellular through the Remote Administration Access Point (RAAP).

The E-PCW application also required CCP hardware, using the Cellular component for data upload to the CDMS and remote access via the RAAP. The Pedestrian Detection Subsystem (PDS) provided detection input to the software applications that generated the MAP and Signal, Phase, and Timing (SPaT) messages, which were then communicated over the DSRC radio; however, the DSRC and GNSS capabilities on the CCP were originally intended to be used for the roadside subsystem, but those decisions were revised later as discussed in the System Modifications section below.

External to the E-TRP system of interest, but supporting its mission, was the transit vehicle itself, which provided data to the E-TRP system CCP about the operational situation of the vehicle, including GNSS data and vehicle telematics data such as speed, turn signal operations, and brake status. The DSRC-enabled Personally Remote Vehicle (ROV) subsystem represented other DSRC-enabled non-transit vehicles that may have interacted with the E-TRP transit vehicles on the roadway. The E-PCW application was deployed at both signalized and un-signalized crosswalks (at the three designated intersections). The E-PCW application leveraged the SPaT data from the Siemens M50 traffic signal controller at the E 12th Street and Superior Avenue signalized intersection.

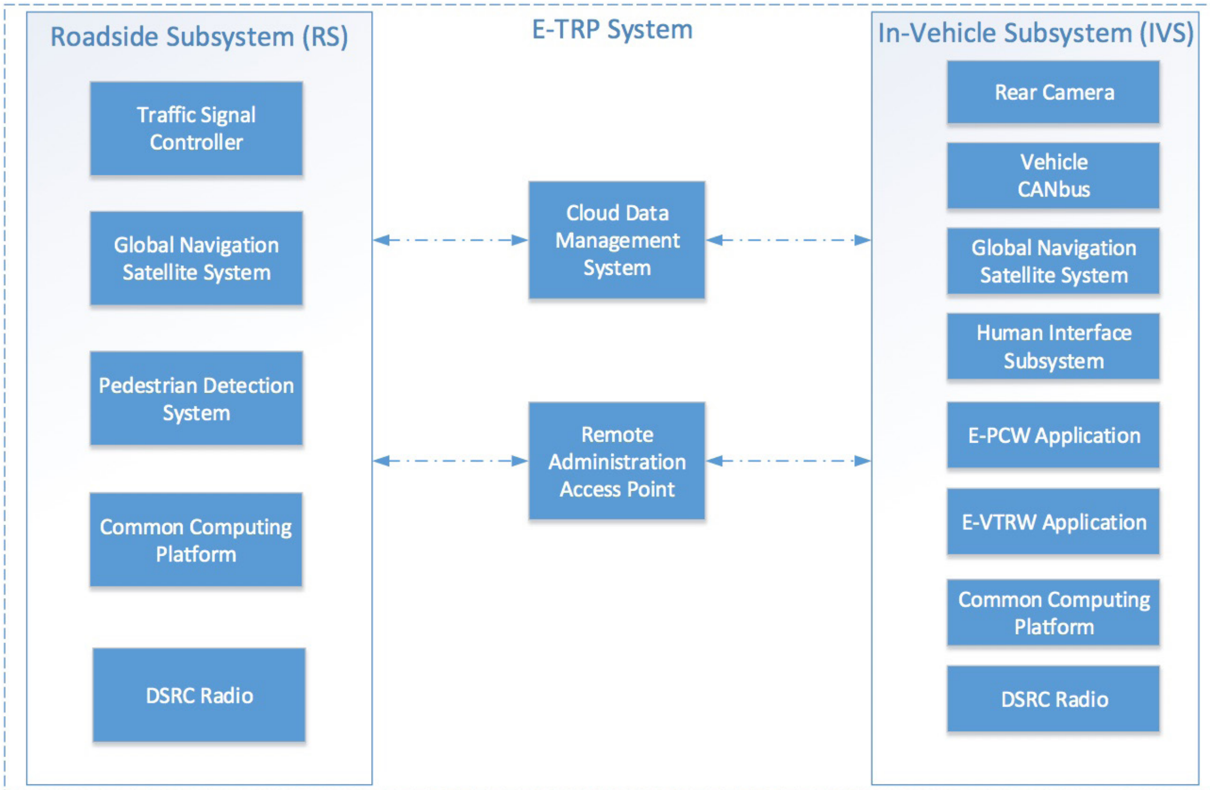

Figure 3-1

Diagram of E-TRP system

The E-TRP system elements from the RS and IVS shown in Figure 3-1 are described below.

- **Common Computing Platform (CCP)** – The heart of the E-TRP system was the CCP, which was used in both the on-board and the infrastructure systems. The CCP was the central processor providing the interface to the other subsystems and hosting the software applications. The CCP also housed the following:
  - **Dedicated Short-Range Communications (DSRC) Radio** – DSRC radios were used in both the on-board and infrastructure-based systems and served as the low-latency wireless communications method between the two systems. One DSRC Radio was installed at each of the three deployed intersections as well as one on each bus, for a total of 27 DSRC Radios deployed for V2I communications.
  - **Cellular Communications** – Each CCP was outfitted with a cellular modem to allow for wireless connectivity to the CDMS.

  - **Global Navigation Satellite System (GNSS)** – A GNSS module was used in the on-board system to provide real-time positioning data to the CCP.
  - **Controller Area Network (CAN)** – A standard automotive interface to the vehicle telemetry data. This project specifically used brake status, gear position, turn signal and door status.
- **Cloud Data Management Subsystem (CDMS)** – The CDMS served as the remote portal for the on-board and infrastructure-based systems collected data storage and retention and for monitoring of the deployed fleet system health status (near real-time operational state dashboard).
- **Pedestrian Detection Subsystem (PDS)** – Intersection-based sensors (FLIR® cameras) to detect the presence of pedestrians inside a specified detection zone. The PDS contained its own processing and software capability, which would then communicate to the infrastructure-based CCP when a pedestrian was detected.
- **Human Interface Subsystem (HIS)** – The E-TRP interface to the transit vehicle driver was developed to provide the transit vehicle driver information and status alerts for the E-PCW, E-VTRW, and Rear Camera Integration to Driver Display applications.
- **Remote Administration Access Point (RAAP)** – An access point implemented over a Virtual Private Network (VPN) accessible only by Battelle to which each CCP connected over the cellular network.
- **Software Applications** – E-PCW and E-VTRW are two CV applications that were improved and enhanced as part of this project. Rear Camera Integration (RCI) to the HIS was also developed software for this system.
- **DSRC-enabled Personally Remote Vehicle (ROV)** – The E-VTRW application was enabled when a ROV was present behind an E-TRP equipped transit bus and activated an alert or warning when the vehicle made an illegal right turn in front of the transit bus as it departed from a near-side bus stop.

Figure 3-2 provides a high-level architectural view of the E-TRP System, including communication protocols between subsystems and external components. Note that the USDOT Security Credential Management System (SCMS) was planned but not implemented due to timing (SCMS was not available in time for use on this project). For the purposes of this project, DSRC message security was not employed based on the low risk of a DSCR security breach and the low impact in the unlikely event that one was to occur.

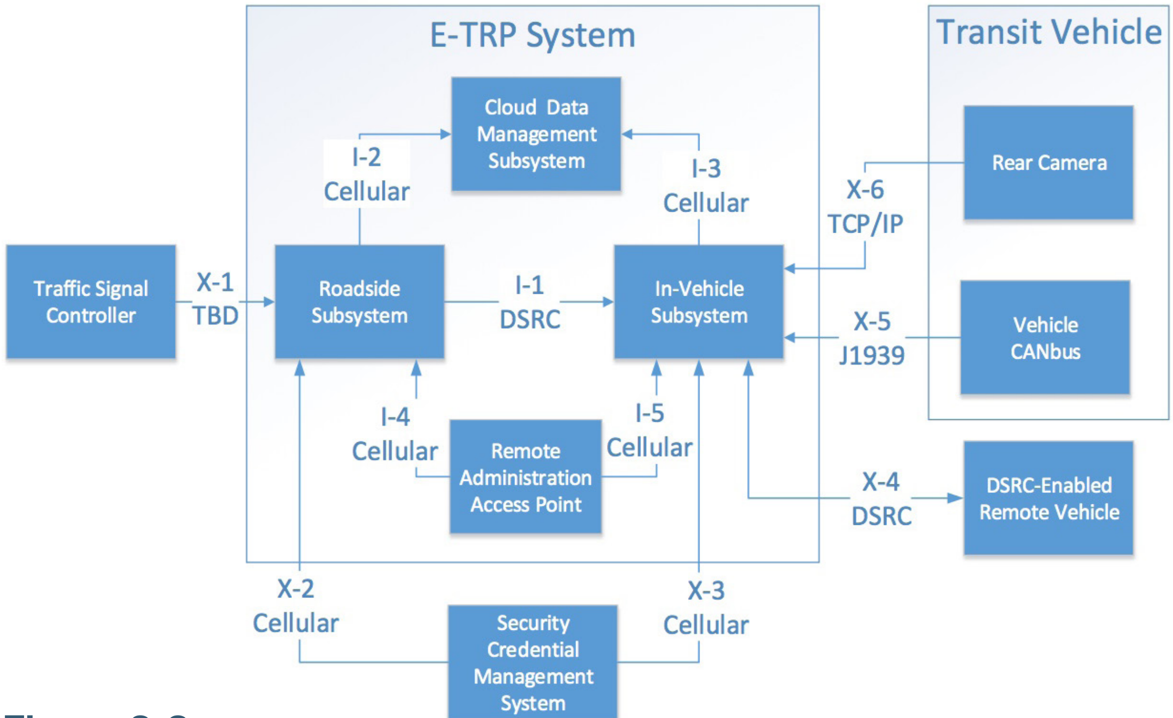

Figure 3-2

E-TRP architecture

A hardware block diagram for the E-TRP and supporting equipment is shown in Figure 3-3. This figure identifies the main components and the associated interconnections that are required.

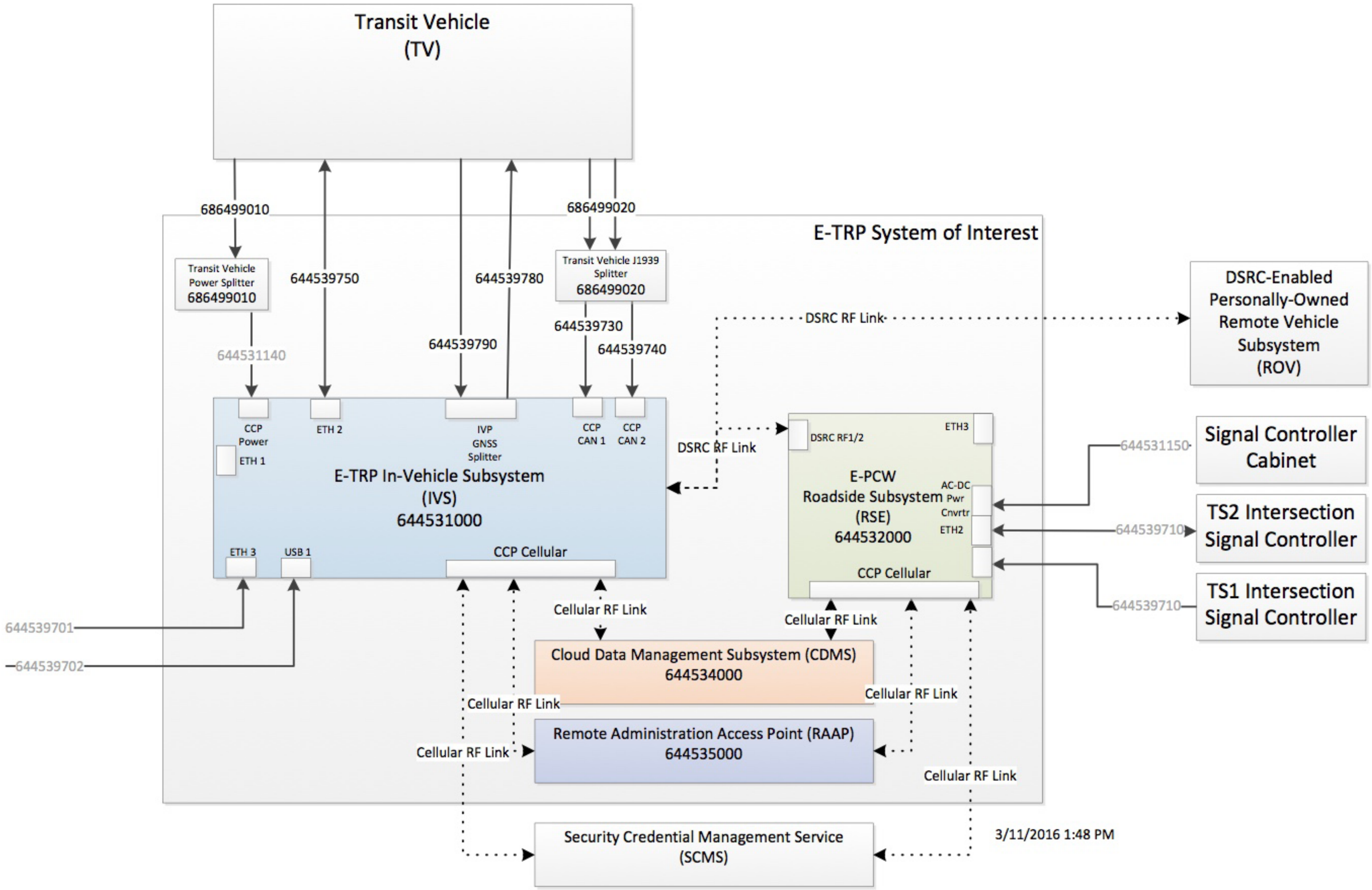

Figure 3-3

Hardware block diagram

The Transit Vehicle CAN Bus is based on the SAE J1939 specification. The specific format and payload definitions of the messages are J1939-compliant. The E-TRP IVS interfaced to the existing transit vehicle's Vehicle CAN Bus to decode the information listed in Table 3-2.

Table 3-2

J1939 Message Label ID

Inputs	J1939 Label ID
Transit vehicle's speed	0xFEF1
Transit vehicle's gear position (PRNDL)	0xF005
Transit vehicle's brake status	0xFF00 or 0xFF50
Transit vehicle's door status	0xFF00
Transit vehicle's turn signal	0xFF00

The DSRC Radio transmitted and received messages in accordance to IEEE 802.11p and 1609.2 standards and the J2735 message standards. The E-TRP System supported the messages shown in Table 3-3.

Table 3-3

DSRC Received Messages

Common Message Name	PSID	Application	SAE J2735 Message	DSRC Channel	DSRCmsgID
Basic Safety Message (BSM)	0x20	E-VTRW	MSG_BasicSafetyMessage	172	
Signal Phase and Timing (SPAT)	0xBFE0	E-PCW	MSG_SignalPhaseAndTiming	172	0x8D
MAP message (aka GID)	0xBFF0	E-PCW	MSG_MapData	172	0x87

System Modifications

Throughout the lifecycle of the E-TRP project, modifications were made to the system's design to accommodate for technological or logistical challenges that were unexpected or not well understood in the design phase. This section indicates each of the challenges and provides an explanation of the challenge experienced and the implemented resolution.

The Data Acquisition System (DAS) CCP was removed from the final IVS design (applies to E-PCW and E-VTRW). The DAS system was originally designed to operate in the IVS alongside the main processor in the primary CCP. Implemented with a second CCP, the role of the DAS was to log test data for the evaluation and to serve as a back-up RAAP connection to the vehicle. The original design featured both CCPs (primary and secondary) working and uploading data independently. The implementation of this proposed design required twice the number of active cellular lines. As the DAS CCP was active only a small portion of the time, given the limited number of intersections, it was decided that such an overhead cost was unnecessary. The primary in-vehicle CCP was proven capable of handling the DAS function, in addition to the required alerting duties, and a lone access point into the vehicle was deemed sufficient. Therefore, the design of the vehicle installations was altered with agreement from FTA, eliminating the DAS CCP.

The Cohda MK5 was used at intersections as the Roadside Unit (RSU) as opposed to the CCP (applies to E-PCW). The original design for the E-PCW Roadside Subsystem specified that a CCP would be used inside the traffic signal cabinet or non-signalized enclosure, with a connected DSRC antenna installed external from the cabinet. However, during testing with the CCP, it was discovered that signal power for DSRC broadcast was fainter in comparison to standard commercially-available off-the-shelf RSU equipment. In particular, signal attenuation was enlarged due to a multimeter-long cable required from the cabinet to the placement of the antenna above the intersection. Subsequent tests failed to uncover a suitable strategy able to reach maximum range for the DSRC equipment using a CCP and extended cabling. Therefore, a technical decision was made to alter the original design of using the CCP for RSU broadcasting and instead using the commercial grade Cohda MK5 RSUs for DSRC broadcast. This solution proved to be more effective, and the DSRC broadcast range was significantly extended with a stronger signal. Part of the improved performance can be explained because the new design implemented had the DSRC antennas directly attached to the RSU which sat outside the traffic signal cabinet or non-signalized enclosure, with the only a single cable required, a CAT5 ethernet connection between the RSU and the CCP. The simplification of the design improved performance, reduced installation and integration challenges with RF cabling, and reduced the amount of hardware required.

The Cohda MK5 RSU deployed complied with the RSU 4.0 specification standard rather than the 4.1 version (applies to E-PCW). Battelle and FTA considered modifying the system requirements so the E-TRP system would comply the RSU 4.1 specification; however, after further consideration, there were no commercially-available RSUs that were fully compliant with the specification. Also, compliance with the 4.1 specification would require the existing J2735 2015 message sets to be converted to the 2016 message sets, which was implemented due to schedule and budget constraints. The system requirement was met with using the 2015 message set over the RSU 4.0 immediate forward protocol.

A combination of changes to the MAP files and E-PCW software logic were made to better tolerate GPS position errors due to poor GPS reception in the urban canyon environment (applies to E-PCW). These included the following:

- **Widening MAP ingress lanes to better capture approaching vehicles with poor position**. The ingress lanes for each approach were significantly widened both to the left and the right, such that the physical ingress and egress lanes and adjacent sidewalk areas were together considered as the ingress lane. These kinds of changes to the MAP files were made possible, in part, due to the next logic modification.
- **Logic changes to consider transit vehicle heading to validate the ingress lane entered.** Using vehicle heading permits the ability to filter out anomalous alerts and warnings when the system detects the vehicle within an ingress lane that does not match the expected approach direction.
- **Logic changes to "latch" onto the ingress lane into which the transit vehicle enters and maintenance of that lane position until entrance into an egress lane is confirmed.** This latching logic allows maintenance of vehicle position (and alerts and warnings to be displayed) when GPS position errors would otherwise cause the system to think the vehicle has wandered outside of the ingress lane but when the vehicle physically has not.
- **A power timer was installed on transit vehicles to ensure proper IVS shutdown/startup (applies to E-PCW and E-VTRW).** While monitoring the transit vehicles through the CDMS and physical inspection, it was discovered that some CCPs were "hanging" in a powered-on state when the vehicle ignition was turned off and, in some cases, remained "hung" (powered-on but non-responsive) when the bus was next operated. This was problematic in two ways—the bus battery could (and did in a couple of instances) discharge while the vehicle was off and out of service for a period, and, if the CCP remained non-responsive when the vehicle was next operated, the vehicle was not participating in the field test. Once this problem was identified, Battelle staff worked with GCRTA to understand and mitigate it.

  The CCP was designed to receive vehicle accessory (VACC) and vehicle battery (VBAT) power. Whereas the VBAT power always should have been present because it was wired from the vehicle's battery, the VACC was intended to be the switching power to turn the CCP on and off as it came from the ignition of the vehicle. As such, when the ignition was turned to accessory on (not just engine on), the CCP should have powered up. When the ignition was turned to the off state, the CCP was intended to gracefully shut down. Inspection of the hardware on the transit vehicles noted that the CCPs were on and in an unresponsive state when the ignition was in an off state.

  The investigation was inconclusive on whether the issue was a software problem or a voltage input circuit robustness issue. Project schedule did not allow further root cause analysis. Since the issue typically could be remedied with a manual power reboot, an alternative solution was implemented and deployed on vehicles exhibiting the problem. A hardware timer device was added as on the voltage input to the CCP as a watchdog with respect to the VACC input line. This watchdog circuit actively monitored the presence of the VACC line when the vehicle was in the on condition, and in this situation, all hardware would boot up as properly as planned. When the VACC signal went low, the CCP should turn off as designed, but in the case that the CCP was in a hung state, the watchdog would kill the battery power to the CCP and force it to power down.

- **Waivers or variance from the system requirements were granted for a limited number of requirements.** The waivers or variances of the requirements included WI-FI capabilities of the CCP, interfacing with the ISO 15765 vehicle interface, capturing DSRC messages, IVS CCP dimensions, IVS CCP standby mode, time synchronization, and hardware component operating temperatures. Table 3-4 summarizes the FTA-approved variances or waivers for the impacted system requirements.

Table 3-4

Summary of Requirements with Approved Variances or Waivers [R10], [R11]

Subsystem	Component/ Function	System Requirement	Performance Effect	Justification
In-Vehicle	Wi-Fi	The E-TRP IVS should implement physical indicator of the operational state of the WI-FI connection.	The CCP possesses a physical indicator of connection status, but this will not be used in E-TRP.	WI-FI was determined to not be needed for E-TRP as remote resets, maintenance, management, monitoring, and data backhaul are being supported via cellular.
In-Vehicle	Wi-Fi	The E-TRP IVS shall implement an interact to extract data files on-demand from the unit locally via WI-FI.	IVS data backhaul will be done by cellular for E-TRP.	WI-FI was determined to not be needed for E-TRP as remote resets, maintenance, management, monitoring, and data backhaul are being supported via cellular.
In-Vehicle	Wi-Fi	The E-TRP IVS shall implement a WI-FI interface with internal antenna.	The CCP possesses a functional WI-FI interface, but an external rather than internal antenna. Nonetheless, WI-FI is not being used for E-TRP.	WI-FI was determined to not be needed for E-TRP as remote resets, maintenance, management, monitoring, and data backhaul are being supported via cellular. This requirement is preserved by the following requirement: "The E-TRP IVS shall implement a 4G cellular interface."

Table 3-4 (cont.)

Summary of Requirements with Approved Variances or Waivers [R10], [R11]

Subsystem	Component/ Function	System Requirement	Performance Effect	Justification
In-Vehicle	Wi-Fi	The E-TRP IVS shall implement an interface to reset/reboot the unit remotely via WI-FI.	WI-FI will not be used by the CCP for E-TRP.	WI-FI was determined to not be needed for E-TRP as remote resets, maintenance, management, monitoring, and data backhaul are being supported via cellular. This requirement is preserved by the following requirement: "The E-TRP IVS shall implement an interface to reset/reboot the unit remotely via cellular."
In-Vehicle	Multiple Protocol	The E-TRP IVS shall be able to simultaneously receive and process data from an ISO 15765 bus AND any of the other protocols listed as required by the system requirements.	The CCP does have the ability to do this, but is not needed for E-TRP.	This functionality is not needed for E-TRP. This requirement is preserved by the following requirement: "The E-TRP IVS shall implement a SAE J1939 bus interface."
In-Vehicle	Multiple Protocol	The E-TRP IVS shall be able to simultaneously receive and process data from two J1939 databus channels.	The CCP does have the ability to do this, but is not needed for E-TRP.	This functionality is not needed for E-TRP. "The E-TRP IVS shall implement a SAE J1939 bus interface."
Roadside	DSRC Messages Capture	The E-PCW roadside subsystem shall capture all E-PCW system generated DSRC messages transmitted by the E-PCW roadside subsystem.	Capturing and logging all DSRC messages generated by the system at all times	The cost is too high to retrieve the data remotely and there is not currently a use for it. Evaluators confirmed that this level of data capture is not needed.
Roadside	DSRC Messages Capture	The E-PCW roadside subsystem shall capture all E-PCW system generated DSRC messages received by the E-PCW roadside subsystem.	Capturing and logging all DSRC messages generated by the system at all times	The cost is too high to retrieve the data remotely and there is not currently a use for it. Evaluators confirmed that this level of data capture is not needed.

