Safety Impact Assessment of THEA Connected Vehicle Pilot Safety Applications

Final Report

Final Report — March 2022

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13. ABSTRACT (Maximum 200 words)

This report presents the methodology and results of the safety impact assessment of four vehicle-to-vehicle (V2V) and three vehicle-to-infrastructure (V2I) safety applications that were deployed in Tampa's Connected Vehicle Pilot site. This assessment was based on the naturalistic driving experience of over 800 vehicles that were equipped with these applications, spanning from March 2019 through June 2020. The V2V applications included forward crash warning, emergency electronic brake light, intersection movement assist, and vehicle turning right in front of transit vehicle warning. Pedestrian collision warning, end of ramp deceleration warning, and wrong-way entry warning comprised the V2I applications. About 320 equipped vehicles received 8,073 alerts from the seven safety applications combined, while about 500 equipped vehicles did not have any alert events. There were 508 V2V alert events (6%) and 7,565 V2I alert events (94%). The analysis methodology assessed the validity of these alerts and determined their usefulness for examining the safety impact of each application. Useful alerts were later used to compare driver/vehicle response after alert onset between silent (human-machine interface or HMI off) and active (HMI on) alert groups. The results provided insight into improving the performance of the safety applications and delineated the conditions and vehicle response to specific alert events.

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
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yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
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m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
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m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
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L	liters	0.264	gallons	gal
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m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl

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List of Acronyms

Ax	Deceleration
BSM	Basic Safety Message
CP_{with}	Crash Probability when exposed to a driving conflict corresponding to a target scenario for vehicles in the active alert mode
$CP_{without}$	Crash Probability when exposed to a driving conflict corresponding to a target scenario for vehicles in the silent alert mode
CV	Connected Vehicle
CVP	Connected Vehicle Pilot
E_A	Crash Avoidance Effectiveness
EEBL	Emergency Electronic Brake Light
EM_{with}	Exposure Measure to a driving conflict corresponding to a target scenario for vehicles in the active alert mode
$EM_{without}$	Exposure Measure to a driving conflict corresponding to a target scenario for vehicles in the silent alert mode
ERDW	End of Ramp Deceleration Warning
FCW	Forward Collision Warning
GIS	Geographic Information System
HMI	Human-Machine Interface
HV	Host Vehicle
IMA	Intersection Movement Assist
LTAP/LD	Left Turn Across Path from Lateral Direction
LTAP/OD	Left Turn Across Path from Opposite Direction
LTIP	Left Turn Into Path
NA	No Alert
OBU	On-Board Unit
PCW	Pedestrian Collision Warning

REL	Reversible Expressway Lane
RSU	Roadside Unit
RTIP	Right Turn Into Path
RV	Remote Vehicle
SA	Silent-Active
SCP	Straight Crossing Paths
SDC	Secure Data Commons
SIM	Safety Impact Methodology
SQL	Structured Query Language
THEA	Tampa Hillsborough Expressway Authority
TTC	Time To Collision
TTI	Time To Intersection
U.S. DOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
Volpe	Volpe National Transportation Systems Center
VTRFTV	Vehicle Turning Right in Front of Transit Vehicle
WWE	Wrong-Way Entry

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Executive Summary

This report presents the methods and results of the independent evaluation of the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) applications deployed in the 2019-2020 Connected Vehicle Pilot (CVP) program in Tampa, Florida. The Tampa-Hillsboro Expressway Authority's (THEA) deployment of connected vehicle (CV) applications was part of the United States Department of Transportation's (U.S. DOT) Intelligent Transportation Systems research program and focused on the deployment and evaluation of crash warning and mobility improvement systems. These applications were based on V2V and V2I technologies that communicate through dedicated short-range communication radio channels. The vision for the CVP program was to deploy operational CV applications in three different pilot sites to determine their effectiveness at reducing crashes and improving overall mobility. The evaluation effort will also identify other similar sites around the U.S. and assess how they would function under a CV application.

The U.S. DOT's Volpe National Transportation Systems Center (Volpe) was an independent evaluator for the CVP program, which conducted the safety assessment portion of the independent evaluation of THEA's CVP deployment. The goals of Volpe's safety assessment were to determine changes in driver performance when driving with the CV safety applications, and to estimate the crash avoidance effectiveness and potential safety benefits of the CVP safety applications.

Methodology

The safety evaluation discussed in this report was based on data collected by around 800 participant light vehicles and seven fixed guideway trolleys equipped with aftermarket CV devices that can issue visual warnings to the vehicle operators. The 16-month deployment period was conducted in a real-world environment on public roadways in downtown Tampa, Florida, by THEA in partnership with the University of South Florida.

A major use case in THEA's deployment was to improve operations and safety at an expressway with Reversible Express Lanes (REL) and a street-level interface. THEA solicited volunteer drivers who frequently travel on this specific route during their daily commute into downtown Tampa. These volunteer participants had CV equipment installed on their personal vehicles. The V2V and V2I safety applications operated in two different modes during the deployment:

1. Silent mode, where the applications were operating in the background but did not issue any alerts to the drivers.
2. Active mode, where the applications were fully active, issuing visual feedback to the vehicle operator.

The Volpe team performed the safety impact assessment separately for each of the safety applications deployed at the THEA CVP site. The participant vehicles in the CVP deployment were equipped with four V2V and three V2I applications:

- V2V safety applications
    - Forward Collision Warning (FCW): warns the driver of stopped or slower vehicle ahead.
    - Emergency Electronic Brake Light (EEBL): makes drivers aware of suddenly decelerating lead vehicles ahead.

- Intersection Movement Assist (IMA): warns drivers of imminent crossing paths when two equipped vehicles are approaching an intersection from lateral directions.
    - Vehicle Turning Right in Front of Transit Vehicle (VTRFTV): warns light-vehicle operators of the presence of a nearby trolley when executing a turning movement, and the trolley operators of a light-vehicle turning right.
- V2I safety applications
    - End of Ramp Deceleration Warning (ERDW): provides speed advice to drivers who are approaching or are in the curve leading to the REL exit.
    - Pedestrian Collision Warning (PCW): warns drivers to the presence of pedestrians in a crosswalk.
    - Wrong-Way Entry (WWE): alerts drivers if the application determines that their vehicles are advancing to enter the REL going the wrong way, and warns other drivers that a wrong-way vehicle is headed toward them.