Table 3-4 (cont.)

Summary of Requirements with Approved Variances or Waivers [R10], [R11]

Subsystem	Component/ Function	System Requirement	Performance Effect	Justification
In-Vehicle	DSRC Messages Capture	The E-PCW IVS shall capture all E-PCW system generated DSRC messages transmitted by the E-PCW roadside subsystem.	Capturing and logging all DSRC messages generated by the system at all times	The cost is too high to retrieve the data remotely, and there is currently no use for it. Evaluators confirmed that this level of data capture is not needed.
In-Vehicle	DSRC Messages Capture	The E-PCW IVS shall capture all E-PCW system generated DSRC messages received by the E-PCW roadside subsystem.	Capturing and logging all DSRC messages generated by the system at all times	The cost is too high to retrieve the data remotely and there is currently no use for it. Evaluators confirmed that this level of data capture is not needed.
In-Vehicle	CCP Dimensions	The E-TRP IVS should be no larger than 2" tall (with respect to the mounting surface) by 8" x 4".	The CCP used as IVS is 2.25" x 7.5" x 6.5". However, the IVS is a subsystem that is actually much larger than just the CCP – ignoring antennas and cables it includes a CCP mounted on an aluminum fixture and is, thus, necessarily much larger than the minimum requirements.	The CCP enclosure dimensions were selected to encapsulate the required components and connectors. The CCP has now been integrated within the applicable GCRTA vehicle types on an aluminum fixture, as well as within intersection traffic signal cabinets.
In-Vehicle	Standby Mode	The E-TRP IVS shall implement an interface for a maintainer to remotely put the subsystem into standby mode from maintenance mode.	The E-TRP system does not have a standby mode. The system is either ON or OFF.	No purpose for supporting this transition. The maintainer can remotely select between maintenance mode, ON, and OFF. This requirement is preserved by the following requirement: "The E-TRP IVS shall implement an interface for a maintainer to remotely wake up the equipment for maintenance purposes."

Table 3-4 (cont.)

Summary of Requirements with Approved Variances or Waivers [R10], [R11]

Subsystem	Component/ Function	System Requirement	Performance Effect	Justification
In-Vehicle	Standby Mode	The E-TRP IVS shall implement an interface for a maintainer to remotely put the subsystem into standby mode from maintenance mode	The E-TRP system does not have a Standby mode. The system is either ON or OFF.	No purpose for supporting this transition. The maintainer can remotely select between maintenance mode, ON, and OFF.
In-Vehicle	Standby Mode	The E-TRP IVS shall implement a non-operational standby mode. Note: Standby mode is when the transit vehicle is not operating and the E-TRP IVS is in power-saving mode.	The E-TRP system does not have a Standby mode. The system is either ON or OFF.	The following features and functions that would be met via a standby mode are implemented via a hardware solution, including: time maintenance, wake on ACC, wakeup at a pre-scheduled time, and power savings.
In-Vehicle	Standby Mode	The E-TRP IVS should consume no more than 10mA when powered via 12VDC in standby mode.	The E-TRP system does not have a Standby mode; the system is either ON or OFF.	The CCP will consume even less power in the OFF state.
In-Vehicle	Standby Mode	The E-TRP IVS shall transfer data files to a remotely hosted CDMS, when connected in both operational and standby modes such that no data files are lost, deleted or corrupted.	The E-TRP system does not have a Standby mode; the system is either ON or OFF. The system will transfer files only in the ON state.	Data backhaul is supported in operational mode. The variance on the requirement is to remove Standby mode
Roadside	Standby Mode	The E-PCW roadside subsystem shall transfer data files to a remotely hosted CDMS, when connected in both Operational and Standby modes such that no files are lost, deleted, or corrupted.	The E-TRP system does not have a Standby mode; the system is either ON or OFF. The system will transfer files only in the ON state.	Data backhaul is supported in Operational mode. The variance on the requirement is to remove Standby mode.
In-Vehicle	Standby Mode	The E-TRP IVS shall transition from Standby to Operational mode when the transit vehicle transitions from ON to OFF.	The E-TRP system does not have a Standby mode; the system is either ON or OFF.	Features and functions that would be met via a Standby mode are implemented via a hardware solution include time maintenance, wake on ACC, wakeup at a pre-scheduled time, and power savings.

Table 3-4 (cont.)

Summary of Requirements with Approved Variances or Waivers [R10], [R11]

Subsystem	Component/ Function	System Requirement	Performance Effect	Justification
In-Vehicle	Standby Mode	The E-TRP IVS shall transition from Standby to Operational mode when the transit vehicle transitions from OFF to ON.	The E-TRP system does not have a Standby mode; the system is either ON or OFF.	Features and functions that would be met via a Standby mode are implemented via a hardware solution and include time maintenance, wake on ACC, wakeup at a pre-scheduled time, and power savings.
In-Vehicle	Standby Mode	The E-TRP IVS shall transition from Maintenance to Standby mode when the transit vehicle ignition transitions from OFF to ON.	The E-TRP system does not have a Standby mode; the system is either ON or OFF.	Features and functions that would be met via a Standby mode are implemented via a hardware solution, including time maintenance, wake on ACC, wakeup at a pre-scheduled time, and power savings.
In-Vehicle	Standby Mode	The E-TRP IVS shall transition from Operational and to Standby mode when the transit vehicle ignition transitions from ON to OFF.	The E-TRP system does not have a Standby mode. The system transitions from Operational to ON/ OFF.	Features and functions that would be met via a standby mode are implemented via a hardware solution and include time maintenance, wake on ACC, wakeup at a pre-scheduled time, and power savings. This requirement is preserved by the following requirement: "The E-TRP IVS should automatically transition to non-operational mode 'OFF' if the transit vehicle engine is off and the transit vehicle battery drops below a configurable value."

Table 3-4 (cont.)

Summary of Requirements with Approved Variances or Waivers [R10], [R11]

Subsystem	Component/ Function	System Requirement	Performance Effect	Justification
In-Vehicle and Roadside	Time Sync	The E-TRP system shall synchronize its system time with GNSS time at a configurable interval between 1 and 1440 minutes. Note: Once a minute to once a day.	System time update configurability was provided.	System time is continuously updated via GPS readings (via PPS skew), which is more frequently synchronized than the smallest configurable interval. The variance on the requirement is to remove configurable interval.
Roadside	WebSwitch	E-PCW Roadside Subsystem shall operate at temperatures between -10 C to 60 C.	The WebSwitch does not operate at temperatures between 10 to 60 C. It operates at temperatures between 20 C to 40 C.	This requirement was written as means of improving system reliability. The manufacturer provided failures modes to Battelle and FTA, and the risk of not meeting the operating temperature requirement was accepted.
In-Vehicle	WebRelay Dual	E-TRP In-Vehicle Subsystem shall operate at automotive temperatures consistent with SAE J1211 (-40 C to +85 C).	The WebRelay Dual does not at operate at temperatures between 40 and 85 C. It operates at temperatures between 20 C to 40 C.	This requirement was written as means of improving system reliability. The manufacturer provided failures modes to Battelle and FTA, and the risk of not meeting the operating temperature requirement was accepted.
In-Vehicle	TVO HIS	E-TRP In-Vehicle Subsystem shall operate at automotive temperatures consistent with SAE J1211 (-40 C to +85 C).	The TVO HIS does not at operate at temperatures between 40 and 85 C. It operates at temperatures between 30 C to 60 C.	This requirement was written as means of improving system reliability. The manufacturer provided failures modes to Battelle and FTA, and the risk of not meeting the operating temperature requirement was accepted.

Table 3-4 (cont.)

Summary of Requirements with Approved Variances or Waivers [R10], [R11]

Subsystem	Component/ Function	System Requirement	Performance Effect	Justification
In-Vehicle	HDMI Cable	E-TRP In-Vehicle Subsystem shall operate at automotive temperatures consistent with SAE J1211 (-40 C to +85 C).	The HDMI cable does not at operate at temperatures between 40 and 85 C. It operates at temperatures between 20 C to 60 C.	This requirement was written as means of improving system reliability. The manufacturer provided failures modes to Battelle and FTA, and the risk of not meeting the operating temperature requirement was accepted.
In-Vehicle	Rear Bus Antenna	E-TRP In-Vehicle Subsystem shall operate at automotive temperatures consistent with SAE J1211 (-40 C to +85 C).	The rear bus antenna does not operate at temperatures between 40 and 85 C. It operates at temperatures between 40 C to 80 C.	This requirement was written as means of improving system reliability. The manufacturer provided failures modes to Battelle and FTA, and the risk of not meeting the operating temperature requirement was accepted.
In-Vehicle	Front Bus Antenna	E-TRP In-Vehicle Subsystem shall operate at automotive temperatures consistent with SAE J1211 (-40 C to +85 C).	The front bus antenna does not operate at temperatures between 40 and 85 C. It operates at temperatures between 40 C to 80 C.	This requirement was written as means of improving system reliability. The manufacturer provided failures modes to Battelle and FTA, and the risk of not meeting the operating temperature requirement was accepted.
In-Vehicle	Windshield Antenna	E-TRP In-Vehicle Subsystem shall operate at automotive temperatures consistent with SAE J1211 (-40 C to +85 C).	The windshield antenna does not operate at temperatures between 40 and 85 C. It operates at temperatures between 40 C to 80 C.	This requirement was written as means of improving system reliability. The manufacturer provided failures modes to Battelle and FTA, and the risk of not meeting the operating temperature requirement was accepted.

Table 3-4 (cont.)

Summary of Requirements with Approved Variances or Waivers [R10], [R11]

Subsystem	Component/ Function	System Requirement	Performance Effect	Justification
In-Vehicle	Delrin Plate	E-TRP In-Vehicle Subsystem shall operate at automotive temperatures consistent with SAE J1211 (-40 C to +85 C).	The delrin plate does not at operate at temperatures between 40 and 85 C. It operates at temperatures between 29 C to 82 C.	This requirement was written as means of improving system reliability. The manufacturer provided failures modes to Battelle and FTA, and the risk of not meeting the operating temperature requirement was accepted.
In-Vehicle	Ethernet Cable	E-TRP In-Vehicle Subsystem shall operate at automotive temperatures consistent with SAE J1211 (-40 C to +85 C).	The rear bus antenna does not at operate at temperatures between 40 and 85 C. It operates at temperatures between 40 C to 80 C.	This requirement was written as means of improving system reliability. The manufacturer provided failures modes to Battelle and FTA, and the risk of not meeting the operating temperature requirement was accepted.

No issues were reported or experienced throughout the six-month deployment period with any of the components or functions that received a waiver or variance on the system requirements identified in Table 3-4.

Test Planning & Results

The objective of verification testing as documented in the E-TRP Acceptance Test Report[7] (8) was to verify and demonstrate that the E-TRP system possessed the functionality and performance necessary to deliver the functions and benefits proposed for the system described in the E-TRP ConOps (9). Verification testing also verified that the E-TRP system met the requirements documented in the System Requirements document (5). Verification testing followed software and hardware testing conducted during the development phase, which was incrementally undertaken during Agile Scrum Sprints (8). Verification testing was conducted across three distinct phases, as described below.

[7]This document may be obtained by request to FTA (steven.mortensen@dot.gov).

Phase 1, Laboratory-Based Verification Testing

Phase 1 testing was performed primarily in the laboratory setting at Battelle (Columbus, Ohio) using simulated input data. There were some exceptions, including Electromagnetic Interference (EMI)/ Electromagnetic Compatibility (EMC) testing, vibration testing, and temperature testing, which were conducted by a third party. For details on the third-party testing, refer to the "E-TRP Acceptance Test Report" (8). Other exceptions included conduct of tests for basic software application functionality, which could not be verified in a laboratory and had to be verified in a parking lot environment and live intersection environment (5th Avenue and Tisdale intersection in Columbus, Ohio; see Phase 2, Testing Approach and Testing Cases, below). Beyond the software functionality tests, the major focus of this phase was on confirming the various discrete hardware and functional requirements of the E-TRP CCP in test cases, including power, supportability, physical requirements, performance requirements (EMC, vibration, temperature, communications protocols), maintainability, modes and mode transitions, and time management.

All test cases did not require all subsystems to be operational and interconnected. Where needed, simulators and test applications were used to supply input data. The controlled laboratory environment of Phase 1 afforded a focus on testing subsystem components in isolation in advance of Phase 2 testing, which required functionally integrated system/subsystem components and focused on performance of the interfaces and exchanged data.

Phase 2, Controlled Parking Lot Testing

Phase 2 testing focused primarily on software application functionality performance cases addressing E-PCW and E-VTRW functions, RCI functions, and E-TRP system-level tests (8). Testing in this phase was initially planned to be conducted in a controlled garage or parking lot environment. Ultimately, all application functionality performance test cases were simulated in the laboratory environment, with selected scenario-based test cases subsequently repeated in the controlled parking lot environment (an equipped intersection for E-PCW and adjacent parking lot for E-VTRW). The software application-oriented test cases in Phase 2 were based upon the scenarios defined in the E-TRP ConOps (9). Each of these, with one text case exception, was initially performed in a laboratory setting on Battelle's Columbus campus using simulated scripts. The test case exception together with the selected scenarios that focused on application functionality listed above were performed in a controlled parking lot verification testing using an equipped intersection at 5th Avenue and Tisdale near the Battelle campus in Columbus.

Phase 3, Controlled Parking Lot Testing

Phase 3 testing was performed in Cleveland using an equipped New Flyer articulated diesel GCRTA transit vehicle (8). This vehicle was driven by a dedicated GCRTA transit operator, as directed, to traverse the three equipped traffic intersections— E 12th Street and Superior Avenue (signalized 4-way intersection), Rockwell Avenue and E Roadway (non-signalized with two intersecting approaches with stop signs), and Euclid Avenue and E 19th Street (non-signalized mid-block intersection with no signage or controls). All supporting communications and management, such as the CDMS and cellular communications, were active. Near the conclusion of live environment verification testing, a series of demonstrations to FTA was conducted to illustrate E-TRP application functionality, including E-VTRW and RCI features, which were exercised in a closed-loop environment.

The Phase 3 verification tests conducted were effectively a substantial subset of the Phase 1 and Phase 2 E-PCW verification tests. A subset of the test cases exercised E-PCW functionality and were conducted for the record using contrived pedestrian positioning (i.e., Battelle test personnel positioned according to test cases) at each equipped intersection. In contrast to the anticipated need to conduct opportunistic testing during scheduled service and expectation that many tests would be confounded by actual pedestrians traversing intersections under test, it was possible to confirm all aspects of each test case due to using a dedicated out-of-service vehicle, a contrived pedestrian, and scheduling traversals at relatively low traffic periods.

Changes in System Design and Need for Regression Testing in Phase 3

Unlike in Phase 1 and Phase 2 testing conducted by Battelle, Phase 3 E-PCW testing of the integrated deployed system revealed anomalous behaviors, including, at times, intermittent appropriate alerts and warnings, lack of anticipated alerts and warnings, and alerts and warnings presented in the wrong locations. In addition, entry into, maintenance within, and exit from the configured E-PCW area was observed to vary from what was expected (i.e., it either never happened when expected or entry/exit was earlier or later than expected). These anomalies initially prevented the successful confirmation of several Phase 3 test cases.

Investigation into the cause of these anomalies revealed that all were the result of poor GPS-based vehicle position due to operation in an urban canyon environment (downtown Cleveland). The poor position performance was typically experienced at the E 12th Street and Superior Avenue intersection (primarily the west and east approaches on Superior), although it was also observed at Rockwell Avenue and E Roadway on occasion. Approaches creating problematic conditions at these same intersections that repeated at a different time of the same day resulted in no observed anomalies, further supporting this finding. As described in the System Modification section, a combination of changes to the MAP files and E-PCW software logic was made to better tolerate GPS position errors due to poor GPS reception in the urban canyon environment.

After successful internal simulation-based testing of these three changes using the collected vehicle position data from anomalous Phase 3 tests, regression testing of anomalous Phase 3 test cases, and selected test cases where the intersection approaches were problematic were performed again in Cleveland ahead of the demonstration and baseline and revenue service periods. These regression tests were each repeated twice, at two different times of the same day. Significant improvement was confirmed, and all tests passed. It should be noted that, even with these modifications, alert and warning anomalies may still be experienced if the transit vehicle position is so poor throughout approach to the equipped intersection that the widened ingress lanes are not intercepted prior to entry into an egress lane or if they entered late. However, based on test experience, this challenge should rarely present itself.

Summary of Sequence of Testing Phases

Due to the readiness of the scripting, equipment, and equipment modes and the supportive environments in which integration was required, testing did not progressively transition from Phase 1 to Phase 2 to Phase 3, as initially envisioned (8). Instead, parts of Phase 2 and Phase 1 testing were intermixed prior to the transition to Phase 3 testing. Verizon-required open development cellular module testing was also undertaken during this period. Table 3-5 provides a summary list of requirement groupings together with the phases in which the requirements comprising each group were verified or demonstrated, as well as the method by which the requirements were verified

Table 3-5

Summary of Requirement Aspects Tested Categorized by Each Phase of Testing

Requirement Aspects	Phase 1: Lab	Phase 2: Controlled Garage (Lab)/ Parking Lot	Phase 3: Live Environment
Application Functionality (E-PCW, E-VTRW, RCI)	I, T, D, A	D	D
Interfaces (Power, Physical, Comm., Environment)	T		
Safety	A		
Maintainability	D		
Modes (operational, standby, non-op, degraded)	D	D	
Mode Transitions	D	D	
Time & Synchronization	T, D		
Calculation of Location, Heading, Speed	D		
Data Log Storage		D	
DSRC Range		T	
Position Accuracy		T	
CONOPS Scenarios (functionality/detection, start/end and suppression of appropriate alerts, configurability, and logging requirements)		D (Simulated)	D (Live for E-PCW, Closed Loop for E-VTRW)
Physical and Hardware as Installed			I or T

I = inspect, T = test, D = demonstrate, and A = analyze

Summary of Performance Relative to E-TRP Goals

Verification testing and demonstration in Phase 3 confirmed that E-TRP achieved its intended purpose to provide an improved system aimed at increasing safety by enhancing and refining the capabilities of the previous Safety Pilot Model Deployment TRP project, customizing them for the urban transit operating environment, and deploying them under real-world conditions on GCRTA transit buses in Cleveland (8). All specified enhancements were confirmed to be implemented. Beyond the design using ruggedized equipment, the following enhancements were made:

- An improved pedestrian detection system was designed, integrated, and deployed. This FLIR TrafiSense integrated thermal traffic sensor-based system significantly improved pedestrian detection while significantly reducing false positive detections.
- The locational accuracy of the transit vehicle was improved through the combined use of an improved u-Blox NEO-7P GPS receiver with a satellite-based augmentation system (SBAS), widened MAP approach zones and application logic that remembers a known approach fix by "latching" vehicle position to a confirmed approach MAP lane, but filters out potentially erroneous position-based alerts and warnings based on known vehicle directionality.

- The transit vehicle driver interface was improved by graphical designers' re-visitation of the visual and audible alerts to be presented and applying human factors guidelines to guide the selection of informative graphics and annunciations to be readily interpreted by transit vehicle drivers. Revisions to the graphics include iconography size and color, animation and flash rate, audible messaging, message/graphic prioritization, annunciation/graphic transitions, and application-level logic prioritization (which was necessitated by the design decision to present a single-panel display, with the logic dictating application-based alerts). Finally, an 8.4-inch color touch screen display with stereo speakers was selected to present graphics and annunciations.
- Improved DSRC communications range and performance were observed through the integration of Cohda Wireless DSRC radios (radio stack integrated into on-board unit CCP and Cohda MK5 used at intersections). Additionally, the integration of the rear DSRC antenna was mounted on the rear of the vehicle rather than on the driver's side-view mirror.
- Cellular-based communications and the design of the software platform permitted remote system management (e.g., software updates), monitoring, and the data backhaul of an expanded logging capability.

With the exception of Phase 1 and Phase 2 tests made non-applicable due to the waiver/variance of all comprising requirements (two tests) and Phase 3 tests that could not be conducted due to lack of a suitable available intersection (several noted tests, the exclusion of which did not preclude the verification of any requirements), all test cases were marked as a pass (8). In addition, all applicable requirements (those without a waiver or variance) were verified successfully.

Training

Once testing was completed and prior to going live with the in-vehicle system, Battelle hosted a training session at GCRTA headquarters to educate GCRTA supervisors on how to train TVOs on their interaction with the system (7). A train-the-trainer approach was applied so GCRTA would be able to address a large number of employees and could integrate this training with existing GCRTA training.

The training session began with an overview of CV technology and history of Battelle's CV experience and capabilities. Next, the GCRTA supervisors were provided with background information about the E-TRP project and its purpose. Battelle then explained the hardware design of the in-vehicle subsystem and showed pictures of the hardware currently being installed on a subset of the vehicles to familiarize GCRTA with the system. The majority of the training focused on the driver's interaction with the display and which vehicles, routes, and intersection locations would be impacted by the system.

With the objective of the system to provide TVOs with greater situational awareness to improve pedestrian safety, the operator's interaction with the display was the most critical part of the project. The GCRTA team was informed about the two different applications being deployed (E-PCW and E-VTRW) and integration with a rear backup camera. For each application, Battelle provided GCRTA with examples (i.e., PowerPoint slides with video and sound clips) of each different visual and audible alert and warnings and the environmental scenarios that activate each type. Battelle provided GCRTA with quick reference guides for each of the vehicles that were outfitted with technology. Refer to Appendix A for a quick reference guide. GCRTA was also informed about the different operational modes of the system and how an operator can diagnose an issue and when it should be reported.

Field Demonstration

After the TVOs received training on the system, Battelle hosted a live-demonstration for FTA in Cleveland on February 1, 2018 (14). The E-PCW application was demonstrated in the live field test environment using Battelle staff as a pedestrian to perform demonstration scenarios. The demonstration also showcased non-staged real-world pedestrians triggering system alerts. One of GCRTA's professional TVOs drove a retrofitted vehicle with FTA and Battelle through all three outfitted intersections to experience pedestrian safety alerts, both staged and real-world. E-VTRW was demonstrated in a closed-loop environment in a closed off GCRTA parking lot. A professional TVO operated a retrofitted vehicle while a Battelle team member drove the DSRC-equipped ROV around the transit vehicle to trigger alerts and warnings received on the vehicle by the TVO.