The data analysis process used to evaluate crash avoidance effectiveness included a number of steps. First, a system capability analysis determined the validity of the alerts in terms of their accurate applicability to the target driving conflict scenario, excluding invalid (false positive) events from the alert analysis. Second, the valid alerts from the capability analysis were reviewed to determine if they were issued during hazardous driving scenarios. Then, alerts were separated based on their silent or active status. Alerts in silent mode were matched together with alerts in active mode that had similar initial kinematic conditions (speed, time-to-collision, brake status, acceleration of host and remote vehicles) at the time of alert onset. Finally, statistical analyses were performed to reveal any statistically-significant differences in driver responses between the silent and active alerts triggered by the CVP safety applications.

The evaluation also examined continuous communications data between equipped vehicles and the equipped infrastructure to assess the frequency with which the equipped vehicles were exposed to other equipped vehicles and the roadway areas where V2I applications were deployed. This exposure analysis provided insight into the likelihood of the safety applications being triggered when a host vehicle (HV) was in the vicinity of another equipped vehicle or in an area where V2I applications were installed.

Key Safety Evaluation Findings

FCW

- Thirty-three percent of FCW events with corresponding basic safety message (BSM) data were found to be valid alerts where the remote vehicle (RV) was in the path of the HV.
- Seventy-eight FCW alerts or 92 percent of the valid FCW alerts were found to be useful FCW alerts received during a hazardous driving scenario.
- The Volpe team identified 40 FCW events that were triggered in silent mode and 38 events that were received in active mode. A total of 36 silent and 27 active alert events were matched into bins based on initial conditions at alert onset.
- The Volpe team found no statistically-significant difference in the time headway at alert onset between the matched silent and active FCW alerts.

- There was no statistically-significant difference in any measures of driver response to FCW alerts between silent and active alerts. Therefore, the crash prevention ratio was set to one, or no effect on driving conflict resolution. Measures of driver response examined included brake response time, mean deceleration, peak deceleration, brake onset time to collision, and brake onset time headway.

EEBL

- Ninety-four percent of the EEBL alerts were determined to be valid events with the RV ahead of the HV in the same or adjacent lanes.
- Thirteen EEBL alerts or 87 percent of the valid EEBL alerts were deemed to be useful alerts triggered in potentially hazardous driving scenarios.
- The Volpe team identified eight silent and five active EEBL alerts. The small sample size for this safety application prevented the Volpe team from adequately matching silent and active alerts.
- Among the 13 hazard EEBL alerts, only three silent and one active events had corresponding data about driver response. Due to the small sample sizes and insufficient data availability for this alert, the Volpe team was not able to estimate driver response metrics or crash prevention ratio for EEBL alerts.

IMA

- Twenty-one percent of the IMA alerts were determined to be valid events with the RV approaching the same intersection as the HV with an intersecting path.
- Twenty-eight valid IMA alerts were considered useful alerts triggered in potentially hazardous driving scenarios.
- The Volpe team identified seventeen silent and eleven active IMA alert events, but there were only two active IMA alerts matching silent IMA alerts in kinematic conditions at alert onset.
- Only three silent and two active IMA alert events had corresponding brake pedal action available. Due to the small sample size and availability of data, statistical conclusions about driver responses or crash avoidance effectiveness could not be gleaned for IMA alerts.

VTRFTV

- Twenty percent of VTRFTV alert events were determined to be valid events with the HV and RV on intersecting paths.
- The nine VTRFTV alert events that were considered valid were examined and assessed differently for participant light vehicles and trolleys.
- Two of these VTRFTV alerts were experienced successively by the same participant vehicle and four were experienced successively by the same trolley as it moved along the track.
- Vehicles that experienced successive alerts were operating in silent mode, and the other VTRFTV alert events were in active mode.
- There was not enough available data for valid VTRFTV alerts to allow for statistical analysis or to make any conclusions about crash avoidance effectiveness for this application.

PCW

- Five PCW alert events, or 56 percent of all PCW alerts, were determined to be valid events with pedestrians crossing or about to cross the equipped crosswalk.
- Only one of the five valid PCW alerts were deemed as potentially hazardous with the pedestrian crossing the sidewalk as the HV accelerated toward the crosswalk.
- There were no active PCW alert events, and thus the Volpe team was not able to perform statistical comparisons between silent and active alerts or estimate a crash prevention ratio for this application.

ERDW

- About half of the ERDW alert events were considered valid, where the HV was traveling above the advisory speed on the exit ramp of the REL.
- All 628 of these valid alerts were deemed to be useful alerts in a potentially hazardous driving scenario. ERDW alerts were often received consecutively by same drivers as they traveled along the exit ramp. Thus, the Volpe team did not analyze these successive alerts separately. Considering consecutive ERDW alerts as one and removing events without human-machine interface information, the Volpe team retained 584 unique ERDW as valid and useful alerts.
- The Volpe team identified 232 silent and 352 active ERDW alerts. The active and silent alerts were matched based on initial kinematic conditions. The matched silent and active alerts were not statistically different at alert onset, and thus statistical analysis was performed to compare driver response metrics between the silent and active alert groups.
- There was no statistically-significant difference between metrics of driver response after ERDW alerts between silent and active alert groups. Therefore, the crash prevention ratio was set to one, or no effect on driving conflict resolution.

WWE

- WWE alert validity was assessed using four programmatic filters that examined HV location, heading, and movement during a WWE alert event, as well as manual examination of alerts that were still deemed potentially valid after the filtering steps:
    - The programmatic filters removed 94 percent of the WWE alerts that had available BSM data.
    - 359 alerts were examined manually.
- GPS inaccuracies during vehicle maneuvers at the WWE intersection caused the likelihood of a WWE alert to increase substantially. 288 WWE alert events had HV GPS offsets when entering the REL outbound, and 56 WWE alert events had heading inaccuracies.
- The Volpe team did not observe any evidence of drivers altering vehicle maneuver or travel path after WWE alerts in any of the 359 WWE alert events. Therefore, the Volpe team was not able to assess the safety impact of the WWE application.