At the completion of the successful client demonstration, the official six-month revenue service field demonstration commenced. During the first month of the field demonstration, the IVS was put into cloaked mode from February 2 to March 1, 2018 (14). Cloaked mode suppressed the system from displaying alerts to the TVO so that baseline data could be collected for the independent evaluation. The data for those alerts and the TVO's reaction time towards engaging the brakes without knowledge of the alerts were recorded and distributed for ITS Roads, the project's independent evaluator. The system continued to be monitored and maintained to ensure that the system was functioning as expected and to confirm the necessary data was being collected for ITS Roads.

On March 2, 2018, the system went live and was taken out of cloaked mode (15). The TVOs now received live alerts when traversing through the different outfitted site locations on the equipped vehicles. The TVOs were notified that the system was going active through training and about the icons that appeared on the display in different situational scenarios. Once the system was active, a specific graphic appeared on the screen as a notification. During this phase of the demonstration, Battelle monitored and processed only that data and did not perform any system modifications to prevent tainted data collection.

The field demonstration concluded on August 2, 2018. After all data were confirmed to be uploaded to the Cloud for ITS Roads' evaluation of the E-TRP system, the system was decommissioned, with the IVS and RS permanently powered down. Battelle's electrical contractor uninstalled all temporary poles, pole bases, mast arms, overhead wiring, and conduit at the intersections.

SECTION

4

Project Results

During the six-month deployment of the E-TRP system, Battelle collected and provided data to ITS Roads for independent evaluation. This included an initial one-month baseline period when the system was cloaked (driver interface was inactive), followed by a five-month operational period with the system fully active and the driver receiving alerts. The objective of the evaluation was to measure the impacts of the E-PCW application deployment and to further analyze the potential benefits of CV technology on pedestrian and transit vehicle safety, as documented in the E-TRP Evaluation Plan (3). The evaluation also provided insight into the feasibility of wider scale adoption of CV technology for other transit agencies due to the involvement and participation of GCRTA. The evaluation excluded the E-VTRW application due to the lack of the presence of DSRC-equipped vehicles (e.g., light vehicles).

Evaluation Summary

Evaluation analysis areas included System Performance, Safety Impact, Return on Investment, and Driver Acceptance (3). The performance measures included in each of the analysis areas along with key findings are summarized in Table 4-1. The performance metrics were developed cooperatively among FTA, Battelle, and ITS Roads to suit the project objectives and, in many cases, mirrored Volpe's evaluation of TRP.

Table 4-1

E-TRP Evaluation Summary

Evaluation Criteria	Performance Measures	Key Findings
System Performance	• False Alarm Rate	• 81% correct alerts (10% incorrect alerts and 9% false alarms).
Safety Impact	• Collision Reduction	• 16% increase in driver response (braking) to PCW warning situation. • 18% decrease in average driver reaction time (braking) to PCW warning situation.
Return on Investment	• Cost Savings	• 20 years[8] to recuperate investment cost in form of E-TRP's safety impact of reducing risk of collision.
Driver Acceptance	• Usability • Perceived Safety Benefits • Unintended Consequences • Desirability	• Only 13 of 751 E-TRP drivers (less than 2%) participated in the survey. With this small sample size, conclusions drawn from the survey could not provide statistically meaningful findings for this criterion. For drivers that responded, results were mixed.

[8]Based on GCRTA transit collision data for a five-year period between April 2011 and May 2016, which included no fatalities. There was one fatality (pedestrian struck by a bus) at E. Roadway and Rockwell Avenue in December 2016. If one fatality over the five-year period was added to the Estimated Value of Preventing Injuries based on USDOT's VSL and MAIS Classification System, the return on investment period would drop from 20 to 5 years.

Evaluation results for each criterion are further summarized below (4).

System Performance

System performance is the primary technical metric of the evaluation and critically affects all subsequent evaluation metrics. The objective of the system performance evaluation was to calculate the false alarm rate of the pedestrian detectors that generate driver alerts; the validity of these alerts is the foundation of the E-PCW application. The system performance evaluation included sample data from four of the six months of testing (February–May 2018) due to data collection gaps in the final two months of testing. Sample alerts—approximately 15% of all available alert data—were analyzed to determine the rate of false positive detections, in which the detector data generates an alert when no pedestrian is present at the bus stop, as well as incorrect alerts, in which the detector incorrectly identifies the location of the pedestrian. It was decided not to evaluate false negative detections (missed detections) since it would have necessitated additional independent monitoring equipment to additionally look for missed detections by the system.

Of the E-PCW alerts analyzed, 9% were false alarms (false positives), 81% were confirmed correct alerts, and 10% correctly detected the presence of a pedestrian but incorrectly classified their location. False alarms were caused primarily by lighting and environmental conditions, and the main driver of incorrectly classified alerts was the proximity of the zones.

Based on evaluator observations and interviews with Battelle and GCRTA staff, several improvements could be made to the system to further improve alert accuracy. Future deployments would benefit from initial calibration of pedestrian detector installation and zone selection to improve performance and use of multi-source augmented location information to improve GPS drift in the urban canyon environment. Battelle staff noted that there have been improvements to both the detector and positioning equipment since the design and installation of this system, including a reduction in equipment costs. Finally, the E-TRP system performance, operation, and resilience would improve with active system monitoring, interim data quality checks, and routine system maintenance.

Safety Impact

Safety impact was the primary functional metric of the evaluation and served as an input to the evaluation of E-TRP's return on investment. The objective of the safety impact evaluation was to assess driver response to alerts as an indication of the number of potentially avoided collisions. The safety impact evaluation compared the driver response rate during the baseline period, during which driver alerts were suppressed, to the active test period, when driver alerts were enabled to determine the safety impact of the E-TRP system.

Quantitative data analysis of driver braking within 2.5 seconds of the Warn alerts showed that the E-PCW application increase driver response by more than 16%, from 12% to 14%. Additionally, the average driver reaction time was reduced by more than 18%, from 1.6 seconds to 1.3 seconds. These findings feed into the return on investment evaluation to support the determination that the value of the safety benefits will offset implementation costs within the system lifecycle.

Return on Investment

Return on investment was the primary policy metric of the evaluation and indicated the system's overall cost effectiveness. The objective of the return on investment evaluation was to determine the value of the system's potential to avoid collisions and reduce resulting agency costs in comparison with the overall cost of the system.

To determine the value of E-PCW's safety benefits, the evaluation team used guidance from the USDOT's Office of the Secretary of Transportation on the treatment of the economic Value of a Statistical Life (VSL). The evaluation team applied adjusted VSL to historical GCRTA collision data to determine the estimated value (total cost) of current safety performance and calculate the cost savings that would result from the E-TRP's estimated safety impact to determine the estimated benefits (total cost savings) of the E- PCW application.

To estimate the cost of a full system deployment, the evaluation team extrapolated reported costs from the instrumentation of three E-PCW locations to a "full coverage" deployment. Locations of GCRTA's historical transit-pedestrian collisions were compared against a map of the relevant transit service area and 24 additional instrumentation locations were identified to equip "high-priority" sites, based on the highest density transit service, pedestrian activity, and historical collisions, with E-PCW.

The evaluation team compared estimates of the annual cost savings and the total deployment cost to determine when the system's benefits would fully offset the initial investment.

In the five years of collision data provided, between April 2011 and May 2016, GCRTA recorded 14 events involving a pedestrian. The evaluation team reviewed the description of each event to estimate the Maximum Abbreviated Injury Scale (MAIS) classification and calculate the associated value of preventing these injuries. Events that did not include injuries in the description were excluded. The estimated average annual benefit of the system was $106,452 and the estimated total deployment cost was $2,163,180.

Comparing estimates of the average annual benefit of the system and the total deployment cost indicates that recuperating the investment in the form of risk reduction value from E-PCW may take more than 20 years (244 months). For comparison, the lifecycle of traditional traffic and safety infrastructure ranges from 5 to 15 years, depending on variables such as the cost of equipment, pace of technological advancement, operational performance, and the quality of infrastructure maintenance. Based on these estimates, the benefits of the E- PCW application are not likely to outweigh the implementation cost of the system, even with a relatively long deployment lifecycle.

Note, however, that there was one fatality (pedestrian struck by a bus) at E. Roadway and Rockwell Avenue in December 2016, just outside the five-year period of data used for the return on investment evaluation. If only this one fatality was added to the Estimated Value of Preventing Injuries, the return on investment period would drop from 20 to 5 years. Additionally, system costs are anticipated to drop substantially for future systems (based on economies of scale, productization of the system, and decreasing costs of electronics), significantly improving return on investment for future deployments.

Whereas the E-PCW deployment in Cleveland did not demonstrate strong, near-term return on investment, the project dramatically improved E-PCW system performance and advanced the state-of-the-practice in CV applications for transit safety. GCRTA staff reported high confidence in the value of the E-PCW system and expressed a desire to deploy the system across its entire transit network as costs decrease over time.

Driver Acceptance

Driver acceptance was the primary operational metric of the evaluation and incorporated user feedback for four different elements, specifically the E-TRP system's usability, perceived safety benefits, unintended consequences, and desirability. The driver acceptance evaluation was adapted from survey questions developed for the evaluation of the original TRP system and was administered both electronically and in-person.

Drivers who participated in the survey rated the system's usability and desirability positively, but expressed mixed responses regarding perceived safety benefits and unintended consequences. Nearly two-thirds (63%) of drivers agreed that they would like the system installed on all vehicles they drive, and more than half (55%) reported that they trusted the cautions and warnings.

In total, 18% of respondents indicated that there were any near misses; however, 73% indicated that drivers observed false positive alarms, and 82% reported observing false negatives (observed an alert or warning situation but did not receive an alert).

Only 13 of 751 of the E-TRP drivers—fewer than 2%—participated in the survey. With this small sample size, conclusions drawn from the survey cannot provide statistically meaningful analysis of the system, as the results were strongly influenced by individual drivers and their specific experience. Results are not necessarily representative of all GCRTA driver experiences with E-TRP and cannot be generally extrapolated to drivers in other regions.

For additional information on the evaluation of the E-TRP system, refer to the "Independent Evaluator Report: Enhanced Pedestrian Collision Warning (E-PCW) Final Evaluation Report" (4), found in its entirety in Appendix B.

Experiences and Lessons Learned

This section captures the unplanned happenings throughout the project and resulting lessons learned.

Prototype installation on GCRTA buses was highly beneficial. Battelle performed prototype installation on four different makes and models of buses. This installation involved 26 cables and other hardware that needed to be tailored to each bus model. The cable length and hardware placement were different on each bus. This activity enabled finalization of design and installation plans to lessen production and installation risks. The ability to monitor the initial prototype on the buses also provided early integration and testing data.

Use of a local "live" intersection for testing prior to deployment was invaluable. Battelle partnered with the City of Columbus and retrofitted an intersection outside of the Battelle campus. The site had a fully-operational pedestrian detection system, DSRC radio communication, and SPaT and MAP messaging. This allowed the initial phases of integration and verification testing to be performed early-on at Battelle, thus lessening field integration and verification risks.

There were technical challenges integrating with the TS-1 traffic signal controller. The E-PCW application requires both MAP and SPaT data from the outfitted intersection. SPaT data are specific to signalized intersections and are critical for knowing when and how to alert or warn TVOs of a pedestrian in the crosswalk or the curbside.

At the beginning of the project Battelle went on a site visit to the E 12th Street and Superior Avenue intersection and noted that the traffic signal controller was an older TS-1 model. Unlike the newer TS-2 models, a simple ethernet cable and configuration of traffic signal controller is unable to output the SPaT data. To interface with the TS-1 controller, custom external sensing of phase cables had to be designed to connect to the traffic signal controller, read the signals, and then output the SPaT data to the CCP without affecting the signal controller's normal operations. Extensive resources went into design, prototyping, and testing of the custom-built device.

New hardware product development should be carefully considered. During the prior TRP project, the IVS system design, excluding antennas and operator display, consisted largely of an On-board Unit (OBU), DSRC radio, ethernet switch, and DAS. This design presented several challenges, as each of these components was an individual component that was not integrated with the others. Challenges experienced on the prior TRP project included the following:

- IVS design required a large amount of physical space available in the transit vehicle.
- Unnecessary amounts of cabling interconnected each component.
- It was difficult to determining the root cause of any issues when troubleshooting.
- Maintenance was highly complex.
- Remote monitoring capability was lacking because the OBU did not have cellular connectivity.

In applying the lessons learned to the E-TRP system design, a custom ruggedized automotive grade computer was developed for the project by a third-party contractor. The CCP was developed to incorporate the OBU, DSRC radio, ethernet switch, and DAS capabilities in a single enclosure that was reasonable in size to be installed in a transit vehicle. The CCP incorporated Wi-Fi, Bluetooth, cellular, DSRC, and GPS in a single unit with a variety of different interfaces, including USB and ethernet ports, digital and analog I/O, a CAN interface, and a 12 VDC output. This design alleviated all challenges experienced from TRP listed above; however, it introduced others. This custom-built computer had to meet many physical and operational requirements to ensure that the device would perform as intended in the field without affecting other electronic equipment installed on the transit vehicles. The challenges presented by the development of the CCP were experienced during third-party testing and are further discussed below.

Cellular and EMI/EMC testing is costly but provides a significant benefit in discovering flaws in the design. System requirements were written for the IVS to comply with selected SAE J1113 specifications related to electromagnetic compatibility, SAE J1211 related to automotive operating temperatures, and SAE J1211 related to shock and vibration resistance. For this type of testing, Battelle had to contract a third party that specialized in testing these standards. In addition to this type of testing, cellular testing was required for the CCP for the wireless company that provided the cellular chips. The wireless company performed the cellular tests at its testing location. Cellular testing was required irrespective of the system requirements, as cellular connectivity would be required for the CDMS. Both sets of testing had significant implications related to project cost and schedule that were not fully anticipated.

Testing helped improve the overall design of the CCP and pinpointed its limitations with respect to the performance related to the standards mentioned above. The following were identified as lessons learned and best practices, while going through the cellular and EMI/EMC testing.

- Set expectations and plan on experiencing issues and having to re-do tests and possibly altering the system's/unit's design.
- Pay for pre-scan/pre-testing (if available) to preserve time on performing an entire battery test when issues are found.
- Understand the consequences and "what happens if" scenarios if problems are experienced during testing and to negotiate favorable terms as to how the test agency will proceed.
- Be prepared to pay for engineering services from the test agency to help diagnose problems.
- Prepare ahead of time and be familiar with the standards/requirements so the performance against them is well understood when reported.
- Participate in (to the extent allowed) and help determine performance requirements (if not specified by project requirements).
- Go into testing with an understanding of what is acceptable performance for the project (this may be a level of performance identified in a standard, whereas the standard itself may specify only a procedure and goal). Some tests may need to be modified to conform with certain technical or configuration issues.
- Plan to be present (if allowed) at testing at key/all times; this speeds up communication of status, resolution of equipment questions, and interactive problem solving and ensures priority in scheduling (most test agencies will be conducting testing for multiple customers simultaneously).
- Plan to have spare equipment on hand for each major type of test to ensure continuity of testing and diagnostics (equipment breaks/fails, allow multiple test configurations, allow testing in parallel).
- Understand how the unit will be tested (which part of the system is being tested, how realistic vs. controlled does the test need to be) and provide ancillary cables (power, communication, shielding, mounts, etc.) needed for operation and testing.
- Provide user and system/unit configuration instructions ahead of time to reduce test setup and configuration questions; provide design documentation if applicable.
- Establish a communication plan for bringing together the test lead and company's subject matter experts to rapidly resolve questions or issues experienced.
- Prepare to have staff on-call to discuss results/problems, and to provide instruction, answer questions, make fixes, etc.

The cost of automotive-grade equipment significantly increases the cost of hardware components. As means to ensure that the E-TRP system was designed to be more reliable than the previous TRP system, the following system requirement was written to specify the IVS operating temperature.

> *E-TRP In-Vehicle Subsystem shall operate at automotive temperatures consistent with SAE J1211 (-40 C to +85 C).*

These requirements had substantial implications on project cost and design. On average, components with automotive-grade operating temperatures cost three times that of standard components. Examples of these components include ethernet and HDMI cables, circuit breakers, relays, terminal strips, operator displays, and remote rebooting hardware. Some of these components with this operating temperature do not exist and required variance on this system requirement.

The cost to deploy the roadside hardware and make modifications to the existing infrastructure was underestimated. With the E-TRP system using V2I technology, a substantial amount of infrastructure hardware was required to be installed to support the E-PCW application. E-PCW required a number of pedestrian detection cameras that were customized to the size of the intersection with respect to curbsides and crosswalks. The cameras required particular viewing angles and positioning at a height of 20 feet at every crosswalk and curbside area; the existing infrastructure to support the ideal mounting of the cameras rarely was available. It was also critical for the RSU to be installed in a central location to the intersection, which also required infrastructure modifications. Each intersection location was unique with respect to its existing infrastructure, geometry, and power source. These differences required a custom installation at each location, which included the following modifications to the infrastructure: installation of 20-ft poles, custom-built cement pole bases, installation of different lengths of mast arms, mounting hardware to support equipment, temporary overhead wiring, and the installation of enclosures at the two non-signalized intersections. Certain locations at each intersection did not permit the installation of poles, pole bases, or mast arms, which limited the performance of the cameras.

Federal Communications Commission (FCC) licensing is required to deploy broadcasting DSRC radios at roadside. To get a site ready for deployment, a license from the FCC was necessary. The FCC licensing process involved getting individual licenses for each intersection location so that installation and deployment could begin. An application for each intersection is done through the FCC portal. Within the application, the location of equipment, frequency, channel count, and broadcast power need to be specified. The application process, while not overly difficult, required several discussions with FCC representatives to verify terminology and expectations. Processing and approval of the application took approximately four weeks, on average, and was the greatest hurdle to the FCC licensing process. Installation of hardware must take place within one year of the FCC license or the deploying agency must repeat the application process. Throughout the project, the intersection locations were changed several times, causing the Battelle team to modify and change the license, which lasts for 10 years. It was the team's experience that questions were best handled by the FCC's support line via phone call.

Notify surrounding property owners of installations on their property. Prior to Battelle performing the installation at each location, its electrical contractor filed obstruction permits with the City of Cleveland's Mayor's Office of Capital Projects. All permits were approved, and installation was successfully carried out at each location. Equipment was in public right-of-way. After a few months, Battelle received notification from the US General Services Administration (USGSA) that USGSA owned the property underneath the sidewalk on the south corner of the intersection where the courthouse was and it wanted the pole and pole based installed on the sidewalk to be relocated due to its weight (13). Battelle relocated the pedestrian detection cameras on an existing nearby pole at the south corner and reinstalled the pole with the RSU and the enclosure containing the other hardware across the street to the east corner. Cleveland Public Power (CPP) was contacted and supported the electrical contractor's efforts to rewire and install new cabling to support the modification. The following day, vehicle and pedestrian detection testing was performed to verify that the intersection was operating properly.

A more robust power supply solution is needed for CCPs to handle power fluctuations and power loss to alleviate CCP "hangs" for intersections and vehicles. Through the course of the project, the CCP hardware located at the intersection locations was periodically (roughly monthly) found to be in a non-responsive state and required a power restart. As covered in the System Modifications section, the CCPs on some of the vehicles experienced power "hangs" for which a timer device mitigation was deployed. For the intersections, hardware was monitored via cellular through the RAAP, and it was observed on occasion that communication to and from the intersection had stopped. In this situation, troubleshooting through remote means was not available due to the loss of network access provided by CCP's cellular communication. Detailed root cause analysis of this situation was not performed at the site due to the need to keep the intersection operational for the field test. Troubleshooting at Battelle's facility was unable to replicate the issue that caused the non-responsive state and led the team to the conclusion that environmental factors could be influencing the hardware state, such as power surges, voltage fluctuations, or personnel working on intersection equipment. The solution for a non-responsive system was to have the power to the equipment reset by on-site personnel. Through a power cycle, the hardware would return back to normal operation.

In terms of lessons learned and future action items to investigate, the project did not have the ability at the time to do a detailed root cause analysis, as noted above. Items that would need to be investigated for future consideration include the following:

- *Increasing the robustness of the CCP design to power manipulations and disturbances* – Although the problem at the intersection that would force the system to be unresponsive at times was not fully understood, the occurrences at the intersections seem to be related to issues in the transit vehicles. In both situations, the CCP was found to be unresponsive and left in an ON state. Although the transit vehicle and intersection power inputs are different due to being direct current powered through the battery of the vehicle vs. being alternating current at the intersection, the end problem appears the same. Although outsourced electrical testing was conducted at a certified test facility, future iterations of the hardware could benefit from testing to more robust scenarios.
- *Increasing the communication redundancy of the intersection system* – When the CCP was in a non-responsive state, the act of remotely power-cycling the system was ineffective because the CCP was supplying the network access. A single point of failure for network access would mean higher mean-time-to-repair and would require an on-site visit from qualified personnel. A possible solution would be to have another network connection available at each intersection and not be fully reliant on the CCP network connection. If a hard-wired network connection was available at the site locations, access could be gained to the already-installed network-enabled power strip allowing the system to be reset remotely. Although this method does not address the overall issue of preventing a non-responsive CCP, it does increase the up-time of the system.
- *Replace the CCP with a work-hardened computer* – An alternative form of hardware could be selected to be inserted at the roadside to run the RS. The Battelle team has experience in running software at the roadside on environmentally-hardened computing hardware. The original purpose of the CCP was to be the RSU for the intersection. With the addition of Cohda radios on the pole, the importance of running the CCP was lessened, allowing the complete retrofit of the unit with a hardened computer. This option was not explored due to not having a reason to replace during the project, but if a root cause cannot be determined regarding CCP non-response issues, simply replacing the CCP could be a solution.

The HIS design proved to be effective at providing alerts and warnings to the TVOs. The lessons learned regarding the HIS design were reflected in the E-TRP HIS design and proved to be effective. The previous TRP project used a tablet as a display that was mounted near the bottom of the windshield and experienced issues with glare, causing the TVO difficulty with identifying visual alerts and warnings. The tablet also had internal speakers, which were not sufficient for providing audible alerts and warnings at and adequate volume. For the E-TRP project, an industrial-grade 8.4-inch display was selected that was shock- and vibe-resistant, sunlight-readable with 1,000-nit brightness, anti-glare, and stereo speakers. The display was installed directly above the TVO next to the rear-view mirror and other existing displays used by the driver for consistency. The mount selected for the display was adjustable, which allowed for TVOs of different heights to customize the angle the display was facing. Along with the display, new graphics were created for E-TRP visual alerts and warnings by Battelle's Human Factors subject matter experts with input from GCRTA. The graphics were simplified from the previous TRP project and were made more readable by including less information within the graphic. All HIS design improvements helped to improve the TVO's engagement with the system and provide adequate alerts and warnings to improve pedestrian safety and situational awareness.

Some intersection data were lost during the last two months of the field test. E-TRP data from the roadside locations and vehicles were uploaded automatically by the equipment to an SQL server database in Azure via cellular connections. To limit the amount of storage used and maintain reasonable database performance, data greater than two weeks old were purged. Typically, data were gathered once per week, making sure that all devices were online prior to data gathering. This ensured that the data were up-to-date on the server. The data were then placed in files in an Azure storage repository. After the project was completed, the data were analyzed and Battelle learned that there were periods of missing data for the intersections. It was determined that there were several instances in which some roadside CCPs showed online, but the cellular network performance was poor enough that it was not able to upload data for several days. This caused some data to be missing when gathered weekly and placed into Azure storage for analysis. By the time this problem was discovered, the data had been successfully uploaded to the database and purged because of its age. The process of automatically uploading data continuously and moving it to Azure storage typically weekly for evaluation proved to be inadequate. For future projects, additional procedures should be put in place for checking the data for completeness and correctness during each step of the data transfer process throughout the data collection period.

CAN bus wiring was implemented incorrectly against the design documentation throughout the period of transit vehicle installations. Each model transit vehicle was wired differently from the next, and the CAN interface locations varied, which led to confusion during installation. Analysis performed in late 2016 and early 2017 of the different transit vehicle types showed that the required telemetry from the J1939 standard was available on each type, with the lone exception of turn signal and door status for the Gillig model trolleys. However, the GCRTA installation staff connected CAN cables at locations deemed convenient for the positioning of the cables. It was discovered that the J1939 data was not fully present at some locations, thus hindering the CAN system on a number of vehicles. Once the cables were installed in the proper locations identified during the pilot installation and documented in the installation plan, the CAN system functioned as expected and provided the necessary data to the CCP.

Transit vehicle rear camera integration was successful, but was not implemented for operational use. Battelle successfully integrated with the rear backup cameras on the E-TRP-outfitted transit vehicles to display the camera's view on the Battelle-installed display; however, it was noticed that the display of the live-camera was delayed, which presented a safety concern to the TVOs. GCRTA and Battelle agreed to disable this feature during the operational deployment period. GCRTA indicated that regardless of the rear camera, operating rules and procedures require a spotter behind the vehicle at all times, regardless of whether the vehicle is in the maintenance garage or in the field.

Establishing good relationships and having superior collaboration with stakeholders was essential in deploying the E-TRP system. The E-TRP system was successfully deployed and operated thanks to GCRTA and the City of Cleveland's participation in this research project. GCRTA was an excellent partner and provided Battelle with transit vehicles, staff, and support throughout the course of this project. The City of Cleveland was also supportive of this effort to improve pedestrian safety around the city's roadways and transit vehicles and granted Battelle permission to install temporary poles, bases, enclosures, pedestrian detection cameras, radios, and mast arms throughout the downtown area. It also provided support around intersection installation and resolved power issues. Cleveland Public Power (CPP) also supported these research efforts and permitted Battelle to use its power source at one intersection locations. Without all stakeholder buy-in, the deployment of this technology would not have been possible.

Conclusion and Recommended Next Steps

The field demonstration proved the E-TRP system to be effective at providing TVOs with timely pedestrian safety alerts and warnings, which positively impacted TVO's response times and increased pedestrian safety. This project has helped to advance the research and development knowledge related to deployments of CV technology and, more specifically, a pedestrian safety and vehicle-turning-right warning application.

Designing, prototyping, testing, and evaluation of the E-TRP system revealed opportunities for enhancements and improvements. The following summarizes the recommendations for improving the system further and expanding on the lessons learned and experiences discussed in the previous section:

- Upgrade the existing 2015 E-TRP system J2735 message set to the 2016 message set to enable the deployment of a 4.1 specification compliant RSU.
- Upgrade the RSU with the latest version of Cohda software compliant with the 4.1 RSU specification standard.
- Implement a Security Credential Management System; the USDOT Security Credential Management System (SCMS) was not employed due to timing (SCMS not available in time for use on this project).
- Upgrade the FLIR TrafiSense cameras to the latest model (FLIR TrafiOne), which has updated pedestrian detection algorithms and is designed to have a greater range of acceptable camera angles to alleviate installation challenges.
- Upgrade the CCP with a graphics card for higher processing capabilities to allow the rear camera to be enabled and used.
- Provide additional hands-on training with GCRTA TVOs to help them be more prepared before the system goes live.
- Support GCRTA with additional resources during transit vehicle installations to reduce field maintenance and to speed up installation.

ACRONYMS/ ABBREVIATIONS

BSM	Basic Safety Message
CAN	Controller Area Network
CCP	Common Computing Platform
CPP	Cleveland Public Power
CV	Connected Vehicle
ConOps	Concept of Operations
CDMS	Cloud Management Subsystem
DAS	Data Acquisition System
DSRC	Dedicated-Short Range Communications
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
E-PCW	Enhanced Pedestrian in Crosswalk Warning
E-TRP	Enhanced Transit Safety Retrofit Package
E-VTRW	Enhanced Vehicle Turning Right Warning
FCC	Federal Communications Commission
FTA	Federal Transit Administration
GCRTA	Greater Cleveland Regional Transit Authority
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HIS	Human Interface Subsystem
IVS	In-Vehicle Subsystem
OBU	On-board Unit
PDS	Pedestrian Detection Subsystem
RAAP	Remote Administration Access Point
RCI	Rear Camera Integration
ROV	Personally Owned Remove Vehicle
RS	Roadside Subsystem
RSU	Roadside Unit
SPaT	Signal Phase and Timing
TVO	Transit Vehicle Operator
USDOT	United States Department of Transportation
USGSA	United States General Services Administration
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VSL	Value of a Statistical Life

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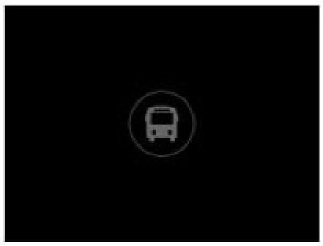
APPENDIX

A

Quick Reference Guide

Quick Reference Guide for E-PCW (Pedestrian Crosswalk Warning) Display Details - E. 12th & Superior Ave, Euclid & E. 19th, and Rockwell & E. Roadway Ave

	Graphic (colored arrow(s) flashes to indicate threat location)	Audible	Situation	Driver Action
SYSTEM OPERATIONAL		None	System is operating normally, but bus in not in range of an equipped intersection (or at a bus stop for E-VTRW). -- If **NOT** operating normally, this image displays → 	***None***
E-PCW ACTIVE NO ALERTS		None	Bus is in range of an equipped intersection and E-PCW has activated, but no alerts apply.	***None / remain alert.***
INFORM ALERT		**"[Single Beep] CAUTION <u>DIRECTION</u>"** *<u>Direction</u> is LEFT, FAR, RIGHT, or FRONT. FAR is shown in this example.*	**At red light / stop sign / midblock:** Pedestrian(s) in curbside by front crosswalk, or curbside by right crosswalk with bus in right turn lane. **Approaching green/yellow / stop sign / midblock or in intersection:** Pedestrian(s) in curbside by crosswalk for signaled direction.	***Proceed with caution.***
WARN ALERT		**"[Double Beep] WARNING <u>DIRECTION</u>"** *<u>Direction</u> is LEFT, FAR, RIGHT, or FRONT. RIGHT is shown in this example.*	**At red light / stop sign / midblock:** Pedestrian(s) in front crosswalk, or right crosswalk with bus in right turn lane. **Approaching green/yellow / stop sign / midblock or in intersection:** Pedestrian(s) in crosswalk ahead of direction of signaled travel.	***Yield to pedestrian(s) before proceeding.***

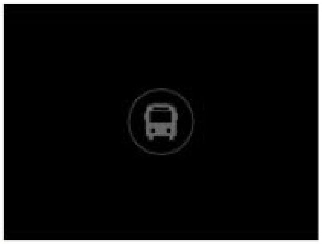
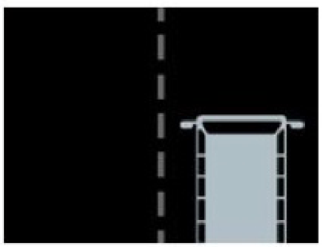
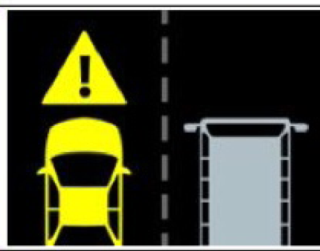
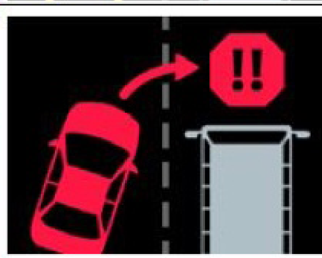
Notes:

- Alerts display only when threat(s) are present: Warn Alert (RED) for pedestrian in cross walk that bus will cross; Inform Alert (YELLOW) for pedestrian near a crosswalk bus will cross who may enter path of bus.
- Multiple alerts can display at once. Alerts of same level are prioritized by location ***(e.g., "[beep] CAUTION FRONT and RIGHT")***. Warnings are first if informs apply ***(e.g., "[beep][beep] WARNING FRONT and FAR")***.
- Alerts are suppressed if threats exist only in crosswalks or curbside zones by crosswalks in other than the direction of travel, or if red light protects pedestrian threats (i.e., left or far side areas).
- Alert is held if bus enters intersection on green/yellow turning red, regardless of threat state change.

This system is for information only and does not supersede GCRTA bus instruments or driver training.

PLEASE REPORT PERSISTENT EQUIPMENT PROBLEMS EACH SHIFT ON A DEFECT CARD

Quick Reference Guide for E-VTRW (Vehicle Turning Right in front of bus Warning) Display Details at Bus Stops

	Graphic (colored graphic displays 3 seconds to indicate threat)	Audible	Situation	Driver Action
SYSTEM OPERATIONAL		None	System is operating normally, but bus is not at a stop (or in range of an equipped intersection for E-PCW). -------------------------------- If **NOT** operating normally, this image displays → 	***None***
E-VTRW ACTIVE NO ALERTS		None	Bus is at stop and E-VTRW application has activated (door has been opened and bus is in forward gear without brake), but no alerts apply.	***None / remain alert and pull away with caution when appropriate.***
INFORM ALERT		**"[Single Beep] VEHICLE ON THE LEFT"**	Equipped vehicle overtakes bus from the rear and passes along the left side of bus while at stop in forward gear without brake. **Note:** this alert will not be issued if equipped vehicle overtakes bus from an adjacent lane.	***Exit bus stop with caution, visually monitoring surrounding vehicles.***
WARN ALERT		**"[Single Beep] VEHICLE TURNING RIGHT"**	Equipped vehicle passes along left side of bus and then turns right in front of the bus, while bus is departing stop without braking. **Note:** Warnings will truncate Inform alerts if applicable. **Note:** this alert is issued even if equipped vehicle does not initially overtake bus from rear.	***Stop and yield to turning vehicle.***

Notes:

- E-VTRW activates with bus at stop after the bus door is opened, and with the bus in forward gear and the brake off (i.e., after the bus has stopped and concluded loading/unload and is departing the stop).
- E-VTRW supersedes E-PCW graphics and annunciations. The rear camera view supersedes both E-VTRW and E-PCW graphics and annunciations when the vehicle is in reverse (rear view is presented on display).
- E-VTRW INFORM and WARN alerts are anticipated to be very rare events, as the only equipped vehicles are select GCRTA buses (24 total buses from the fleet), and because of limiting E-VTRW active conditions.

This system is for information only and does not supersede GCRTA bus instruments or driver training.
PLEASE REPORT PERSISTENT EQUIPMENT PROBLEMS EACH SHIFT ON A DEFECT CARD

APPENDIX

B

"Enhanced Pedestrian Collision Warning (E-PCW) Final Evaluation Report"

Enhanced Pedestrian Collision Warning (E-PCW)

Final Evaluation Report

To

U.S. Department of Transportation
Federal Transit Administration

Submitted by

ITS Roads

February 2019

Version	Author(s)	Date Published	Description/Summary of Changes
0.0	J. Evans, T. Ahmad, I. Jawad	8/7/2018	Preliminary Outline
1.0	J. Evans, T. Ahmad, I. Jawad	9/26/2018	Preliminary Draft
2.0	J. Evans, T. Ahmad, I. Jawad	2/7/2019	Final Report

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Executive Summary

This report presents the methods and results of the independent evaluation of the Enhanced Transit Safety Retrofit Package (E-TRP) deployed for the Greater Cleveland Regional Transit Authority (GCRTA). The E-TRP is part of the United States Department of Transportation's (USDOT's) Intelligent Transportation Systems (ITS) research program and focuses on the development and evaluation of a crash avoidance system for buses.

In 2013, the Transit Safety Retrofit Package (TRP) was developed to enhance pedestrian and transit safety as part of the Connected Vehicle Safety Pilot Model Deployment, including various vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) applications that were installed on three transit vehicles at the University of Michigan campus and operated for 12 hours per day over the course of 8 months. The E-TRP builds on the success and lessons learned of the original TRP project and seeks to collect data from a larger pool of transit vehicles, intersections, and operators to enhance the application performance for operation in a live traffic environment.

The E-TRP system is based on V2I technology that transmits data over Dedicated Short-Range Communication (DSRC) to enable in-vehicle driver alerts when pedestrians are detected at instrumented intersections and crosswalks to prevent crashes. The Federal Transit Administration (FTA) entered into a cooperative agreement with Battelle Memorial Institute to design and build the E-TRP system with a subcontract for ITS Roads (ITSR) to serve as the independent evaluator. Battelle subcontracted with ITSR to serve as the independent evaluator for the deployed Enhanced – Pedestrian Crossing Warning (E-PCW) application.

The objective of this evaluation is to measure the benefits of the deployment in Cleveland, specifically assessing the system performance, safety impact, return on investment (ROI), and driver acceptance of the E-PCW application. Because the deployment was limited to transit vehicles and did not include any equipped passenger cars, the independent evaluation did not include assessment of the E-VTRW performance.

Methodology

This evaluation of the E-PCW application is based on data collected from the E-TRP system during six months of testing, including a baseline data collection period and active system testing. Baseline data were collected for the first month of system operation, and during this period driver alerts were suppressed to assess the rate at which drivers respond to pedestrian presence without the system. Driver alerts were subsequently enabled for five months of active system testing.

During all six months of data collection, professional transit bus drivers drove 24 GCRTA transit buses in revenue service that were equipped with the E-TRP safety applications. The evaluation team aggregated disparate data sets from various system components for analysis in accordance with the evaluation objectives, specifically to assess the system performance, safety impact, ROI, and driver acceptance of the deployed E- PCW application. The analysis focused on the E-PCW, a V2I safety application in which pedestrian detector data generate driver alerts to prevent safety conflicts at instrumented intersections and crosswalks. The E-PCW application generates two different types of

driver alerts, the first to “inform” the driver of a pedestrian detected on the sidewalk near the crosswalk and the second to “warn” the driver of a pedestrian detected in the crosswalk.

System data analysis was supplemented by GCRTA’s historical collision data and system cost data provided by the implementation team. This report contains the approach, results, and analysis for all four evaluation criteria. Table ES-1 is an overview of the four evaluation criteria and the associated performance metrics.

Table ES-1. E-TRP Evaluation Criteria Overview

Evaluation Criteria	Performance Metrics	Notes
System Performance	• False Alarm Rate	Focused on performance of pedestrian detection
Safety Impact	• Collision Reduction	Determined by alert-triggered deceleration and braking events
Return on Investment	• Cost Effectiveness	Derived in conjunction with safety impact
Driver Acceptance	• Usability • Perceived Safety Benefits • Unintended Consequences • Desirability	Consistent with methodology used in Volpe evaluation of TRP system for additional comparative analysis

System Performance

System performance is the primary technical metric of the evaluation and critically affects all subsequent evaluation metrics. The objective of the system performance evaluation was to calculate the false alarm rate of the pedestrian detectors that generate driver alerts; the validity of these alerts is the foundation of the E-PCW application. The system performance evaluation included sample data from four of the six months of testing (February through May 2018), due to data collection gaps in the final two months of testing. Sample alerts, approximately 15% of all available alert data, were analyzed to determine the rate of false positive detections, in which the detector data generates an alert when no pedestrian is present at the instrumented intersection, as well as incorrect alerts, in which the detector incorrectly identified the location of the pedestrian.

Key Findings

Of the E-PCW alerts analyzed, only 9% were false alarms, with 81% confirmed correct alerts, and 10% of the alerts correctly detected the presence of a pedestrian, but incorrectly classified their location. False alarms were caused primarily by lighting and environmental conditions, and the main driver of incorrectly classified alerts was the proximity of the zones to each other based on the camera angle.

Based on evaluator observations and interviews with Battelle and GCRTA staff, several improvements could be made to the system to further improve alert accuracy. Future deployments would benefit from additional calibration of pedestrian detector installation and zone selection to improve performance and use of multi-source augmented location information to improve GPS drift in the urban canyon environment. Battelle staff noted that there have been further improvements to both the detector and positioning equipment since the design and installation of this system, including a reduction in equipment costs. Finally, the performance, operation, and resilience of both the E-PCW application and the E-TRP system as a whole would improve with active system monitoring, interim data quality checks, and routine system maintenance.

Safety Impact

Safety impact is the primary functional metric of the evaluation and serves as an input to the evaluation of E-TRP's ROI. The objective of the safety impact evaluation was to assess driver response to alerts as an indication of the number of potentially-avoided collisions. The safety impact evaluation compared the driver response rate during the baseline period, during which driver alerts were suppressed, to the active test period, when driver alerts were enabled to determine the safety impact of the E-PCW application.

Key Findings

Quantitative data analysis of driver braking within 2.5 seconds of the Warn Alerts showed that the E-PCW application increase driver response by more than 16%, from 12% to 14%. Additionally, the average driver reaction time was reduced by more than 18%, from 1.6 seconds to 1.3 seconds. These findings feed into the ROI evaluation to support the determination that the value of the safety benefits will offset implementation costs within the system lifecycle.

Return on Investment

ROI is the primary policy metric of the evaluation and indicates the system's overall cost effectiveness. The objective of the ROI evaluation was to determine the value of the system's potential to avoid collisions and reduce resulting agency costs in comparison with the overall cost of the system.

To determine the value of E-PCW's safety benefits, the evaluation team used guidance from the USDOT's Office of the Secretary of Transportation on the treatment of the economic value of a statistical life (VSL). The evaluation team applied adjusted VSL to historical GCRTA collision data to determine the estimated value (total cost) of current safety performance and calculate the cost savings that would result from the E-TRP's estimated safety impact to determine the estimated benefits (total cost savings) of the E- PCW application.

To estimate the cost of a full system deployment, the evaluation team extrapolated reported costs from the instrumentation of three E-PCW locations to a "full coverage" deployment. The evaluation team compared the locations of GCRTA's historical transit-pedestrian collisions against a map of the relevant transit service area and identified 24 additional instrumentation locations to equip "high-priority" sites, based on the highest density transit service, pedestrian activity, and historical collisions, with E-PCW.

The evaluation team compared estimates of the annual cost savings and the total deployment cost to determine when the system's benefits would fully offset the initial investment.

Key Findings

In the five years of collision data provided, between 2011 and 2016, GCRTA recorded 14 events involving a pedestrian. The evaluation team reviewed the description of each event to estimate the Maximum Abbreviated Injury Scale (MAIS) classification and to calculate the associated value of preventing these injuries. Events that did not include any injuries in the description were excluded. The estimated average annual benefit of the system amounted to $106,452, and the estimated total deployment cost was $2,163,180.

Comparing estimates of the average annual benefit of the system and the total deployment cost indicates that recuperating the investment in the form of risk reduction value from E-PCW may take more than 20 years (244 months). For comparison, the lifecycle of traditional traffic infrastructure ranges from 5 to 15 years, depending on variables such as the cost of equipment, pace of technological advancement, operational performance, and the quality of infrastructure maintenance. Based on these estimates, the benefits of the E- PCW application are not likely to outweigh the implementation cost of the system even with a relatively long deployment lifecycle.

At nearly $70,000 per site, full deployment of the E-PCW infrastructure likely exceeds current transit agency budgets. However, as more Connected Vehicle applications are deployed across the U.S., the marginal cost of associated deployment infrastructure will decrease and likely will be distributed across different agencies with cost sharing between state departments of transportation, municipal governments, and transit agencies. For example, it is reasonable to assume that cities will cover much of the deployment costs for intersection infrastructure (e.g., roadside units), which would broadcast Map Data Message (MAP) and Signal Phase and Timing (SPaT) messages. Transit agencies would cover the deployment costs for bus on-board equipment and transit Connected Vehicle applications software.

While the E-PCW deployment in Cleveland does not demonstrate strong, near-term ROI, the project dramatically improved the E-PCW system performance and advanced the state-of-the-practice in Connected Vehicle applications for transit safety. GCRTA staff reported high confidence in the value of the E-PCW system and expressed a desire to deploy the system across their entire transit network as costs decrease over time.

Driver Acceptance

Driver acceptance is the primary operational metric of the evaluation and incorporates user feedback for four different elements, specifically the E-PCW application's usability, perceived safety benefits, unintended consequences, and desirability. The driver acceptance evaluation was adapted from survey questions developed for the evaluation of the original TRP system and was administered both electronically and in-person.

Key Findings

Drivers who participated in the survey rated positively the system's usability and desirability, but expressed mixed responses regarding perceived safety benefits and unintended consequences. Nearly two-thirds (63%) of drivers agreed that they would like the system installed on all buses they drive, and more than half (55%) reported that they trusted the cautions and warnings.

In total, 18% of the responses indicated that there were no near misses; however, nearly three-quarters (73%) indicated drivers observed false positive alarms, and 82% reported observing false negatives, in which they observed an inform or warning (potential collision) situation but did not receive an alert.

Only 13 of 751 of the E-TRP drivers, fewer than 2% participated in the survey. With a small sample size, conclusions drawn from the survey cannot provide statistically meaningful analysis of the system, as the results are strongly influenced by individual drivers and their specific experience. Results are not necessarily representative of all GCRTA driver experience with E-TRP and cannot be generally extrapolated to drivers in other regions.

Conclusions

Overall, the evaluation of the E- PCW application deployed in Cleveland demonstrates reliable system performance, a positive safety impact, a reasonable ROI, with general driver acceptance. Future deployments may consider minor improvements to system design, including potential improvements to positioning and detector equipment, as well as operational measures such as active system monitoring, interim data quality checks, and regularly scheduled maintenance.

As part of USDOT's broader ITS and Connected Vehicle research program, the E-TRP system deployment illustrates the significant safety benefits of DSRC-based advanced safety applications.

Section 1 Introduction

The purpose of this document is to present the results of the evaluation of the Enhanced Transit Safety Retrofit Package (E-TRP) system deployed in Cleveland, Ohio. The following sections provide background information about the project, an overview of the E-TRP system, information about the Cleveland deployment, a summary of the evaluation goals, and a list of data used in the evaluation.

Background

In 2013, the Transit Safety Retrofit Package (TRP) was developed to enhance pedestrian and transit safety as part of the Connected Vehicle Safety Pilot Model Deployment. As part of the TRP, the implementation team delivered three Vehicle-to-Vehicle (V2V) safety applications, including Forward Collision Warning (FCW), Emergency Electronic Brake Lights (EEBL), and Vehicle Turning Right in Front of Bus Warning (VTRW), as well as two Vehicle-to-Infrastructure (V2I) safety applications including Curve Speed Warning (CSW) and Pedestrian in Signalized Crosswalk Warning (PCW). The applications were installed on 3 University of Michigan transit buses and operated for 12 hours per day over the course of 8 months.