Key Exposure Analysis Findings

- Over half of the equipped vehicles communicated with at least another vehicle. On average, vehicles communicated for 86.6 minutes throughout the deployment phase of the project.
- There was no statistically-significant difference in V2V interactions between vehicles that only received silent alerts and vehicles that only received active alerts.
- For V2V interactions, on average, vehicles spent the most time interacting in potential EEBL scenarios at around 10 minutes over the course of the deployment period. They spent the least amount of time interacting in potential VTRFTV scenarios, at around 1 minute. For V2I interactions, vehicles crossed through the intersection when the WWE application was active the most number of times, around 70 times over the course of the deployment. They crossed through the PCW location the least number of times.
- The valid alert rates by minutes of interaction were clearly lower for vehicles receiving only active alerts than for vehicles receiving only silent alerts. However, these differences were not statistically significant, so no conclusions can be made about safety effectiveness based on these results.

Conclusions

THEA's CVP deployment demonstrated that V2V and V2I applications can be deployed in a real-world environment and alerts from safety applications can be issued to drivers. However, the infrequency of valid alerts during the deployment indicated that some improvements might be made to the safety applications deployed at the Tampa CVP site. This included accounting for difference in elevation and heading between the HV and RV for IMA and FCW applications, and adjustments to the timing of WWE alert applications.

During the CVP deployment, there were limited V2V interactions, and a relatively small percentage of the deployment fleet received any alerts (39 percent). Based on the data available to conduct the safety evaluation of THEA's CVP safety applications, it was difficult to make conclusions about crash avoidance effectiveness or changes in driver performance. This was mainly due to insufficient numbers of valid alert events and statistically-insignificant differences in results between silent and active alerts.

1 INTRODUCTION

1.1 Background

This report describes the technical approach, data analysis, and results of the independent evaluation that assessed the safety impact of safety applications deployed by the Tampa Hillsborough Expressway Authority (THEA) in Tampa, Florida, as part of the Connected Vehicle Pilot (CVP) program. In September of 2015, the United States Department of Transportation's (U.S. DOT) Intelligent Transportation Systems Joint Program Office selected three sites, Tampa, New York City, and Wyoming, to participate in their national CVP deployment program.[1] The goal of this program is to spur innovation among early adopters of connected vehicles and to gain a better understanding of the impact that connected vehicle (CV) technologies have on traffic safety, mobility, and the environment.

Each of the three sites has followed three phases of system deployment:

- Phase 1: Develop concept
- Phase 2: Design, deploy, and test
- Phase 3: Maintain and operate

To understand the impacts of the CVP deployments, the U.S. DOT's Volpe National Transportation Systems Center (Volpe) and the Texas A&M Transportation Institute are performing an independent evaluation of the deployments at each of the three CVP sites. These independent evaluations rely heavily on data obtained from CVP systems during Phase 3 of the deployments. The goals of the two evaluations are delineated as follows:

- Volpe
    - Conduct safety impact evaluations of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) safety applications.

- Texas A&M Transportation Institute
    - Conduct evaluations on mobility and environmental impacts from the CVP sites
    - Conduct national-level extrapolations of CVP impact assessments to evaluate the suitability of other urban areas or states in the U.S. for CVP system deployment
    - Evaluate the success of the CVP program

The two evaluation teams are collaborating on the overall program evaluation efforts. Additionally, the safety impact results developed by the Volpe team will contribute to site-specific and national-level evaluations by the Texas A&M Transportation Institute.

The Volpe team is performing the independent safety evaluation of the safety applications deployed at all three sites. This report delineates the evaluation goals and objectives, technical approach, data analysis steps, software used, and detailed outcomes of the safety impact assessment of THEA CVP safety applications. The safety evaluation results produced by the Volpe team for New York City and

[1] https://www.its.dot.gov/pilots/

Wyoming CVP sites—and evaluation results by the Texas A&M Transportation Institute for all three sites—are described in separate reports.

1.2 THEA CVP Site Overview

The THEA CVP deployment aimed to create a connected urban environment in Tampa's downtown area. This environment has a rich variety of traffic, mobility, and safety challenges that V2V and V2I applications can address using dedicated short-range communications [1]. The deployment area encompasses a tolled expressway with a street-level interface, transit bus and trolley (i.e., streetcar) service, high pedestrian densities, special event venues, and a highly dynamic traffic demand over the course of a typical day. This diverse environment is located in one concentrated deployment area in downtown Tampa, Florida, as seen in Figure 1 [2].

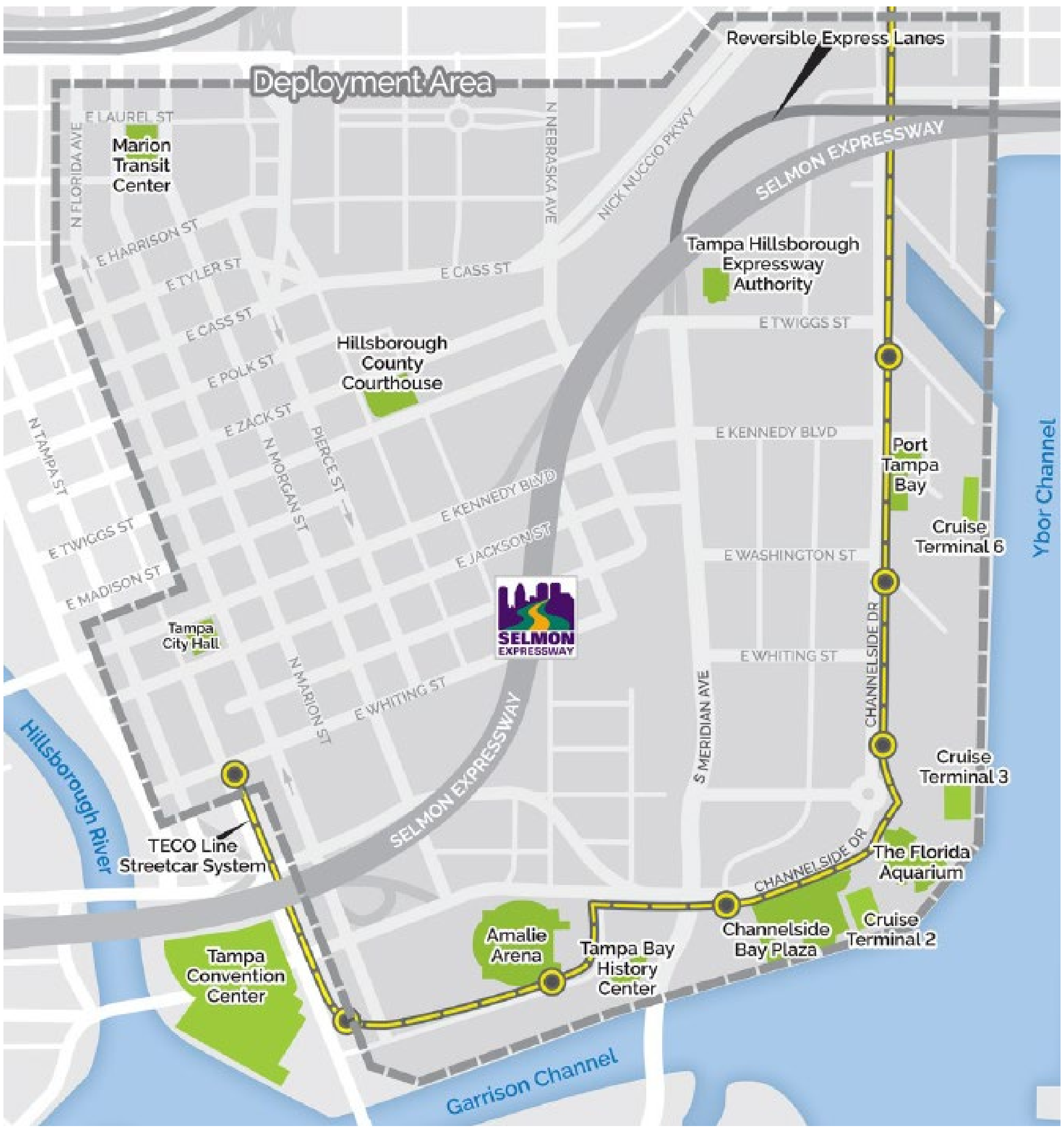

Figure 1. THEA CVP Deployment Area

THEA and CV technology vendors have implemented a number of CV applications that address six Use Cases illustrated in Figure 2 [2].

Figure 2. THEA CVP Use Cases

Use Case 1 addresses morning backups and related rear-end crashes on the Selmon Expressway exit. During peak traffic morning hours, there is often a backup of traffic on Selmon Expressway's Reversible Expressway Lanes (REL) that end at E. Twiggs Street in downtown Tampa. The at-grade intersection at the end of the express lanes is not visible to oncoming cars on the approach due to a sharp curve in the exit ramp as well as the change in elevation of the ramp as the express lanes approach the intersection. As a result, there is a high risk for rear-end crashes along the ramp. Use Case 2 deals with wrong-way entries onto the REL, where traffic is designed only to exit the RELs at the intersection of E. Twiggs Street and Meridian Avenue during the morning hours. However, sometimes vehicles attempt to enter these lanes going the wrong way, creating a risk of wrong-way driving crashes.

Use Case 3 addresses pedestrian crossing conflicts at the George E Edgecomb Courthouse on E. Twiggs Street, where there is one mid-block crosswalk for pedestrian access to and from the courthouse's primary parking garage. Lack of attention by drivers causes a safety concern for pedestrians crossing at this inconspicuous location.

Use Case 4 focuses on bus mobility from the REL to Marion Street, a two-lane urban arterial in the heart of Tampa, which serves as the primary bus route. Many of the bus stops along this route are on the near side approaches to intersections. During times of congestion, buses are unable to reach their bus stops, causing delays. Use Case 5 addresses driving conflicts with trolleys that run along Channelside Drive in the downtown area. There are many intersections where vehicles can take a right turn across the trolley tracks in front of the trolley. Often when this scenario occurs, the vehicle needs to stop to let pedestrians cross, blocking the trolley tracks. Since the trolley cars cannot stop quickly, this scenario poses a crash risk.

Finally, Use Case 6 addresses enhanced signal coordination to resolve significant congestion along major corridors during morning peak travel, involving personal and transit vehicles as well as pedestrians.

1.2.1 Safety Applications

THEA has deployed seven distinct CV safety applications, comprised of four V2V and three V2I applications, which address Use Cases 1, 2, 3, and 5. Table 1 provides a summary of these safety applications, while Appendix A delineates specific information about each application. V2V applications utilize data exchanged between vehicles equipped with on-board units (OBUs), traveling in close proximity. V2V applications may be triggered by any vehicle that is within the range of radio communications, which varies depending on the relative positioning and speeds of the vehicles, as well as the surrounding physical environment that might affect the radio waves. V2I applications act on data exchanged between equipped vehicles and the surrounding roadway infrastructure equipped with roadside units (RSUs). This report assesses the safety impact of these seven applications.

Table 1 categorizes the safety applications according to the levels of urgency specific to their relative impact on safety of the vehicles involved. These levels are as follows:

- <u>Imminent warnings</u> induce drivers to respond immediately in order to avoid a potential crash (e.g., FCW application warns the driver to quickly brake or steer to avoid a rear-end crash).
- <u>Advisory warnings</u> provide information to drivers that raises their awareness of the surrounding driving environment and helps them drive more safely (e.g., recommended travel speed). A driving scenario that triggers an advisory warning may or may not evolve to a crash-imminent scenario, depending on the host vehicle's (HV) actions and the actions of surrounding vehicles.

Table 1. Safety Applications in the THEA CVP Deployment

Safety Application	V2V/ V2I	Urgency Level	Description
Forward Collision Warning (FCW)	V2V	Imminent	Warns the driver in order to help avoid or mitigate the severity of crashes into the rear end of other vehicles on the road (Use Case 1).
Emergency Electronic Brake Light (EEBL)	V2V	Advisory	Makes drivers aware of suddenly decelerating lead vehicles ahead in the traffic queue, traveling in the same direction (Use Case 1).
Intersection Movement Assist (IMA)	V2V	Imminent	Warns drivers of an imminent crossing-paths crash in vehicles approaching an intersection from lateral directions (Use Cases 2 and 5).
Vehicle Turning Right in Front of Transit Vehicle (VTRFTV)	V2V	Imminent	Warns trolley drivers of other vehicles that are turning right in front of them, and alerts drivers of right-turning vehicles to the presence of a nearby trolley (Use Case 5).
Pedestrian Collision Warning (PCW)	V2I	Imminent	Warns drivers to the presence of pedestrian in the crosswalk (Use Case 3).
End of Ramp Deceleration Warning (ERDW)	V2I	Advisory	Provides speed advice to drivers who are approaching or are in the curve leading to the REL exit (Use Case 1).
Wrong-Way Entry (WWE)	V2I	Advisory	Alerts drivers if the application determines that their vehicles are advancing to enter the REL going the wrong way, and warns other drivers that a wrong-way vehicle is headed toward them (Use Case 2).