Figure 1-1. GCRTA Bus

Source: Cleveland.com

To follow-up on the success and lessons learned of the original TRP project, the Federal Transit Administration (FTA) funded a new project (E-TRP) to enhance the transit-specific TRP applications (VTRW and PCW), customize them for the larger transit operating environment, demonstrate them in real world conditions, and collect data from a larger pool of transit vehicles, intersections, and operators. Battelle, the implementation team, partnered with the Greater Cleveland Regional Transit Authority (GCRTA) to deploy an enhanced version of two of the original TRP applications: Enhanced Pedestrian Crossing Warning (E-PCW) and Enhanced Vehicle Turning Right in Front of Bus Warning (E-VTRW). FTA entered into a cooperative agreement with Battelle to implement the project, and Battelle hired ITS Roads (ITSR) to conduct an independent evaluation of the E-TRP deployment. Because the deployment was limited to transit vehicles and did not include any equipped passenger cars, the independent evaluation did not include assessment of the E-VTRW performance.

System Overview

Architecture

The E-TRP system comprises an on-board, a transit vehicle-based system, and an infrastructure-based system at each of the three selected sites. These subsystems comprise equipment for object detection, positioning, communications, processing, and a human-machine interface. Data sets are collected by and exchanged across these systems to enable the E-PCW application.

Figure 1-2 depicts the high-level system architecture for the E-TRP, which includes the following components:

- **Common Computing Platform (CCP)** – The heart of the E-TRP system is the CCP, which is used in both the on-board and the infrastructure systems. The CCP is the central processor that hosts the software applications and interfaces with the other subsystems.
- **Dedicated Short-Range Communications (DSRC) Radios** – DSRC radios serve as the low-latency wireless communications link between the vehicle and roadside systems and are installed in both the on-board and infrastructure-based systems.
- **Cellular Communications** – Each CCP has a cellular modem for wireless connectivity between deployed equipment and the backend Cloud-based Management System (CMS) to support data storage and remote monitoring capabilities.
- **Cloud-based Management System (CMS)** – The CMS is the remote portal for the on-board and infrastructure-based systems for data storage and status monitoring for all active systems (near real-time operational state dashboard).
- **Pedestrian Detection System (PDS)** – The PDS uses Forward-Looking Infrared (FLIR) cameras to detect the presence of pedestrians inside a specified detection zone with a local processor and communicates to the infrastructure-based CCP whether a pedestrian is detected.
- **Global Positioning System (GPS)** – A GPS module is incorporated in the on-board system to provide real-time, lane-level positioning data to the CCP.
- **Human Interface System (HIS)** – The HIS is the E-TRP interface that provides audio/visual (A/V) alerts to the transit vehicle driver.

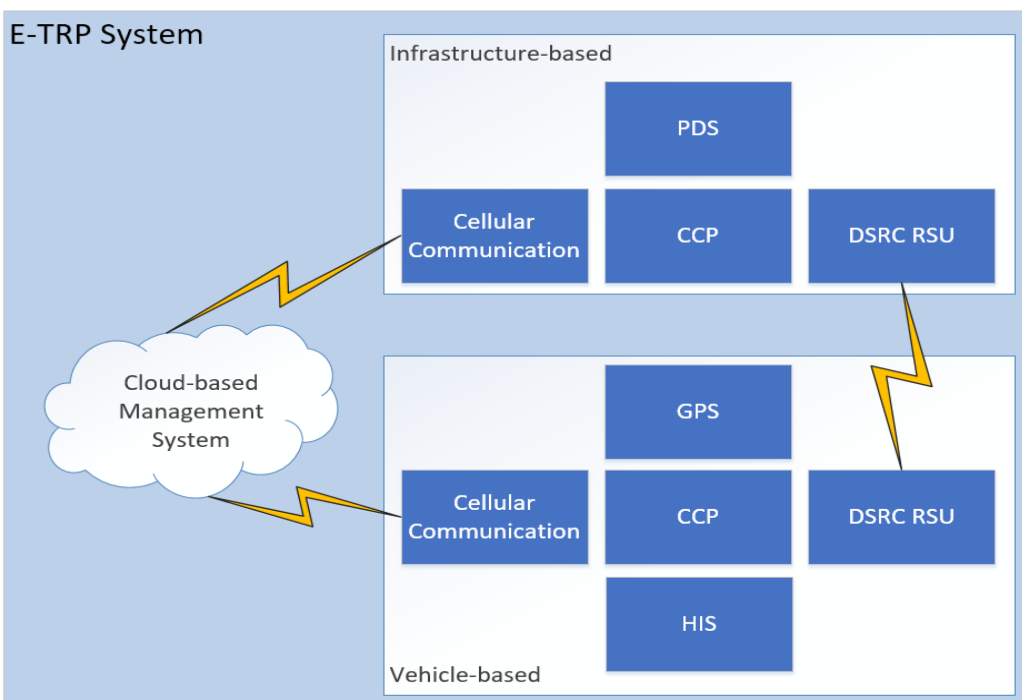

Figure 1-2. Conceptual E-TRP Architecture

Enhanced Pedestrian Crossing Warning (E-PCW)

The scope of this evaluation was limited to a single application, the E-PCW, which provides alerts to the bus driver when a pedestrian is detected in the intended path of the bus on the adjacent curb or in the crosswalk. The on-board CCP records system log application files and vehicle information to determine how the information and alerts affected driver braking.

The E-PCW application detects pedestrians in crosswalks or at the curb whose location or movement establishes a potential safety conflict for both signalized and non-signalized crossings. The application delivers information in the form of alerts that either inform or warn the transit vehicle operator of a potential conflict or imminent danger based on the detected location of the pedestrian(s) and location and state of the bus. Figure 1-3 highlights the driver display, alert type, and associated pedestrian location. Alerts are generated only when the system detects pedestrian presence in predefined locations and the bus is expected to traverse the potential path of the pedestrian; the system cannot detect pedestrians outside of designated camera locations.

Figure 1-3. Inform Alert – Yellow Display for Curbside Pedestrian

Figure 1-4. Warn Alert – Red Display for Pedestrian in Crosswalk

Deployment

The E-TRP system was deployed, operated, and tested in live traffic on 24 GCRTA buses and at 3 roadside sites—one signalized intersection, one non-signalized intersection, and one non-signalized mid-block location, as shown in Table 1-1 and displayed on the map in Figure 1-5. These sites constitute the Field Operational Environment in which the E-TRP system operated normally in accordance with existing traffic laws.

Table 1-1. E-TRP Deployment Sites

Site ID	Deployment Location	Location Type
1	E 12th St & Superior Ave	Signalized intersection
2	Rockwell Ave & E Roadway Ave	Non-signalized intersection
3	Euclid Avenue & E 19th St	Mid-block location

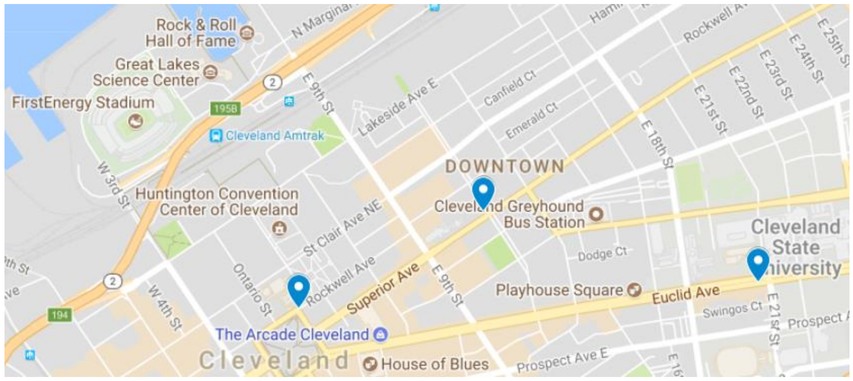

Figure 1-5. E-TRP Deployment Sites

Data Sources

Evaluation data included both objective and subjective data obtained from operational system data, historical transit data, driver surveys, and institutional interviews. Objective data analysis was the primary tool for the evaluation, resulting in a quantitative measurement of system performance, safety impact, return on investment (ROI), and driver acceptance. Subjective input from drivers, agency staff, and the implementation team was used to provide context for all quantitative findings.

Objective Data

Objective data consisted of numerical data from a variety of sources—system log files, historical transit collision, system cost data, and image files from the pedestrian detectors as depicted in Figure 1-6.

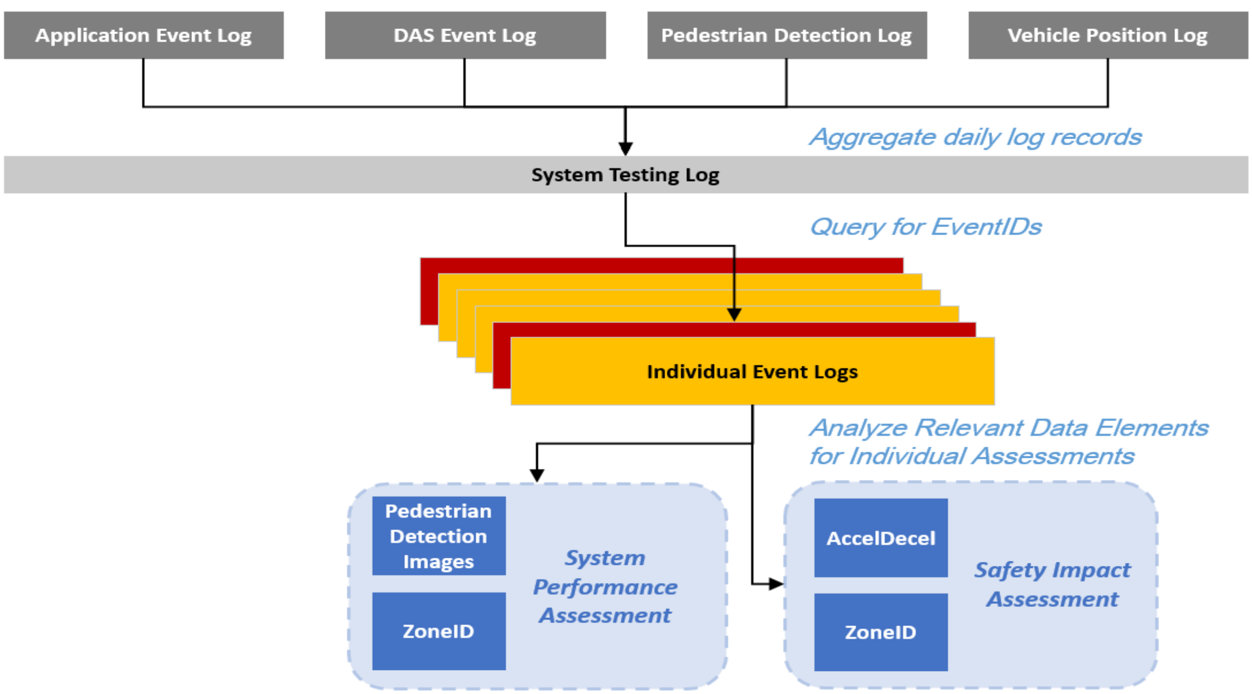

Figure 1-6. High-Level Data Analysis Flow Chart

Operational system data were furnished by the implementation team through a cloud-based shared file. The evaluation team used data from the system log files, specifically from the Application Data log files, associated Pedestrian Detector images, and Vehicle Data log files. Sample log files are included in Appendix A. The Application Data and associated Pedestrian Detector images were used to evaluate system performance. The log files with Application and Vehicle data were combined for the safety impact evaluation. The results of the safety impact evaluation were used in the ROI assessment as the basis for the potential cost savings based on improved driver responsiveness. Transit safety data were obtained directly from GCRTA, including historical transit collision data for a five-year period between April 2011 and May 2016.

Subjective Data

At the end of system testing, E-TRP drivers were encouraged to complete a driver survey that was administered both electronically by the evaluation team and in-person by GCRTA staff. In total, 13 drivers completed the survey, which consisted of both open-ended and Likert-scale questions. Data from the surveys were aggregated electronically and served as the basis for the Driver Acceptance evaluation. Additionally, the evaluation team interviewed staff from the Battelle implementation team and GCRTA's safety team. Interview findings are included throughout the evaluation to provide context for the quantitative results of objective data analysis.

Map of Data to Evaluation Measures

Table 1-2 illustrates the data sources used to assess each of the evaluation measures. The system performance, safety impact, and ROI analyses incorporated both objective and subjective data, and the assessment of driver acceptance was limited to subjective data.

Table 1-2. Map of Data to Evaluation Measures

	Application Data	*Pedestrian Detector Images*	*Vehicle Data*	*Historical Transit Data*	*Driver Surveys*	*Institutional Interviews*
System Performance	✓	✓			✓	✓
Safety Impact	✓		✓		✓	✓
Return on Investment	✓		✓	✓		
Driver Acceptance					✓	

Evaluation Approach

The purpose of this evaluation was to assess the benefits of the E-PCW application, deployed in Cleveland, Ohio, including evaluation of the system's performance, safety impact, ROI, and driver acceptance. The evaluation report is divided into individual sections for each evaluation measure, with an explanation of specific evaluation metrics and methodologies. This subsection presents the overall evaluation approach as well as a high-level explanation of the evaluation methodology for each performance measure.

The E-PCW application evaluation included both qualitative and quantitative analysis; subjective input from the Battelle implementation team and GCRTA's safety staff and bus drivers was used to establish context for the objective results from quantitative data analysis. System data were collected during six months of operational testing, and alerts were suppressed during the first month to establish a baseline for the safety impact analysis.

System performance was included in the evaluation to determine the accuracy of the FLIR cameras used as pedestrian detectors at roadside installations. The evaluation included a random sampling of system alerts and manual review of associated pedestrian detector images to classify the alerts as either false alarms, incorrect alerts, and accurate alerts. False alarms were identified by the absence of pedestrians in the relevant detector image, and incorrect alerts were marked when the pedestrian in the image was not in the location identified by the detector, resulting in the wrong type of alert. Accurate alerts are those in which the pedestrian in the photo is identified in the correct zone by the pedestrian detector image. Qualitative inspection of the resulting images also allowed for the identification of various causes for false alarms and incorrect alerts. The scope of this assessment was limited to false positives and did not include consideration of false negatives.

The objective of the **safety impact** assessment was to determine the extent to which the E-PCW application improved driver responsiveness to situations where pedestrians were in the crosswalk in front of the bus. The evaluation team aggregated log files from the application and vehicle data to determine whether drivers braked within 2.5 seconds[1] of receiving a warning alert. Inform alerts were not considered in this portion of the analysis, as the driver may not have needed to brake to avoid pedestrians standing on the curb. The evaluation team compared the driver braking response during the baseline period to that during the active test period. This comparison allowed the team to quantify the improvement in driver braking as a response to the new alerts and assumed that the operational conditions and traffic environment did not change between the baseline and active testing period.

The simplified **ROI** assessment estimated the monetary value of the system's safety benefits in comparison with the implementation cost. This evaluation was limited to the benefits of the E-PCW application, such as a reduction in annual transit-related pedestrian injuries and fatalities. The evaluation of ROI combined the system's safety impact with associated cost data to determine the potential cost savings of the E-PCW application. To determine the potential benefits, the evaluation team applied the safety impact rate to historical GCRTA data regarding pedestrian injuries and fatalities. System cost data were furnished by the Battelle implementation team and were exclusive of development costs to be representative of the future implementation cost. The ROI evaluation also includes a qualitative discussion of all relevant data.

Driver acceptance was measured by survey responses collected in-person by GCRTA and included four assessment criteria—system usability, perceived safety benefits, unintended consequences, and desirability. The survey was adapted from the survey administered by the Volpe team during the evaluation of the original TRP deployment and condensed to encourage driver responsiveness to the survey. The survey included both open-ended and Likert-scale questions, and the results were analyzed as a separate measure and incorporated into other sections as context for other quantitative results.

All test data were furnished by the Battelle implementation team through a shared drive hosted on the cloud. Sample data, surveys, survey responses, and interview questions are provided in the appendices to this report.

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[1] Based on the American Association of State Highway and Transportation Officials (AASHTO) design perception-reaction time (PRT).

Section 2 System Performance

System performance is the primary technical metric of the evaluation and qualitatively affects all subsequent evaluation metrics. The objective of the system performance evaluation was to calculate the false alarm rate of the pedestrian detectors that generate driver alerts; the validity of these alerts is the foundation of the E-PCW application. The system performance evaluation included sample data from four of the six months of testing (February through May 2018), due to data collection gaps in the final two months of testing. Sample alerts—15% of all alert data—were analyzed to determine the rate of false positive detections, in which the detector data generates an alert when no pedestrian is present at the instrumented intersection, as well as incorrect alerts, in which the detector incorrectly identified the location of the pedestrian.

Approach

To determine the false alarm rate of the system, the evaluation team reviewed data from both the application logs and associated images during system operational periods; data were not evaluated for periods of system downtime. Daily application log files aggregated data for each application event, including event time, type of application, alert, and event code, as well as device, vehicle, and roadside identification number. Additional information about the raw data file is included in Appendix A–Objective Data, as excerpted from Battelle's E-TRP Data Dictionary. The team used date, time, camera internet protocol (IP) address, and zone and event numbers to identify the pedestrian detector image associated with each sample alert. For each alert analyzed, the evaluation team manually compared the alert information to the detector image to determine the alert accuracy in accordance with the schema defined in Table 2-1.

Table 2-1. System Performance Classification Schema

Classification Type	Classification Definition
False Alarm	No pedestrian is present in any defined zone.
Incorrect Alert	Pedestrian detected in different zone than indicated by alert.
Correct Alert	Pedestrian detected in zone indicated by alert.

The following pages contain examples of each type of alert, and additional examples are included in the Results section to illustrate the various causes of incorrect alerts and false alarms, including lighting and environmental conditions, objects, and equipment failures.

Correct Alert – Warn Alert

Figure 2-2 is an example of the classification for a "correct alert" in the warning scenario. In the image, the crosswalk zone is highlighted in white, indicating the detection of a pedestrian, and the person in the image is located in the highlighted zone, crossing the street in front of the bus.

Figure 2-1. Example of Correct "Warn" Alert

Correct Alert – Inform Alert

Figure 2-2 is an example of the classification for a "correct alert" in the inform scenario. In the image, the sidewalk zone is highlighted in white, indicating the detection of a pedestrian, and the person in the image is located in the highlighted zone, standing near the curb on the sidewalk.

Figure 2-2. Example of Correct "Inform" Alert

Incorrect Alert – Warn Alert

Figure 2-3 is an example of the classification for an "incorrect alert" in the warning scenario. In the image, the crosswalk zone is highlighted in white, indicating the detection of a pedestrian; however, the person in the image is standing on the curb. Due to the camera angle, the person's torso appears in the warning zone of the image creating an incorrect alert.

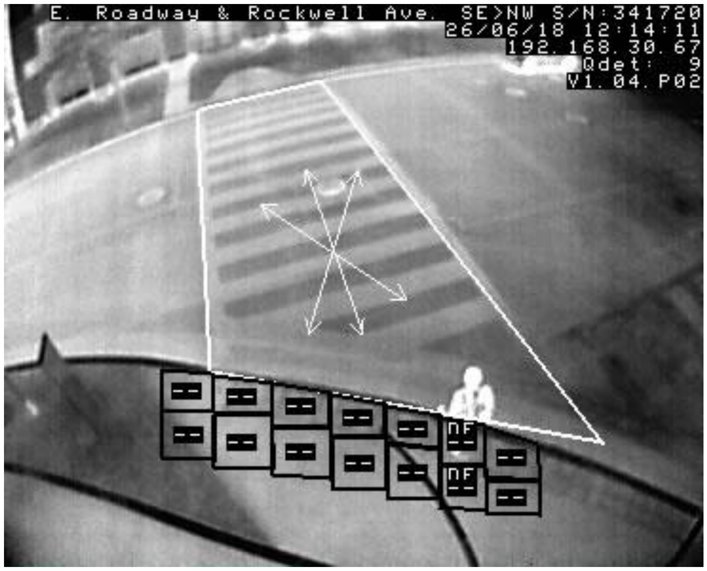


Figure 2-3. Example of Incorrect "Warn" Alert

False Alarm – Warn Alert

Figure 2-4 is an example of the classification for a "false alarm" in the "Warn" alert scenario. In the image, one of the designated curb zones is highlighted in white, indicating the detection of a pedestrian, when there are no pedestrians present.

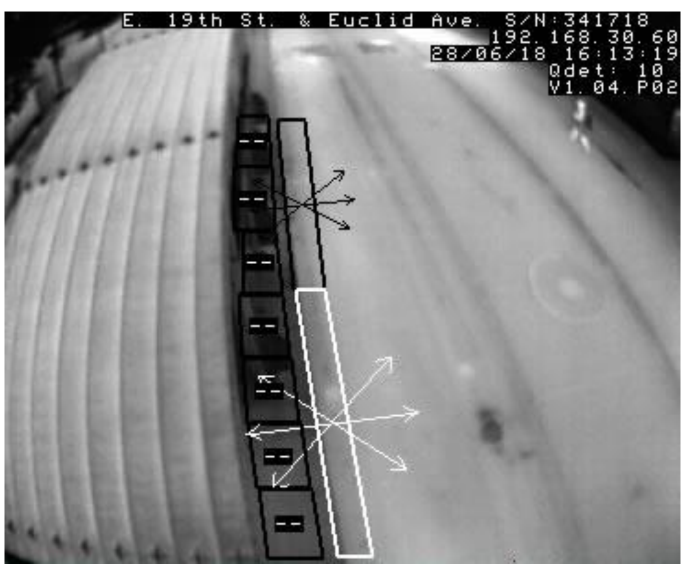


Figure 2-4. Example of False Alarm (Warn)

False Alarm – Inform Alert

Figure 2-5 is an example of the classification for a "false alarm" in the "Inform" alert scenario. In the image, one designated curb zone is highlighted in white, indicating the detection of a pedestrian, when there are no pedestrians present.

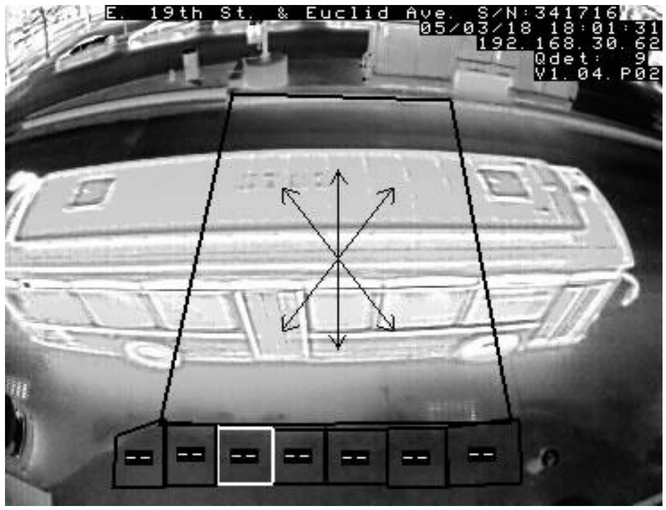


Figure 2-5. Example of False Alarm (Inform)

The team aggregated daily log files into monthly data sets and randomly selected sample alerts for analysis. In total, 2,310 sample alerts were considered of the 15,609 E-PCW alerts generated between February and May 2018. The tally for each alert classification type was compared with the total sample size to determine the rate of each alert classification type. Alert data for June and July were incomplete and could not be adequately sampled for the analysis, but results across the analysis of each month of data indicate that the false alarm rate and alert accuracy were consistent throughout the system testing.