1.2.2 Planned Vehicle Deployment and Experimental Design

Table 2 shows a breakdown of the RSUs and equipped vehicles that THEA had planned to deploy in the CVP site, including the installation of 47 RSUs at downtown intersections and 1,098 OBUs on light-duty personal vehicles and transit vehicles. Personal vehicles were equipped with all safety applications and the streetcars were equipped with IMA and VTRFTV applications. Section 2 provides information about the actual number of equipped vehicles that the Volpe team has observed from THEA CVP data set.

Table 2. Summary of Planned Devices and Vehicles for THEA CVP Deployment

THEA Devices	Planned Number
RSUs at Downtown Intersections	47
Private Light-Duty Vehicles Equipped with OBU	1,080
Fixed Route Transit Bus Equipped with OBU	10
Streetcars or Trolleys Equipped with OBU	8

THEA's planned CVP deployment included a longitudinal study with before and after periods, as well as control and treatment groups for participant light-duty vehicles. Table 3 summarizes the planned vehicle groups for this experimental design. The before and after periods were planned respectively for approximately three and 12 months. In the silent mode, the safety applications did not issue any warnings to drivers but the OBUs still triggered warnings in the background (i.e., silent alerts). On the other hand, the safety applications issued warnings to drivers in the active mode (i.e., active alerts). THEA planned to have the control group include about one third of the participant vehicles. The same before and after periods were planned for streetcars that all belonged to the treatment group.

Table 3. Planned active states of warnings for vehicles groups in the THEA experimental design

Experiment Period	Before	After
Duration	3 months	12 months
Control Participant Vehicle State	Silent	Silent
Treatment Participant Vehicle State	Silent	Active
Streetcar State	Silent	Active

1.3 Safety Evaluation Approach, Data, and Tools

1.3.1 Approach

The safety impact analysis assessed how the safety applications influence HV driver's response to specific driving conflict scenarios. The Volpe team adopted and applied the approach shown in Figure 3 for its safety impact assessment of each of the THEA CVP safety applications [3]. This approach consists of the following five steps:

1. System capability analysis determines the validity of the alerts in terms of their accurate applicability to their target driving conflict scenarios, and excludes invalid (i.e., false positive) alerts from further analysis.
2. Assessment of alerts for safety analysis reviews the valid (i.e., true positive) alerts from the system capability analysis to determine if they were issued during a hazardous driving scenario in which the participant would have potentially benefited from the alert.
3. Breakdown of silent and active hazard alerts distinguishes silent from active hazard alerts issued in similar driving conflicts, and identifies their initial kinematic conditions at the time of alert onset.
4. Matching of silent and active alert samples assembles silent and active alert events by their similar initial kinematic conditions at alert onset, in order to compare HV driver response between the two alert modes under the same conditions for each safety application. [2]

[2] The initial conditions considered for statistical matching depend on the alert type being studied. For example, for FCW alerts, initial conditions used for matching include time headway, host vehicle speed, and range rate between the host and remote vehicles at alert onset. Alerts do not have to occur at similar timestamps to be matched.

5. Statistical analysis of safety impact reveals any statistically-significant differences in various measures of HV driver response between silent and active alerts issued for specific driving conflict scenarios.

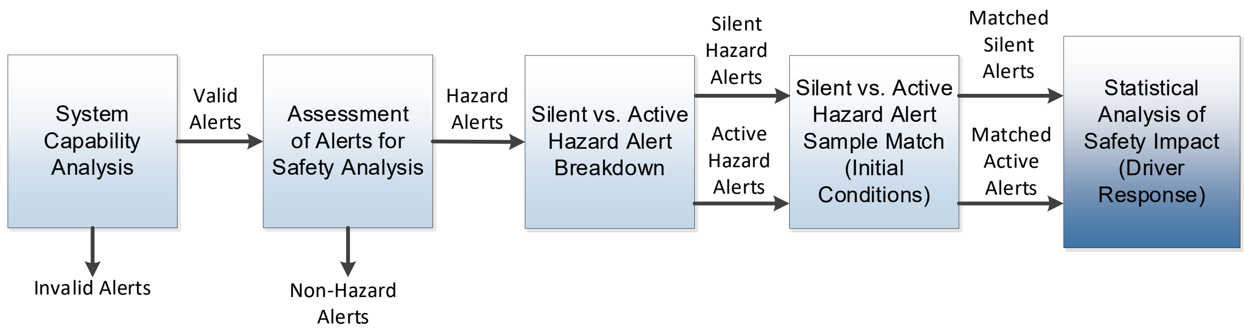

Figure 3. Safety Impact Assessment Approach

The Volpe team would estimate the crash avoidance effectiveness for each of the safety applications if the statistical analysis in Step 5 above found statistically-significant differences in some measures of HV driver response. This effectiveness estimation is based on estimates of the crash probability risk and exposure to driving conflicts. Estimates of the crash probability in distinct driving conflicts are obtained using the Safety Impact Methodology (SIM) that relies on real-world data, including historical crash data and non-crash data about driver/vehicle performance during encounter and response to driving conflicts [4]. The Volpe team exercised the SIM tool to estimate the safety effectiveness of the IMA and left turn assist safety applications in the National Highway Traffic Safety Administration's V2V Readiness Report [5]. [3]

The crash avoidance effectiveness (**E_A**) is estimated from vehicle/application performance data collected during the CVP deployment using the following equation:

$$\mathbf{E_A} = 1 - \text{Driving Conflict Exposure Ratio} \times \text{Crash Prevention Ratio} \qquad (1)$$

The driving conflict exposure ratio measures the ability of a safety application to reduce the encounter rate of HVs to driving conflicts when receiving active alerts, in comparison to HVs without active alerts (i.e., silent alerts) [6]. The crash prevention ratio measures the ability of a safety application to reduce the likelihood of a crash when HVs in active alert mode encounter a driving conflict, in comparison to HVs in silent alert mode. Equation (1) can be expressed as follows to account for the silent alert mode (i.e., without application assistance) and active alert condition (i.e., with application assistance):

$$\mathbf{E_A = 1 - \frac{EM_{with}}{EM_{without}} \times \frac{CP_{with}}{CP_{without}}} \qquad (2)$$

[3] Left Turn Assist addressed the left turn across path/opposite direction pre-crash scenario. A vehicle attempts to turn left across the path of another vehicle, who is approaching the intersection head-on from the opposite direction.