Results

The team aggregated the analysis results from the monthly data sets to compare system performance across the testing period. Table 2-2 shows the number of alerts analyzed (Sample Size) alongside the frequency and percentage of alerts that were classified as False Alarms, Incorrect Alerts, and Correct Alerts.

Table 2-2. System Performance – Alert Accuracy by Month

Month	Sample Size	False Alarm		Incorrect Alert		Correct Alert	
February	498	60	12%	52	10%	386	78%
March	608	70	12%	46	8%	492	81%
April	601	38	6%	55	9%	508	85%
May	603	47	8%	68	11%	488	81%
Total (Average)	2,310	215	9%	221	10%	1,874	81%

Of the total E-PCW alerts analyzed, only 9% were false alarms, with 81% confirmed correct alerts, and 10% of the alerts issued correctly detected the presence of a pedestrian but incorrectly classified their location. Figure 2-6 illustrates the alert accuracy by month and indicates that the number of false alarms and inaccurate alerts was relatively consistent across the test period. Qualitative analysis of the pedestrian detector images, including examples described on the next page, indicates that the primary causes of false alarms were lighting and environmental conditions, non-pedestrian moving objects, and equipment failure.

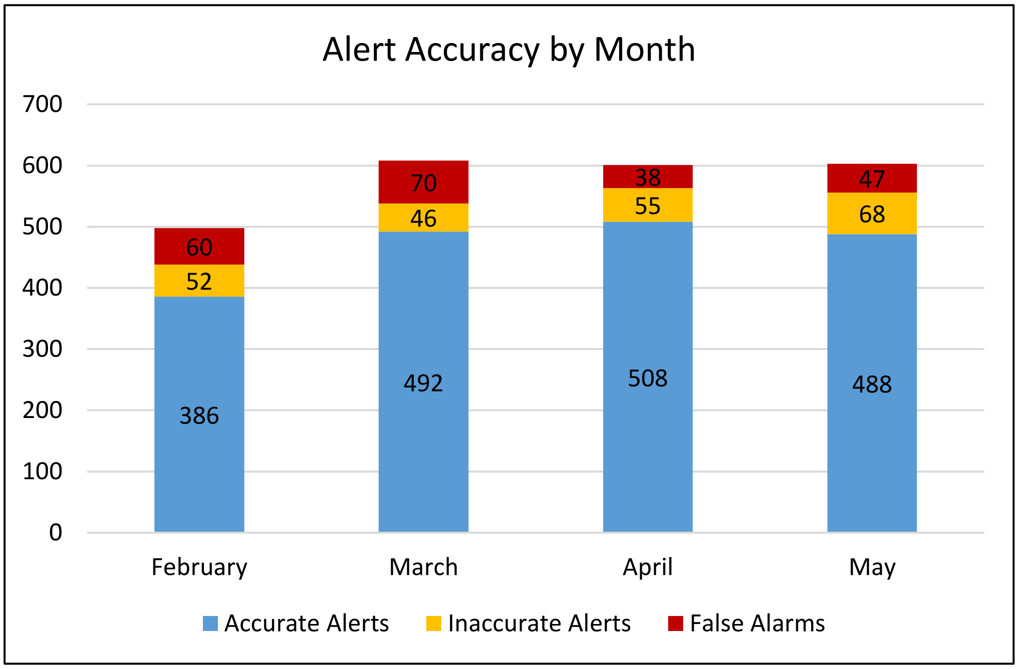
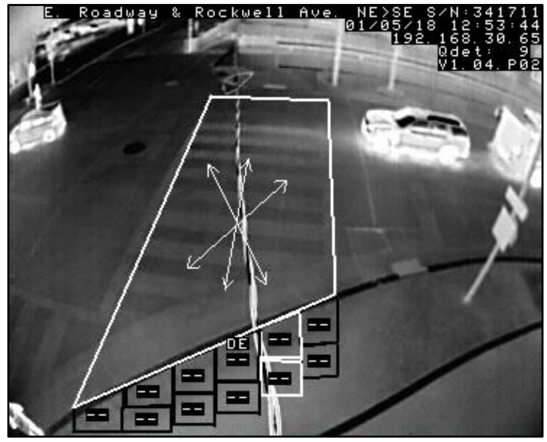


Figure 2-6. System Performance – Alert Accuracy by Month

The following images illustrate various false alarms, including those caused by vehicle and other non-pedestrian objects, lighting and environmental conditions, as well as equipment failures or malfunctions.

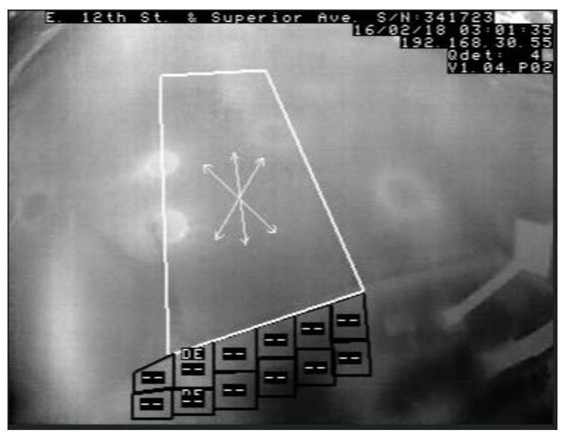
False Alarms Caused by Non-Pedestrian Objects

The images below illustrate instances where a false warn alert was issued in response to the detection of a vehicle in the crosswalk zone. Calibration of the pedestrian detector software to prevent vehicle-initiated detection may increase system performance.



False Alarms Caused by Lighting Conditions

The images below illustrate examples of false alarms caused by lighting and environmental conditions. The image on the left shows an instance in which light bouncing off the pavement caused a false detection in the "Inform" alert zone. The image on the right contains circular light patterns that were present in many of the false alarm images. Calibration of the detectors and investigation of the source of the circular light patterns may increase system performance significantly.



False Alarms Caused by Equipment Failure

The images below illustrate examples of false alarms caused by failure of the pedestrian detector equipment. The image on the left appears to have poorly-calibrated detection zones, and the image on the right contains a line through the image that may be a crack in the camera lens. Further investigation of these failures would be useful to identify potential remedies, such as active system monitoring, interim data quality checks, and scheduled routine maintenance.

Conclusions

The E-PCW application is designed to alert the bus driver if a pedestrian is present in the crosswalk or on the curb as the bus approaches one of the instrumented intersections. Specifically, the application generates warn alerts when a pedestrian is detected in the crosswalk and inform alerts when the pedestrian is near the curb. For system performance, the team analyzed the pedestrian detection images associated with selected sample alerts to determine the number of accurate alerts and to identify the rate at which the system generated false alarms or incorrect alerts. A random sample of alerts—15% of the overall dataset—were selected and the evaluation team manually reviewed the associated pedestrian detector images to determine alert accuracy.

In total, 9% of the sample alerts analyzed show a highlighted detection zone where no pedestrian was present in the image, resulting in a false alarm. In 10% of the sample alerts, the pedestrian detector incorrectly classified the location of the pedestrian, resulting in an inaccurate alert. In 81% of the sample alerts, accurate alerts were shown, in which the detector image showed the presence of a pedestrian in the highlighted detector zone.

Moving objects, lighting conditions, and equipment failure appear to be the main causes of false alarms. Additional calibration, interim data quality checks, and routine maintenance could reduce the false alarm rate of the E- PCW application. All future deployments should consider relevant upgrades to pedestrian detector technology that may further reduce the false alarm rate. Incorrect alerts often were caused by the camera angle; when pedestrians stood on the curb, the camera often captured their torso in the crosswalk zone and generated a warn alert when the driver would be expecting an inform alert. Raising the mounting height may decrease the camera angle and reduce the number of incorrect alerts. Further, calibration of the detector zones in each deployment location may also increase alert accuracy.

Based on evaluator observations and interviews with Battelle and GCRTA staff, several improvements could be made to the system. As noted, future deployments would benefit from additional calibration of pedestrian detector installation and zone selection to improve performance. Additionally, several of the system's engineers recommend use of multi-source augmented location information to improve GPS drift in the urban canyon environment. Battelle staff noted that there have been improvements to both the detector and positioning equipment since the design and installation of this system, including a reduction in equipment costs. Finally, the performance, operation, and resilience of both the E- PCW application and the E-TRP system as a whole would improve with active system monitoring and interim data quality checks.

Section 3 Safety Impact

Safety impact is the primary functional metric of the evaluation and serves as an input to the evaluation of E-PCW's return on investment. The objective of the safety impact evaluation was to assess the driver response to alerts as an indication of the number of potentially-avoided collisions. The safety impact evaluation compared driver response rate during the baseline period, during which driver alerts were suppressed, to the active test period, when driver alerts were enabled to determine the safety impact of the E- PCW application.

Approach

The safety impact analysis included both baseline and active test data to estimate the change in driver response to E-PCW warnings. The sample analysis data consisted of all alerts from six randomly-selected days from each month. Baseline data were collected during the first month of operational testing by suppressing driver alerts. During this period, the system registered logs of alert data and driver braking data that were used to determine how often drivers braked in response to "warn alert" scenarios without receiving alerts. After the first month of testing, alerts were turned back on and the same driver braking data was collected. From the application and vehicle data logs, the evaluation team aggregated files to determine how often drivers braked in response to "warn alert" scenarios during both baseline and active testing. The evaluation used the American Association of State Highway and Transportation Officials (AASHTO) design perception-reaction time (PRT) of 2.5 seconds to determine whether a driver braking event was attributable to the warn alert and classified the events in accordance with the schema defined in Table 3-1.

Table 3-1. System Performance Classification Schema

Classification Type	Classification Definition
Indeterminate	No driver response recorded within evaluation window.
Response to Alert	Driver braked within 2.5 seconds after alert event.

Results

The team aggregated results from each analysis day for both the baseline and active test period to determine the safety impact of the system, calculated as the percent improvement in driver response to alerts. For each test period, Table 3-2 shows the number of alerts analyzed (Sample Size) alongside the frequency and percentage of alerts that were classified as either an Indeterminate Response or a Response to the Alert. Additionally, the team recorded the average reaction time for events that were classified as a responsive to the alert (within 2.5 seconds).

Table 3-2. Safety Impact – Driver Response Rate

Test Period	Sample Size	Indeterminate		Response to Alert		Average Reaction Time (sec)
Baseline	1363	1205	88%	158	12%	1.6
Test	1697	1467	86%	230	14%	1.3
Improvement					16.6%	18.8%

During the baseline period, when system alerts were suppressed, drivers responded to 12% of the situations that were identified by the application as warn alerts, with an average reaction time of 1.6 seconds. With the E-PCW alerts enabled during the active test period, drivers responded to 14% of warn alerts, and the average reaction time was 1.3 seconds. The driver response rate to E-PCW alerts increased 16.6%, and the average driver reaction time was reduced by 18.8%. Both results indicate that the E-PCW application has the potential to reduce collisions, and the increased driver response rate is used in the ROI assessment to estimate the value of the system safety benefits.

Conclusions

The E-PCW application is designed to alert a bus driver if a pedestrian is present in the crosswalk as the bus approaches one of the instrumented intersections. Operational testing of the E-PCW application included a baseline period, when the system was operational and driver alerts were suppressed, and an active test period, when drivers received alerts from the system. For safety impact, the team analyzed approximately 20% of the test days to determine whether alerts increased driver response rate to Warn Alerts.

Quantitative data analysis of driver braking within 2.5 seconds[2] of the warn alerts showed that the E-PCW application increases driver response by more than 16%, from 12% to 14%. Additionally, the average driver reaction time was reduced by more than 18%, from 1.6 seconds to 1.3 seconds. These improvements demonstrate the operational viability and effectiveness of the E-TRP system and E-PCW application to improve transit and pedestrian safety.

[2] Based on the AASHTO design PRT.

Section 4 Return on Investment

ROI is the primary policy metric of the evaluation and indicates the E-PCW application's overall cost effectiveness. The objective of the ROI evaluation is to determine the value of the application's safety benefits in comparison with its overall cost. This evaluation included operational system data (derived from the safety impact assessment), historical GCRTA collision data, and system cost data furnished by the implementation team.

Approach

The evaluation team used guidance[3] from the USDOT's Office of the Secretary of Transportation on the treatment of the economic VSL to determine the value of the E-TRP's system safety benefits. The 2016 USDOT guidance uses $9.6 million[4] for VSL and instructs the use of an adjusted VSL, based on coefficients for the MAIS, to determine the value of preventing injuries. The MAIS is based on a rating of each injury type based on severity and duration to establish a scale of "quality-adjusted life years" in comparison to perfect health.

The evaluation team applied these adjusted VSL to historical GCRTA collision data alongside the E-TRP estimated safety impact to determine the cost effectiveness of the E-PCW application. For each MAIS level, Table 4-1 shows the various severity classifications, with the VSL coefficient recommended in USDOT's guidance, and the estimated value for preventing each type based on the 2016 adjusted VSL.

Table 4-1. Estimated Value of Preventing Injuries based on USDOT VSL and MAIS Classification System

MAIS Level	Severity Classification	VSL Coefficient	2016 Value
1	Minor	0.003	$28,800
2	Moderate	0.047	$451,200
3	Serious	0.105	$1,008,000
4	Severe	0.266	$2,553,600
5	Critical	0.593	$5,692,800
6	Unsurvivable	1.000	$9,600,000

Results

This section specifically identifies the data used in the ROI assessment, applies the E-TRP safety impact, and compares the estimated benefits with overall system costs.

System Benefits

GCRTA's historical collision records, including data from six bus lines between 2011 and 2016, lists 14 events involving a pedestrian, including several that indicate no injury occurred. Figure 4-1 illustrates the distribution of collisions across the greater Cleveland region.

[3] U.S. DOT Office of the Secretary of Transportation, *Guidance on the Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses*, 2016.
[4] It is important to note that VSL is a valuation of the potential to reduce risks, not a valuation of life. VSL is defined as the additional cost that individuals would be willing to bear for improvements in safety (risk reduction) that reduce the expected number of fatalities by one.

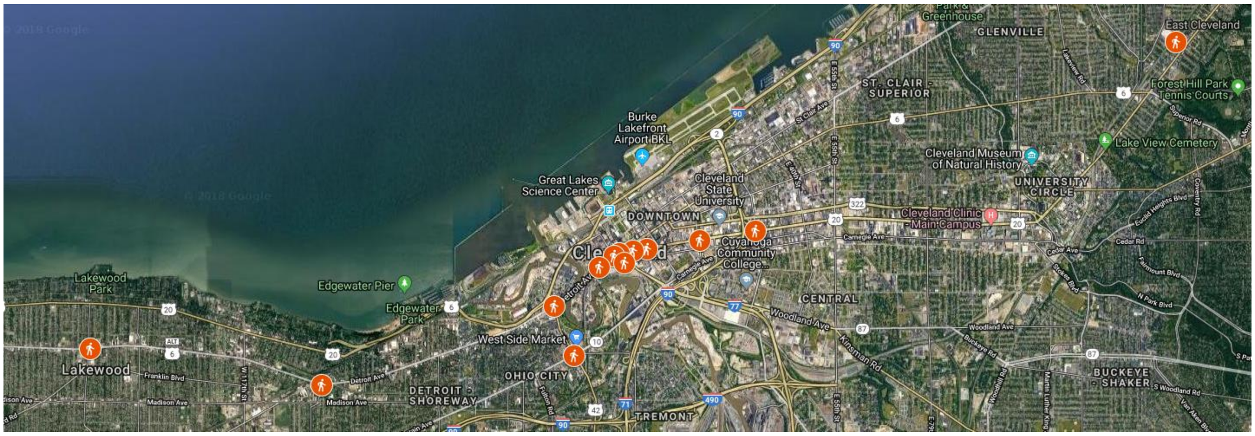


Figure 4-1. Map of 5-Year Cleveland Historical Transit-Pedestrian Collisions

Using the description of each event, the evaluation team estimated the MAIS level for each incident and calculated the overall value of preventing the injuries. Table 4-2 shows the tabulated frequency for each MAIS level classification within the five-year reporting period and calculates the total value of preventing these injuries. For event descriptions that did not include information about an injury, the evaluation team did not include the event in the benefits estimate.

Table 4-2. Estimated MAIS Level for GCRTA's Historical Pedestrian Collisions

MAIS Level	Severity Classification	Five-Year Frequency	Total Value
1	Minor	7	$201,600
2	Moderate	1	$451,200
3	Serious	0	$0
4	Severe	1	$2,553,600
5	Critical	0	$0
6	Unsurvivable	0	$0
5-Year Value of Preventing Injuries			$3,206,400
Annual Value of Preventing Injuries			$641,280

The estimated total value of preventing injuries from nine collision events involving pedestrians over the five-year reporting period is more than $3.2 million, an average value of $641,280 per year. Based on data analysis from the safety impact assessment, the estimated safety impact of the E- PCW application is the potential to reduce collisions by 16.6%. Applying this to the average annual value of preventing injuries, the evaluation team estimates that the annual E- PCW application benefits amount to approximately $106,452.

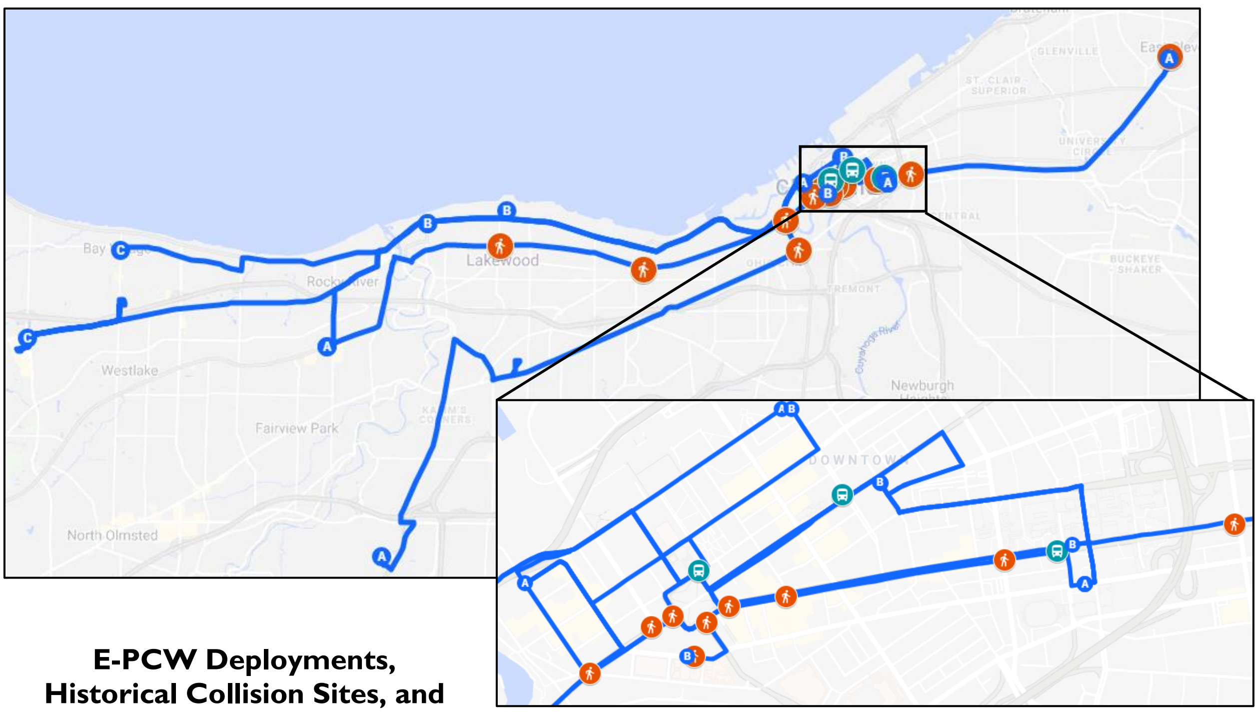
System Costs

Table 4-3 shows the actual system costs for the E-PCW implementation in Cleveland, inclusive of equipment, material costs, and intersection installation and maintenance labor, as reported by the installation team. These costs do not include software or development costs and assumes there is no additional cost of bus instrumentation beyond GCRTA's normal staffing. These costs also exclude cellular service that was used for remote system monitoring and is not necessary for E-TRP operation. The average unit cost for a bus installation is $6,342, and the average cost for a site installation is $69,078.

Table 4-3. System Implementation Costs

Cost Element	Element ID	Element Description	Unit Cost	Qty	Total Cost	Average Unit Cost
Bus	Type 1	2900 Series	$ 6,379.06	4	$ 25,516.24	$6,342
	Type 2	3200 Series	$ 6,320.51	4	$ 25,282.04	
	Type 3	3000 Series	$ 6,379.06	8	$ 51,032.48	
	Type 4	3700 Series	$ 6,296.90	8	$ 50,375.20	
Intersection Infrastructure	Intersection 1	12th & Superior	$ 82,768.17	1	$ 82,768.17	$69,078
	Intersection 2	Rockwell & Roadway	$ 71,771.52	1	$ 71,771.52	
	Intersection 3	19th & Euclid	$ 52,695.53	1	$ 52,695.53	

Because the E-PCW implementation in Cleveland was limited to 24 buses and 3 instrumented intersections, the evaluation team extrapolated available data to estimate the system cost for a full deployment. Figure 4-2 illustrates the dense concentration of existing E-PCW deployment locations (teal circles), the relative spread of historical collisions (orange circles), and the full coverage of the relevant six bus routes (blue lines).



E-PCW Deployments, Historical Collision Sites, and Bus Route Coverage

The evaluation team mapped and carefully reviewed each of the six bus routes to identify all pedestrian crossings along each route and categorized each site into three categories: (1) high-priority, (2) near-term safety, and (3) long-term safety. Table 4-4 shows the number of proposed additional sites for each category along with the general classification criteria for each site type, and Figure 4-3 illustrates the existing deployment locations and proposed new deployment sites.