EM_{with} ≡ Exposure Measure to a driving conflict corresponding to a target scenario for vehicles in the active alert mode

$EM_{without}$ ≡ Exposure Measure to a driving conflict corresponding to a target scenario for vehicles in the silent alert mode

CP_{with} ≡ Crash Probability when exposed to a driving conflict corresponding to a target scenario for vehicles in the active alert mode

$CP_{without}$ ≡ Crash Probability when exposed to a driving conflict corresponding to a target scenario for vehicles in the silent alert mode

1.3.2 Datasets and Data Access

THEA collected different datasets in various ways during the CVP deployment. Of primary interest to this evaluation were the log files generated by the OBUs while vehicles were running and during V2V/V2I interactions and alert events. These log files contain records of basic safety messages (BSMs) sent by HVs and received from other equipped vehicles while in the study area, and records of the alert events triggered by the safety applications on the OBUs. These aggregate log files are stored onboard the vehicles and uploaded over-the-air to RSUs when vehicles are within range. The uploaded log files are then transferred to THEA's traffic management center, and stored and secured locally for THEA's own performance evaluation. In addition, these log files are uploaded on a nightly basis to the U.S. DOT's Secure Data Commons (SDC) to support analysis by the independent evaluators and other U.S. DOT partners. The SDC is a secure data storage and analysis platform that provides data storage and processing functionality, as well as controlled access to these datasets for analysts from U.S. DOT managed, cloud based desktops. Due to the existence of personally identifiable information in THEA's records, the SDC was required to protect study participants' privacy. Figure 4 shows the SDC's informational page on the U.S. DOT's website.[4]

[4] For more information on the Secure Data Commons, see visit https://www.transportation.gov/data/secure

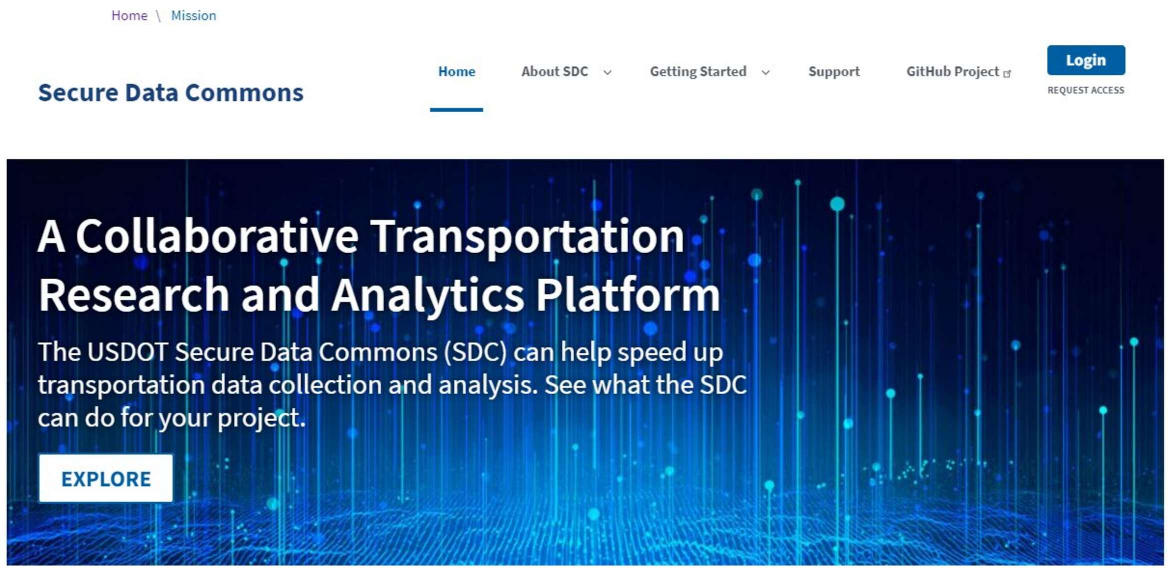

Figure 4. SDC's informational Page on U.S. DOT's Website

The raw OBU Log files uploaded to the SDC by THEA are subject to a processing algorithm developed by the SDC technical support team with input from the Volpe team. This algorithm separates the log file data into its component data types, including sent BSMs, received BSMs, and alert event records for each of the safety applications. These individual records are then inserted into a Structured Query Language (SQL) equipped database storage system maintained by the SDC technical support team.

1.3.3 Volpe Independent Evaluation Database

In an effort to streamline the analysis processes for the safety impact assessment of THEA's safety applications, the Volpe team created its own separate database to:

- Remove data duplicates
- Remove unused columns
- Remove test vehicle identification numbers
- Adjust date-time errors
- Calculate kinematic parameters
- Store results of alert validation analysis

Appendix B provides a detailed description of the independent evaluation database in terms of tables and their attributes.

1.3.4 Data Analysis Tools

The Volpe team utilized a number of data analysis and processing tools during the safety impact assessment. The Volpe team developed some of these tools and directly used other publicly-available tools to analyze the data provided by THEA.

The Volpe team developed the following tools to support the data analysis:

- Python data transfer and processing algorithms transfer data from the SDC's default data storage location into Volpe's proprietary database, and organize data for that purpose.
- BSM data interpolation algorithms allow for matching HV and remote vehicle (RV) data from BSM datasets at timestamps representing every tenth of a second (10 Hz).
- Event visualization tool, built in Python and in JavaScript, allows for visualizations of vehicle locations, movements, and interactions during an alert event. This tool was instrumental in categorizing the alert event data provided by THEA as valid or invalid alert events, and allowed the Volpe team to gain a better understanding of the HV behavior during vehicle interactions. Appendix C describes the event visualization tool.
- Vehicle kinematics calculator SQL plugin generates kinematic metrics between HVs and RVs during V2V interactions in driving conflict and non-conflict scenarios, written in Microsoft's .NET framework. These kinematic metrics include relative range and range rate-of-change between the two vehicles, relative position information, and qualitative descriptions of the interaction scenario. Appendix D delineates the equations used in relative position data processing.

The Volpe team utilized the Microsoft SQL Server as the platform to build its own evaluation database and to perform data processing and aggregation to support the statistical analysis. The team also used MSSQL Server Management studio as the primary development platform to develop numerous SQL scripts involved in processing the alert event and vehicle interaction data. Finally, the Volpe team used QGIS to categorize certain alert types based on their locations and vehicle headings, as well as to create visualizations of alert and vehicle data.[5]

[5] QGIS is an open source geographic information system tool that provides a vast number of features in support of geographical data analysis.

2 THEA CVP OBSERVATIONS

THEA began Phase 3 of their deployment in March of 2019. As stated previously, the original experimental design dictated that a silent period, when all vehicles would have their OBUs set to "silent mode," was planned to last the first 90 days of the deployment. The active period was supposed to last 12 months, from June 2019 through May 2020. However, due to relatively low numbers of certain alerts generated from some of the applications deployed by THEA, the Volpe team decided to extend the evaluation period through the end of June 2020, hoping to observe more alert events.

2.1 CVP Vehicles

Figure 5 illustrates a breakdown of the total number of unique OBU vehicle identification numbers (IDs), by vehicle type, as observed in THEA dataset from March 2019 through June 2020. Vehicle types include passenger vehicles (ParticipantVehicle), buses (FixedRouteBus), and trolleys (TrolleyOBU1/2). Trolleys had two OBUs installed, one in the front and another in the rear, as shown in Figure 5. Overall, there were 829 unique OBU IDs observed in the dataset, representing 823 unique vehicles throughout the deployment. While all streetcars should have two OBUs installed, for one of the streetcars, only one of the OBUs had data available to Volpe for analysis.

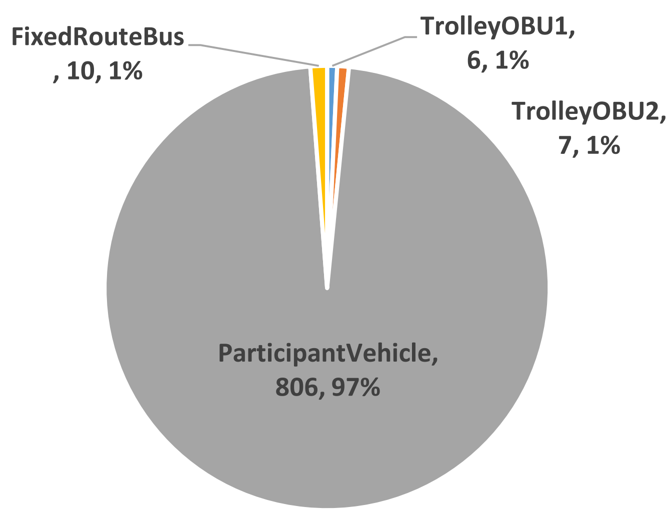

Figure 5. Breakdown of the Number of THEA CVP Vehicles by Type

THEA's deployment recruitment efforts focused on residents of the Hillsborough County region of Florida, specifically on commuters who regularly traveled the Selmon Expressway's REL. THEA targeted these residents as CVP participants to increase the likelihood that CVs would interact with each other and with RSUs on Tampa's roadways, and thus providing better opportunities for the safety applications to issue alerts. Additionally, this participant group is assumed to benefit the most from receiving the alerts while operating their vehicles.

The THEA CVP site team and the Volpe team observed a decline in the number of equipped vehicles driving in the deployment area over the course of the deployment period. Figure 6 shows the number of equipped vehicles observed by the RSUs within Tampa's deployment area, along with the 7-day moving average of these observations and some important dates to take note of. The following factors might explain the reduction in the number of equipped vehicles in the deployment area over time:

- Some participants might have purchased new vehicles and stopped driving the equipped vehicles.
- Some OBUs might have experienced malfunctions and stopped communicating with the RSUs in the deployment area.
- Some participants might have moved or had career changes that altered their commuting patterns.

Another anomaly that occurred during the deployment period was the onset of the COVID-19 pandemic across the entire nation. In March of 2020, many workplaces and local governments began recommending employees work from home to the greatest extent possible to keep themselves safe and reduce the spread of the virus. This resulted in a significant reduction in the number of participants who were regularly entering the deployment area on a daily basis. Figure 6 clearly shows this abrupt reduction between March and April of 2020. Consequently, interactions among multiple CVs and between CVs and RSUs were dramatically reduced, which in turn lowered the number of alert events generated by the CV safety applications.