Table 4-4. New Deployment Count and Classification

Symbol	Category	Count	Classification Criteria
	High-Priority	23	• Dense urban pedestrian population • Right-turn bus maneuver (2 crosswalks in path of bus) • Proximity to multiple historical collisions
	Near-Term Safety	65	• Dense suburban shopping area • High-speed crossing • Proximity to school
	Long-Term Safety	110	All other pedestrian crossings along bus routes
	Existing	3	Selected by implementation team

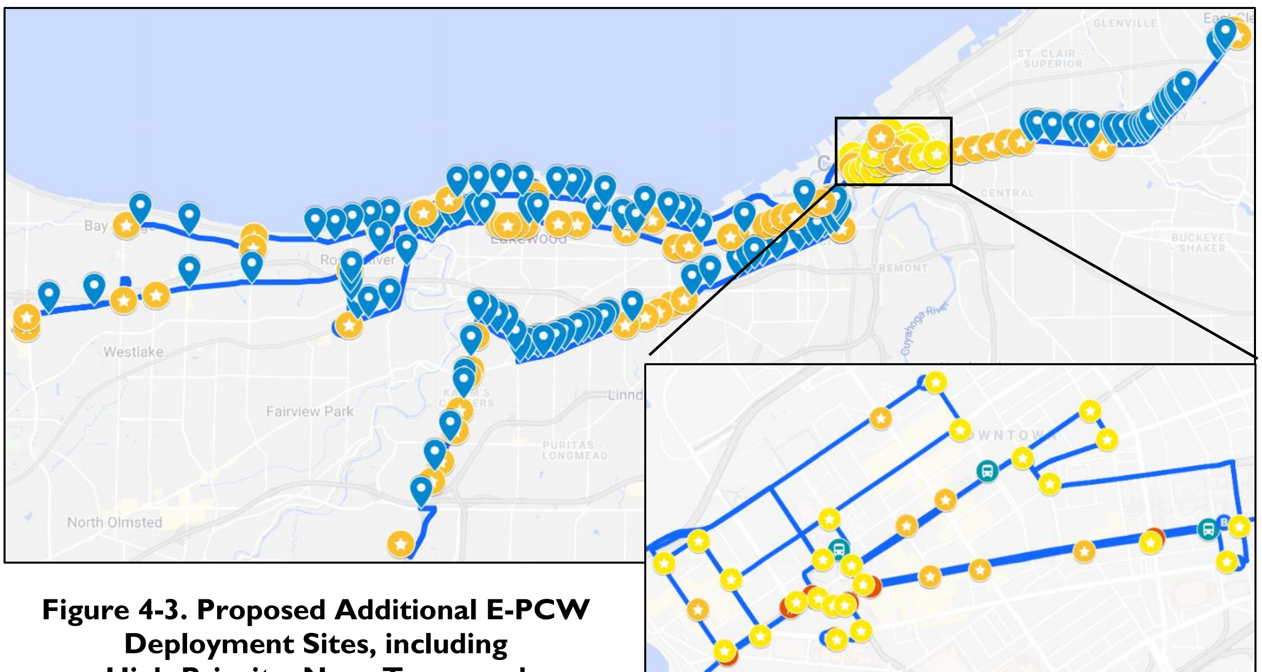


Figure 4-3. Proposed Additional E-PCW Deployment Sites, including High-Priority, Near-Term, and Long-Term Safety

The ROI calculation includes all 3 existing sites and the 24 high-priority locations, for a total of 27 infrastructure installation sites.

Table 4-5 shows the number of buses reported in current operation for each of the six bus routes. To align the scale of the system costs with the system benefits, the evaluation team extrapolated system costs to include all 47 buses currently servicing the selected bus routes and a total of 27 instrumented intersections. The estimated total deployment cost of a full-coverage system is tabulated in Table 4-6.

Table 4-5. GCRTA Bus Route Data

Bus Route	Number of Buses
Cleveland State Line (55ABC)	13
Healthline	12
E-Line Trolley	4
B-Line Trolley	2
Routes 22 and 26	16
Total	47

Table 4-6. Estimated Cost of Full Deployment

Cost Element	Average Unit Cost	Quantity	Total Cost
Bus	$6,342	47	$298,074
Intersection	$69,078	27	$1,865,106
Estimated Total Deployment Cost			$2,163,180

Conclusions

In the five years of collision data provided, between 2011 and 2016, GCRTA recorded 14 events involving a pedestrian. The evaluation team estimated the MAIS classification and calculated the associated value of preventing these injuries. Estimates exclude five events that did not include description of any injuries.

Comparison of estimates of the average annual benefit of the system ($106,452) and the total deployment cost ($2,163,180) indicates that recuperating the investment as reduced safety risks from E-PCW may take more than 20 years (244 months). For comparison, the lifecycle of traditional traffic infrastructure ranges from 5 to 15 years, depending on variables such as cost of equipment, pace of technological advancement, operational performance, and quality of infrastructure maintenance. Based on these estimates, the benefits of the E- PCW application are not likely to outweigh the implementation cost of the system even with a relatively long deployment lifecycle.

The estimated benefits and costs in this assessment are specific to the Cleveland implementation and will vary by deployment region. The average unit cost of instrumenting buses and intersections will likely decrease significantly over time. Computing components of the on-board equipment for buses will become smaller, cheaper, and higher performance. The DSRC on-board units (OBUs), which cost as much as 30% of the total cost of bus instrumentation, will decrease as the technology matures and with discounts for full fleet instrumentation. The pedestrian detection sensors are constantly improving, and future products may allow detection across multiple crosswalks by a single unit, which would dramatically reduce the cost of site deployments.

At nearly $70,000 per site, full deployment of the E-PCW infrastructure likely exceeds current transit agency budgets. However, as more Connected Vehicle applications are deployed across the U.S., the marginal cost of associated deployment infrastructure will decrease and likely will be distributed across different agencies with cost sharing between state departments of transportation, municipal governments, and transit agencies. For example, it is reasonable to assume that cities will cover much of the deployment costs for intersection infrastructure (e.g., roadside units), which would broadcast Map Data Message (MAP) and Signal Phase and Timing (SPaT) messages. Transit agencies would cover the deployment costs for bus on-board equipment and transit Connected Vehicle applications software.

Although the E-PCW deployment in Cleveland does not demonstrate strong, near-term ROI to individual transit agencies, the project dramatically improved E-PCW system performance and advanced the state-of-the-practice in Connected Vehicle applications for transit safety. GCRTA staff reported high confidence in the value of the E-PCW system and expressed a desire to deploy the system across their entire transit network as costs decrease over time.

Section 5 Driver Acceptance

Driver acceptance is the primary operational metric of the evaluation and incorporates user feedback for five different elements, specifically the E- PCW application's usability, perceived safety benefits, unintended consequences, and desirability. The driver acceptance evaluation was consistent with survey questions developed for the evaluation of the original TRP system.

Approach

Driver acceptance is an inherently qualitative metric that aggregates how a driver perceives various aspects of the E- PCW application in daily, operational usage. Although the data collected are subjective, they provide context for the results of previous evaluation metrics from the user perspective. Survey responses were aggregated into tables in an attempt to quantify the overall reception of the E-PCW application, and the following sections present the results of both open-ended and Likert-scale questions.

The evaluation of driver acceptance included four components:

- Usability – is the E- PCW application easy to understand and use
- Perceived Safety Benefits – does the E- PCW application contribute to driving safety
- Unintended Consequences – does the E- PCW application create distraction or overreliance
- Desirability – do drivers want to have and use the E- PCW application in their vehicle

Both open-ended and Likert-scale questions were used to capture data for these four components. An open-ended question prompts the survey responder to provide a written response to a prompt (e.g., "Please describe anything you would change about the system."). For this analysis, open-ended questions cannot be compared statistically, but they capture a dimension of system performance beyond the numbers. Whereas individual responses to open-ended questions can present individual reactions with limited bearing on the overall system, the results have increased significance when multiple users report similar feedback.

Likert-scale questions prompt users to respond to a statement not simply with a "yes" or "no," but rather on a sliding scale based on how strongly they agree or disagree with the statement. On this survey, respondents were permitted to check a box indicating "Disagree," "Somewhat Disagree," "Neither Agree nor Disagree," "Somewhat Agree," or "Agree" to a statement or prompt. Likert-scale questions are one of the most common types of survey questions, as they allow for a statistical comparison of subjective opinion assuming a strictly and judiciously defined prompt on the part of the evaluator. Subjectivity, however, cannot be entirely avoided, as two respondents may have two different definitions of "Agree" and "Somewhat Agree," for example.

The survey was administered both electronically by distributing a link to Google Forms to the driver email distribution list and by posting a QR-code link to the survey at GCRTA facilities and in-person by GCRTA staff as a paper questionnaire. All survey responses were anonymous.

Results

The survey was distributed to 751 GCRTA drivers;13 drivers completed the survey. Of these, 11 had experience driving an E-PCW-equipped bus; survey responses from two drivers who reported having no experience with the E-PCW application were not included in the analysis. The survey questions and associated responses are presented in Table 5-1, with analysis and discussion in the subsections below. A sample survey and all collected paper survey responses are included in Appendix B.

Table 5-1. Driver Survey Responses

Survey Question	Options	Survey Results	Results (%)
Approximately how often did you drive an E-TRP-equipped bus?	Daily	7	64%
	Weekly	2	18%
	Every other week	1	9%
	Every few weeks	1	9%
	Never	2	18%
Was the display easily seen from your driver's seat?	Yes	11	100%
	No	0	0%
Were the auditory notifications easily heard?	Yes	8	73%
	No	3	27%
What behaviors do you think changed as a result of having the technology in your bus?	I became more aware of driving situations that could cause a caution or warning	4	36%
	I was more cautious after receiving a caution or warning	4	36%
	I started to pay less attention because I relied on the cautions and warnings	0	0%
	I drove differently to prevent the system from warning me	0	0%
	None	3	27%
	Other (It made the alert after I crossed the crosswalk at E. 19th Station WB. The alert will come on after docking at E. 19th WB)	1	9%
Were there any near misses avoided because of the alerts?	Yes	2	18%
	No	9	82%
How often did you receive false alarms (i.e., there was no danger present?).	Multiple times per shift	4	36%
	Once per shift	0	0%
	Every few shifts	1	9%
	Very Rarely	3	27%
	Never	3	27%
How often did you observe situations where no caution or warning was generated when there may have been a danger present (i.e., a false negative).	Multiple times per shift	4	36%
	Once per shift	2	18%
	Every few shifts	0	0%
	Very Rarely	3	27%
	Never	2	18%
The difference between a caution and warning alert was clearly evident on the display.	Disagree	0	0%
	Somewhat Disagree	1	9%
	Neither Agree nor Disagree	2	18%
	Somewhat Agree	1	9%
	Agree	7	64%

It was clear why the system issued a caution when it did.	Disagree	1	9%
	Somewhat Disagree	1	9%
	Neither Agree nor Disagree	0	0%
	Somewhat Agree	5	45%
	Agree	4	36%
It was clear why the system issued a warning when it did.	Disagree	1	9%
	Somewhat Disagree	1	9%
	Neither Agree nor Disagree	0	0%
	Somewhat Agree	4	36%
	Agree	5	45%
I trusted the cautions and warnings.	Disagree	1	9%
	Somewhat Disagree	2	18%
	Neither Agree nor Disagree	2	18%
	Somewhat Agree	3	27%
	Agree	3	27%
The system was effective at drawing attention to the presence of a pedestrian at the curb or in the crosswalk.	Disagree	2	18%
	Somewhat Disagree	2	18%
	Neither Agree nor Disagree	0	0%
	Somewhat Agree	3	27%
	Agree	4	36%
The system was easy to use and understand.	Disagree	0	0%
	Somewhat Disagree	1	9%
	Neither Agree nor Disagree	2	18%
	Somewhat Agree	4	36%
	Agree	4	36%
Additional training was needed in order to use the system properly.	Disagree	3	27%
	Somewhat Disagree	2	18%
	Neither Agree nor Disagree	2	18%
	Somewhat Agree	1	9%
	Agree	3	27%
I would like the system to be installed on all of the buses that I drive.	Disagree	2	18%
	Somewhat Disagree	1	9%
	Neither Agree nor Disagree	1	9%
	Somewhat Agree	0	0%
	Agree	7	64%

Usability

This assessment metric measures whether the E-TRP safety applications are easy to understand and use from the driver's perspective. All drivers reported that the location of the display adequate, and 73% reported that the auditory notifications were easily heard.

Table 5-2. Usability-related Yes/No Survey Questions

Question	Yes	No
Was the display easily seen from your driver's seat?	100%	0%
Were the auditory notifications easily heard?	72.7%	27.3%

Figure 5-1 illustrates the survey responses to usability-related questions on the Likert scale.

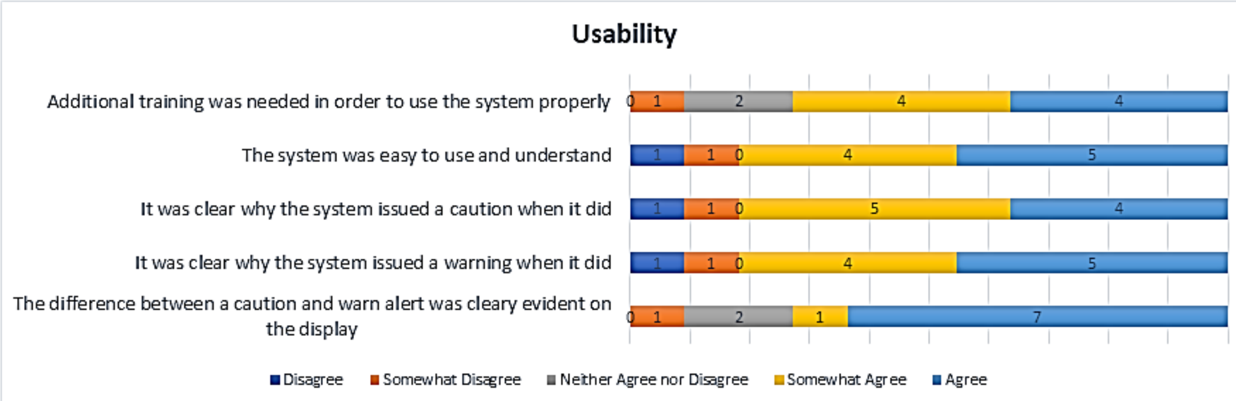


Figure 5-1. Summary of Usability Feedback

In total, 71% agreed or somewhat agreed that the system was "easy to use and understand" and that it was "clear why the system issued a caution/warning when it did." Although 82% reported that the difference between alerts was clearly evident, the same proportion (82%) agreed or somewhat agreed that "additional training was needed in order to use the system properly."

Perceived Safety Benefits

This assessment metric measures whether the E-PCW application contributes to driving safety. In total, 40% of drivers responded that they felt they "became more aware of driving situations that could cause a caution or warning," 36% responded that they were "more cautious after receiving a caution or warning," 27% reported that they felt the E-PCW application did not elicit any changes in their driving behavior. Pedestrian collisions are relatively rare within the GCRTA service area; however, 18% of drivers reported that they avoided a near miss because of an alert.

Table 5-3. Safety-related Yes/No Survey Question

Question	Yes	No
Were any near misses avoided because of alerts?	18.2%	81.8%

False alarms are events in which the system generates an alert to the driver when no pedestrian is present in the sidewalk or crosswalk detection zones. The system performance analysis indicated a false alarm rate of less than 20% (195); However, as depicted in Figure 5-2, the perception of the false alarm rate among drivers is mixed; drivers were almost equally divided in reporting experiencing no, some, and multiple false alarms. In total, 27.3% reported never experiencing what they perceived as a false alarm, and 36.4% reported experiencing false alarms multiple times per shift. The discrepancy between actual and perceived false alarm rates may be attributable to pedestrians outside the driver's field of view or to reports by drivers still learning to trust the new system; nearly half (45%) of drivers did not yet agree that they trusted the cautions and warnings.

In total, 36% of drivers reported that they perceived a pedestrian in a caution or warning scenario multiple times per shift, but that they did not register an alert from the system; 18% reported never experiencing a false negative. It should be noted that these results can be difficult to parse, as drivers may have different or evolving understandings over time about what constitutes a caution or a warn alert scenario despite the training they received from the system operator.

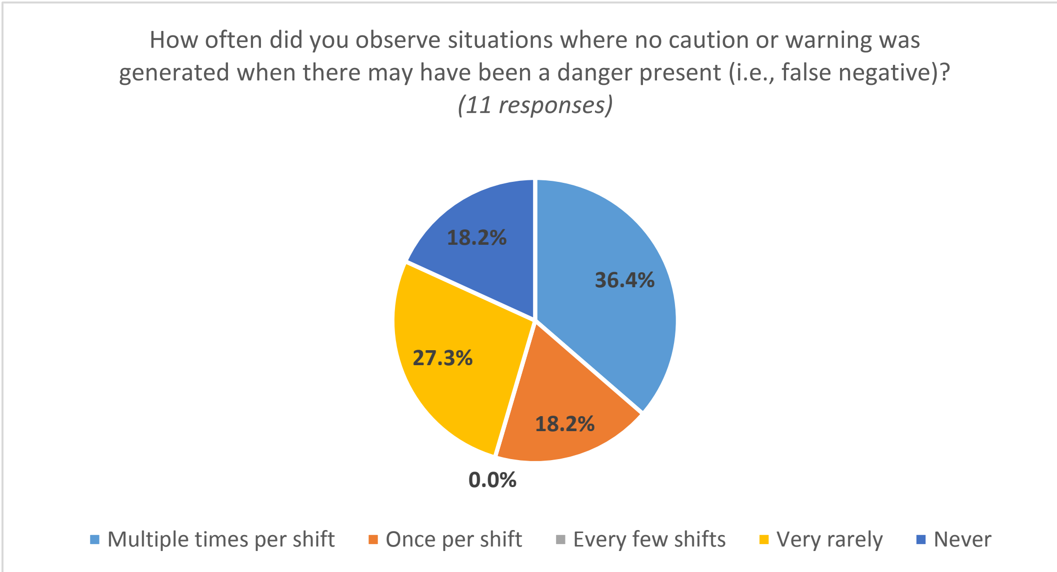


Figure 5-2. False Negative Responses

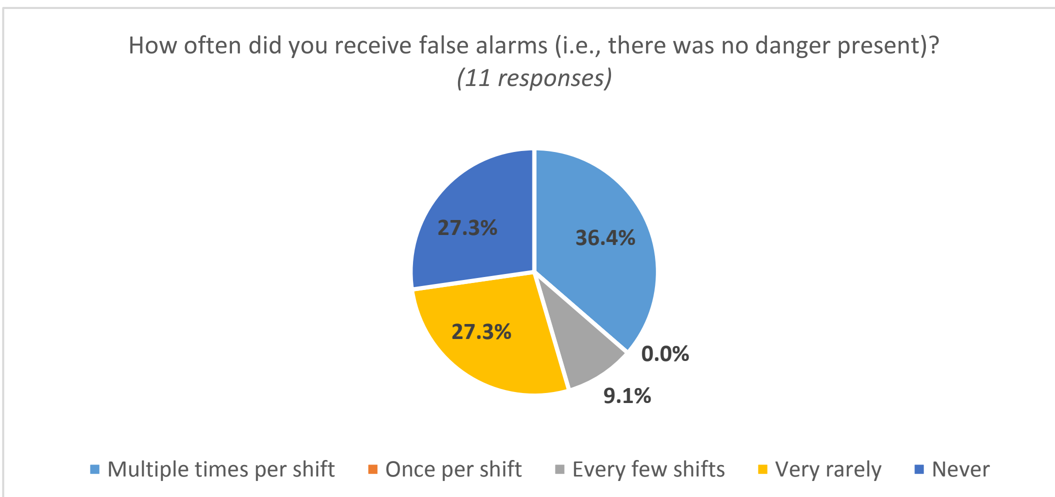
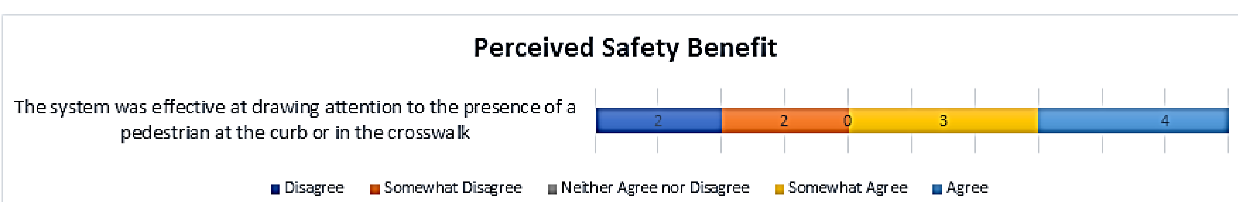


Figure 5-3. False Alarm Responses

Further, nearly two-thirds of drivers (64%) reported that the system was "effective at drawing attention to the presence of a pedestrian at the curb or in the crosswalk."



Unintended Consequences

This assessment criteria measures whether the E-PCW application is distracting to drivers, fosters overreliance such that drivers are no longer adhering to established and standard pedestrian awareness techniques while driving, or causes unintended behavioral changes. None of drivers reported that they started to pay less attention because they relied on the cautions and warnings or drove differently to prevent the system from warning them. Total of 30% of drivers reported that the E-PCW application did not cause them to change their behavior in any way. Although the surveys were completely anonymous, it should be noted that drivers may have felt uncomfortable about reporting any negative characteristics about their driving behavior.

Desirability

This assessment criteria measures whether drivers want to have and use the E-PCW application in their vehicle. This is an important qualitative metric, as drivers are the primary users of the system. Nearly two-thirds (64%) of drivers agreed that they would like the system installed on all buses they drive, and more than half (55%) reported that they trusted the cautions and warnings.

The graph below illustrates the responses to desirability-related Likert-scale survey questions. Each question and the responses are visualized below.

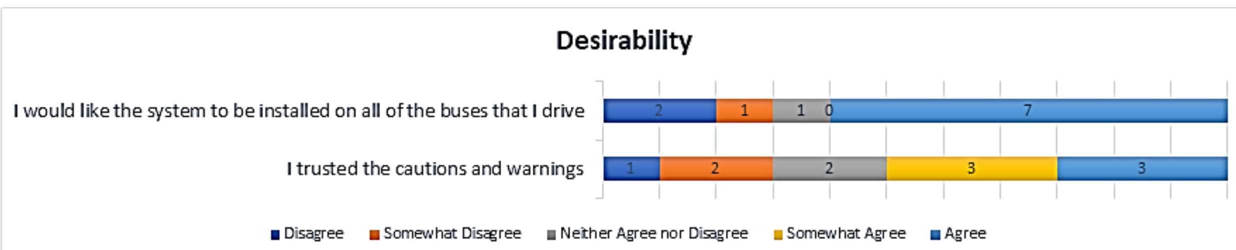


Table 5-4 shows responses from the three drivers to the open-ended question, “Please describe anything that you would change about the system.”

Table 5-4. Open-ended Desirability-related Survey Question

Please describe anything you would change about the system:
“Make sure it is working.”
“Regular scheduled maintenance to make sure they work properly.”
“Great idea, helps improve awareness of surroundings.”

Conclusions

Whereas fewer than 2% of E-TRP drivers participated in the survey, overall, they rated their experience with the E-PCW application neutrally. With such a small sample size, conclusions drawn from the survey cannot provide statistically meaningful analysis of the system, as the results are strongly influenced by individual drivers and their specific experience. Results are not necessarily representative of all GCRTA driver experience with E-TRP and cannot be generally extrapolated to all GCRTA drivers or drivers in other regions.

Table 5-5. Conclusions by Assessment Criteria

Driver Acceptance Assessment Criteria	Overall Rating	Key Findings
Usability	Positive	• Display easily seen • Visual and auditory alerts clear and distinguishable • Additional training likely helpful to promote ease-of-use
Perceived Safety Benefits	Neutral	• Few near-misses avoided due to alerts • High perceived false positive and false negative rate • Mixed perceived system effectiveness • Presence of system on bus seems to promote increased driver awareness of surroundings
Unintended Consequences	Neutral	• Minimal risk of unintended consequences. E-PCW application seems to have minimal effect on driving behavior.
Desirability	Positive	• Mixed "trust" in cautions and warnings • Perception that system frequently down or not working • Medium desirability for having system installed on bus

Appendix A – Objective Data Elements

A.1 – Application Data – Sample Log File Excerpt

Id	AlertId	EventId	InteractionId	EventTimestamp	ApplicationType	AppMessageType	EventCodeType	DeviceId	VehicleId
132697	0a2aa90a-5192-4503-92d2-3481b4ad4c5b		ae2e68be-9060-49dc-b5d9-5ac730ef766c	02:49.1	EPCW	Info	EnteredArea	17	2
132698	a1a3bdbf-bc4f-4efb-bf54-b618cffdc3a7		ae2e68be-9060-49dc-b5d9-5ac730ef766c	02:49.5	EPCW	Info	InArea	17	2
132699	5ecb327c-611c-45b8-ba54-fe4eb9d7f989		ae2e68be-9060-49dc-b5d9-5ac730ef766c	02:55.9	EPCW	Info	ExitedArea	17	2
132700	8d161b5a-1ac5-4b28-b265-1e517ac220d0		16da6379-c9e2-443c-97cb-35979c3d9cd6	10:32.9	EPCW	Info	EnteredArea	17	2
132701	05cbf01e-508f-4f28-a574-f6e851243250		16da6379-c9e2-443c-97cb-35979c3d9cd6	10:33.3	EPCW	Info	InArea	17	2
132702	babcc7a1-c8ab-4254-9748-3cb77ec477f9	2790bc6e-b2a1-42f1-816d-1e0f28ea4f66	16da6379-c9e2-443c-97cb-35979c3d9cd6	10:37.2	EPCW	InformAlert	FarsidePed	17	2

A.2 – Pedestrian Detector Data – Sample Image

A.3 – Vehicle Data – Sample Log File Excerpt

Id	Vehicle_Id	StateChangeTimestamp	VehicleParamType	VehicleParamPreState	VehicleParamPostState
6685386	2	00:14.0	Brake	Brake_Off	Brake_On
6685388	2	00:19.6	TurnSignal	Turn_Off	Turn_Left
6685389	2	00:21.2	TurnSignal	Turn_Left	Turn_Right
6685390	2	00:21.5	TurnSignal	Turn_Right	Turn_Left

Appendix B – Subjective Data Elements

B.1 – GCRTA Operator Survey

NOTE: All input is collected anonymously, and no personal information is requested.

1. Approximately how often did you drive an E-TRP equipped bus?

- ◯ Daily
- ◯ Weekly
- ◯ Every other week
- ◯ Every few weeks
- ◯ Never (IF NEVER, DO NOT FILL OUT THE REMAINDER OF THIS FORM, BUT DO TURN IT IN)

2. Was the display easily seen from your driver's seat?

- ◯ Yes
- ◯ No

3. Were the auditory notifications easily heard?

- ◯ Yes
- ◯ No

4. What behaviors do you think changed as a result of having the technology in your bus?

- ◯ I became more aware of driving situations that could cause a caution or warning
- ◯ I was more cautious after receiving a caution or warning
- ◯ I started to pay less attention because I relied on the cautions and warnings
- ◯ I drove differently to prevent the system from warning me
- ◯ None
- ◯ Other: ____

5. Were any near misses avoided because of the alerts?

- ◯ No
- ◯ Yes

6. How often did you receive false alarms (i.e., there was no danger present)?

- ◯ Multiple times per shift
- ◯ Once per shift
- ◯ Every few shifts
- ◯ Very rarely
- ◯ Never

7. How often did you observe situations where no caution or warning was generated when there may have been a danger present (i.e., a false negative)?

- ◯ Multiple times per shift
- ◯ Once per shift
- ◯ Every few shifts
- ◯ Very rarely
- ◯ Never

Thinking about the alerts, please indicate the extent to which you agree or disagree with each statement and if you have any additional comments please write them in the space below.

	Disagree	**Somewhat Disagree**	**Neither Agree nor Disagree**	**Somewhat Agree**	**Agree**
8. The difference between a caution and warning alert was clearly evident on the display.	○	○	○	○	○
9. It was clear why the system issued a caution when it did.	○	○	○	○	○
10. It was clear why the system issued a warning when it did.	○	○	○	○	○
11. I trusted the cautions and warnings.	○	○	○	○	○
12. The system was effective at drawing attention to the presence of a pedestrian at the curb or in the crosswalk.	○	○	○	○	○
13. The system was easy to use and understand.	○	○	○	○	○
14. Additional training was needed in order to use the system properly.	○	○	○	○	○
15. I would like the system to be installed on all of the buses that I drive.	○	○	○	○	○

16. Please describe anything that you would change about the system:

____

____

____

B.2 – GCRTA Interview Questions

Topic	Questions	Responses
Project Origin	How did you first become aware of E-PCW and what were your initial thoughts?	• Project was in motion staff came on board in 2015. • Battelle was good with their updates and about providing information on-time.
	At the onset of this project, what were your project goals?	• Larger, live, operational environment – started with 100 buses, but whittled down to 24 and from 6 intersections to 3 – typical pilot budget. • Wanted to see the technology on the bus which is readily available in a lot of cars.
Implementation	Were there any challenges (technical or operational) during the implementation of the E- PCW application?	• Getting all the equipment installed and running in the beginning was a little bit tough – the buses are scheduled for routine maintenance that made them unavailable to Battelle from time to time. • Tried to train all bus drivers in the technology, but it was only available on certain routes.
	How was training administered to drivers prior to system use?	• Training was done through training personnel (GCRTA). • Drivers are assigned to a particular route for 3-4 months.
Operation	How much did you get to observe the system in operation?	• Often; rode around in the buses many times. • Love it, can see it having a real-world application; if we had it all throughout downtown, it would be another layer of defense for pedestrians trying to dart out across the crosswalks.
	Did you receive any interim feedback from drivers?	Had about a 70/30 split from operators that liked/did not like the system.
	Do you think the E- PCW application is effective?	It can work, but not sure about the upkeep and maintenance.
Project Close Out	Why did GCRTA choose not to continue operation of the system?	Chose not to respond.
	Do you think that the project goals were achieved?	Yes – wish more intersections and buses were equipped to get a greater cross section of operators.
	What changes would you make to the system?	• Take out the monitor and put the icons in the mirror – may not even need the audio. • The more we can take out of the cab and streamline notifications that would be great.

B.3 – Battelle Interview Questions

Topic	Questions	Responses
System Goals	What was the purpose of the enhanced deployment and what specific changes were made to the system?	• Original TRP had too many false positives, GPS was bad, especially with location in the turn lane, improve overall/longer-term maintenance. • Add remote access via cellular. • Designed to improve the way the information was delivered (driver interface) and the algorithm to reduce "nuisance alerts" when the pedestrian is outside the bus travel path • Improve the false alarm rate, implementing the most accurate FLIR cameras (selected from 3 different models). • More robust hardware implemented on the vehicles themselves, TRP was a bit "flakier" – better hardware that did not need as much power cycling and that could be remotely managed and incorporated SAE requirements. • Improved GPS accuracy, better interface for the driver, and better management of the hardware – this deployment had cellular connectivity for remote management.
	What are the main advantages and limitations of the current E-TRP system?	*Advantages* • Planned improvements are operational as intended – better driver interface, algorithm improvements. • Improved alert accuracy, ability to push updates remotely, real-time system monitoring. • Smaller footprint than last time, more data, more bus types (4), more interactions, more location types (3), more representative of normal operations. *Disadvantages* • Multiple vehicle types and distinct intersection geometries complicated design/implementation (different CAN bus integration, different power management and wiring locations). • Technology limitations – FLIR cameras were best available at the time, but could benefit from additional tuning and a bird's eye view angle and GPS was non-augmented single source signal. • Sometimes there are draping wires between intersections that would obstruct the view of the cameras when there was wind or bad weather – it is not going to be perfect.
	What hardware or software changes would you recommend for future deployments?	• Upgraded detectors – multiple sources to ensure full coverage, bird's eye view angle, initial and interim calibration. • Multi-source, augmented GPS with error checking to correct drift in urban canyon environment.
	What challenges did you face during implementation of the system?	• CAN information/addresses varied even across the same model of bus and required more coordination with bus manufacturers than anticipated. • Contracted installation work rather than having on-site staff for installation and oversight. • Engineering challenges typical of integration work.

Implementation	Was it easy to coordinate access to GCRTA Facilities, Equipment, and Staff throughout the project?	• GCRTA was an excellent partner, had buy-in from multiple levels of the agency which is very necessary for CV projects (policymakers, operators, maintenance level). • Really went out of their way to accommodate the project staff – provided a dedicated bus driver for the whole month of verification.
	How many drivers were trained to use the system? How did drivers respond during training?	• Two training sessions initially and then GCRTA staff took over, left one-page training sheet to familiarize them with the different alerts. • Eventually the entire bus driver population was trained – originally intended to do it by video.
Operation	Did you get any interim feedback from GCRTA staff or drivers during operation of the system?	• Conflicting feedback from GCRTA – some commentary on the graphics after they were finalized, some people did not want any peripheral hardware on the buses. • GCRTA staff were very involved in the equipment location selection. • Drivers that used the system really seemed to like it and were very eager to help.
Lessons Learned	What would you change in a future deployment?	• More robust planning for selected sites – late-stage changes were approved by GCRTA, but didn't have time to discuss plans with adjacent residents/tenants and had to move hardware. • Reduce the complexity of hardware. • Fewer bus types. • Data monitoring and alerts would be a huge improvement, but it was outside the project budget.

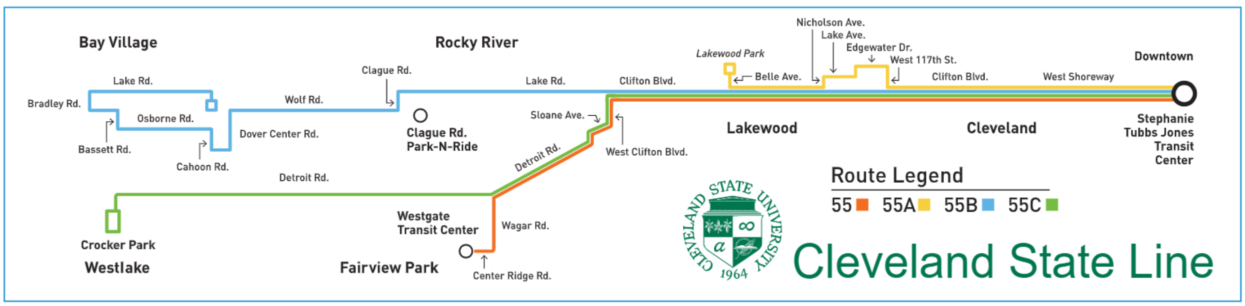
Appendix C – GCRTA Route Maps

This section contains images of the GCRTA route maps for the relevant six bus lines:

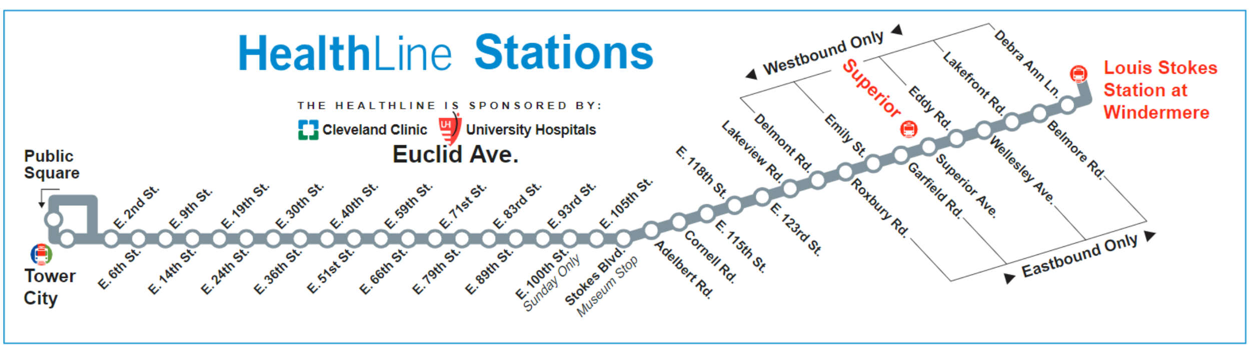
- Cleveland State Line
- Healthline
- E-Line Trolley
- B-Line Trolley
- Route 22
- Route 26

Map images were captured from the GCRTA website, current as of December 7, 2018.

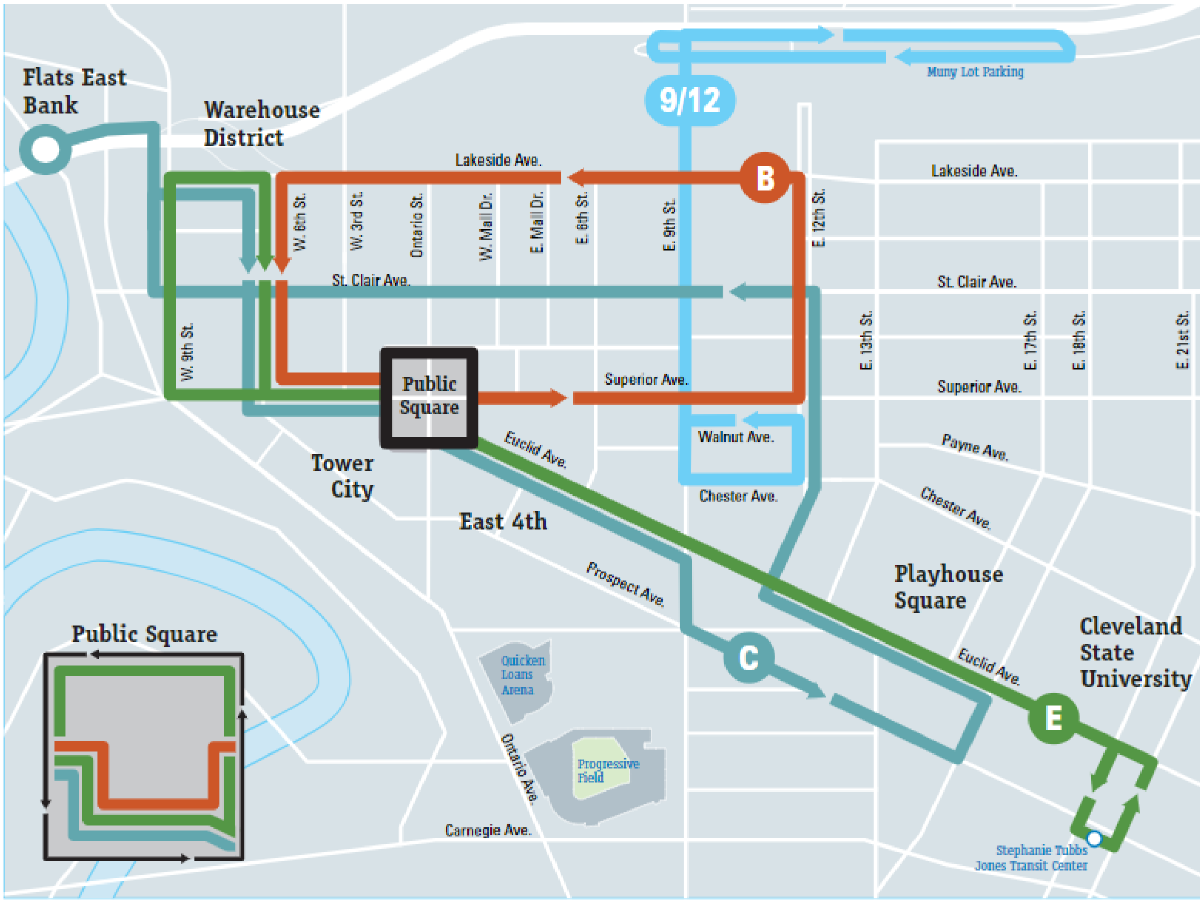
Cleveland State Line



Healthline



B-Line and E-Line Trolleys



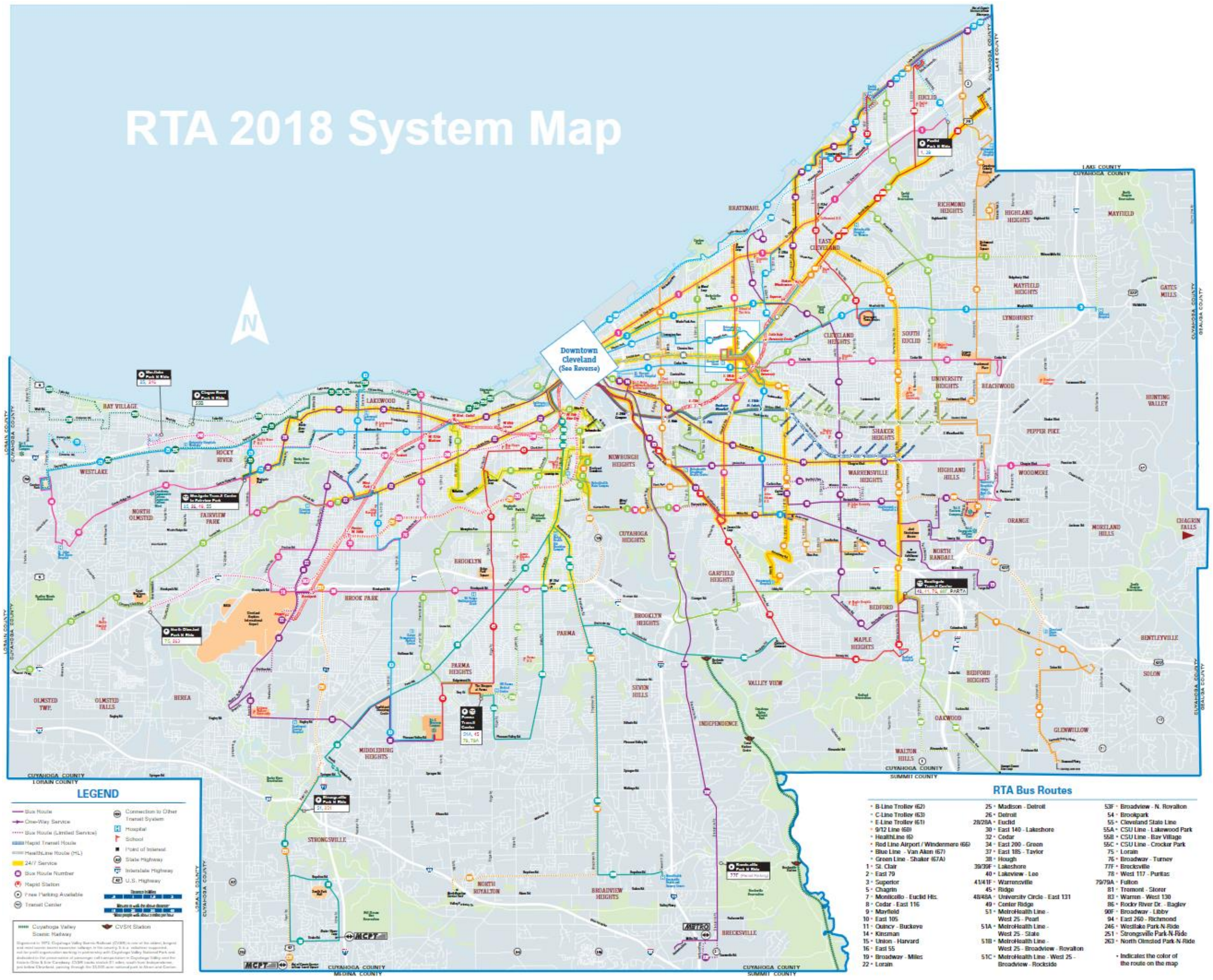
B **B-Line Trolley**
Weekdays only
Every 10 minutes
7 a.m. - 7 p.m.

E **E-Line Trolley**
Weekdays only
Every 10 minutes,
7 a.m. - 7 p.m.

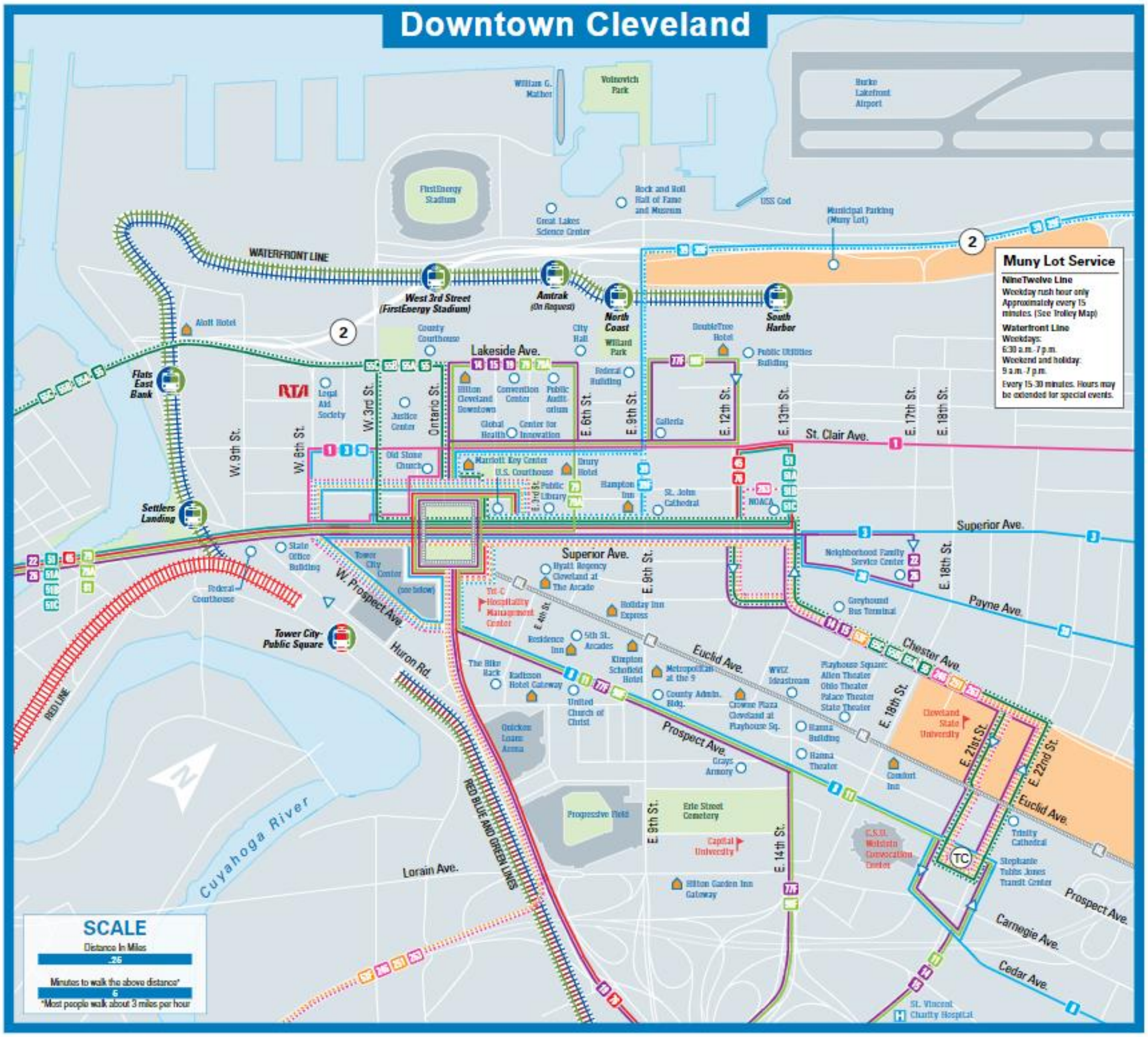
C **C-Line Trolley**
Every 10 minutes
Weekdays 7 p.m. - 11 p.m.
Weekends 11 a.m. - 11 p.m.

9/12 **NineTwelve Trolley**
Every 15 minutes
Weekdays,
AM Rush and PM Rush

Routes 22 and 26



Routes 22 and 26 (cont'd)



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