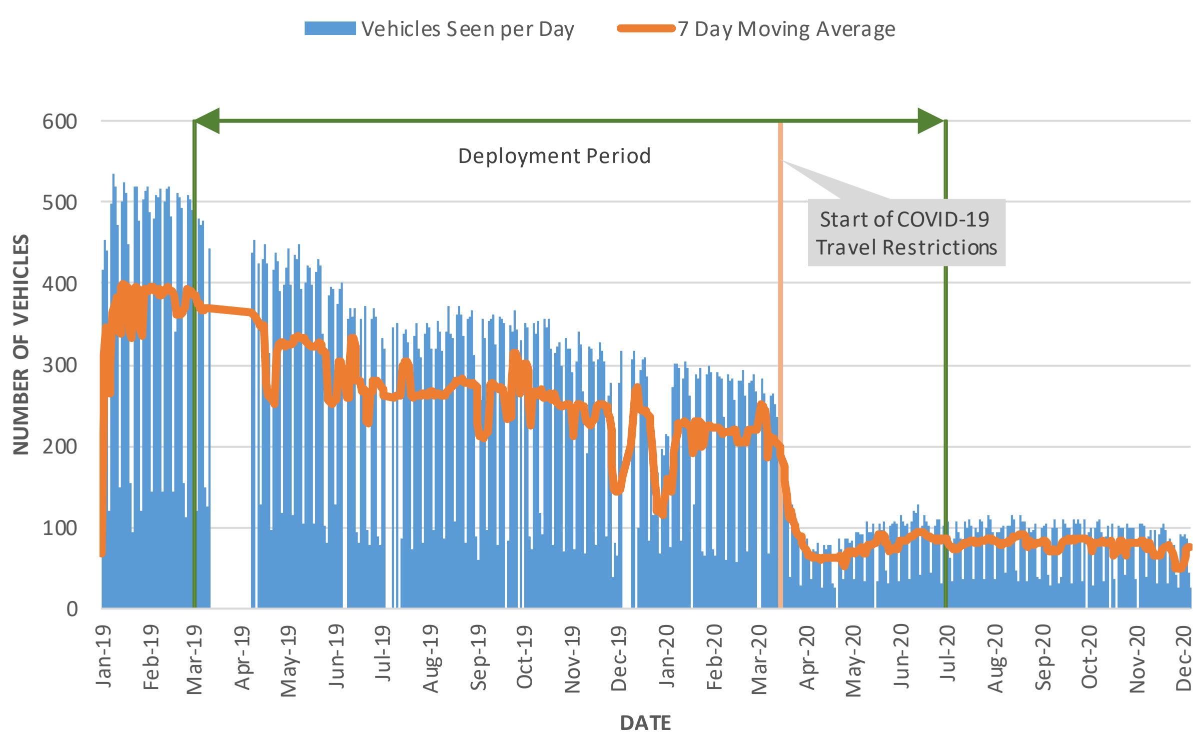

Figure 6. Trend in Equipped Vehicles Observed per Day within the Tampa Deployment Area

2.2 Alert Events

In order to assess the safety impact of THEA's safety applications, the Volpe team focused on alert events triggered by the applications installed on vehicle OBUs. This section shows numerical counts of the alert events included in the analysis and the vehicles that received those alerts. Overall, the Volpe team analyzed a total of 8,073 alerts. Figure 7 shows the breakdown of these alerts by alert type.

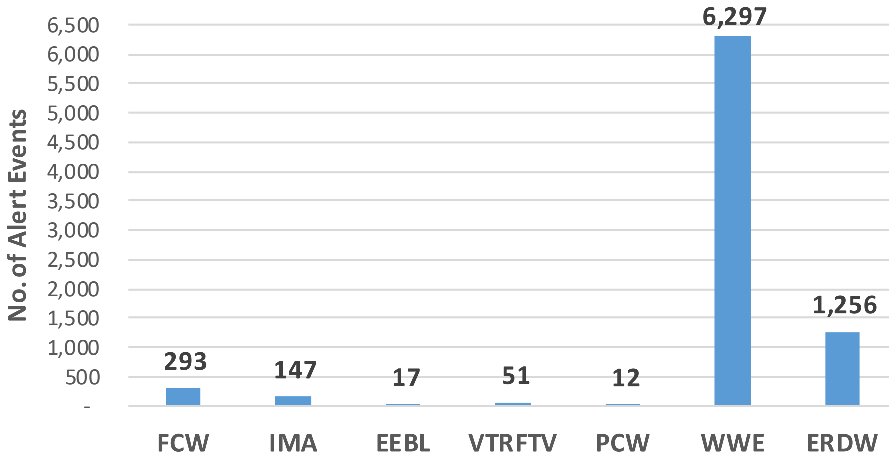

Figure 7. Breakdown of All Alert Events by Alert Type

2.3 Experimental Groups

After assessing the number of alerts available for analysis in each alert type, the Volpe team determined that there would not be enough data points to perform meaningful statistical analyses along the experimental groups that were originally delineated by Tampa. To alleviate this issue, the Volpe team decided to perform statistical analysis based solely on comparisons between alerts issued in the silent human-machine interface (HMI) state (i.e., silent group) and alerts issued in the active HMI state (i.e., active group). This would yield statistical comparisons of driver response and safety impact between specific events with and without alerts provided to drivers. Consequently, the Volpe team identified 3,425 alert events issued in the silent mode (i.e., HMI off) and 4,587 alert events issued in the active mode (i.e., HMI on). Figure 8 shows the breakdown of these alert events by HMI status and alert type, according to these two experimental groups. Figure 9 provides the number of distinct vehicles that received these alerts in the silent and active HMI settings. A total of 342 and 363 distinct vehicles received silent and active alerts, respectively. On average, the silent group and the active group received respectively 10.0 silent alerts and 12.6 active alerts per vehicle.

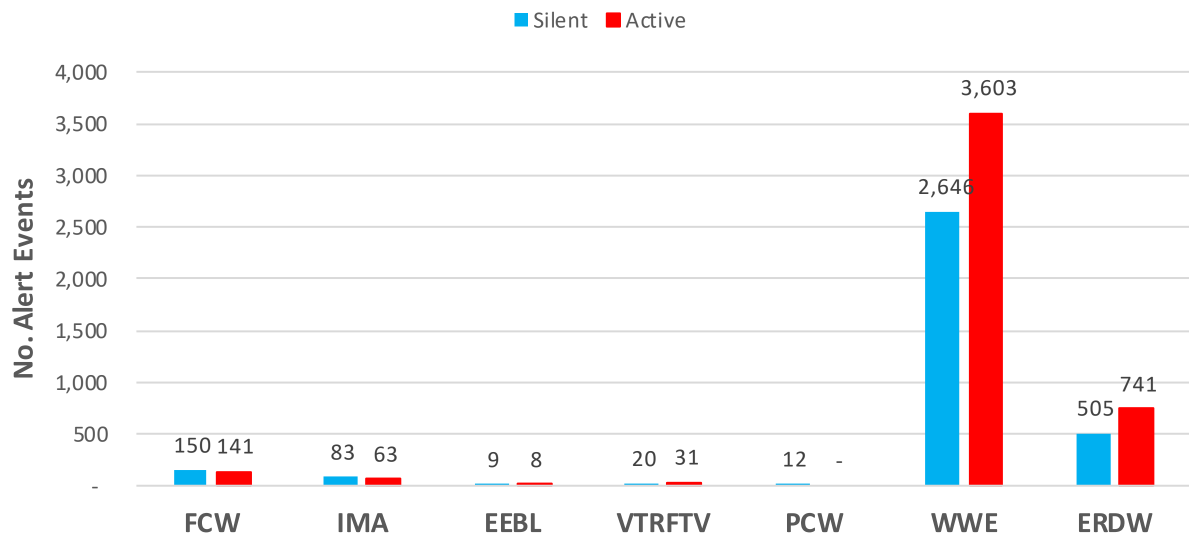

Figure 8. Breakdown of Silent and Active Alert Events by Alert Type

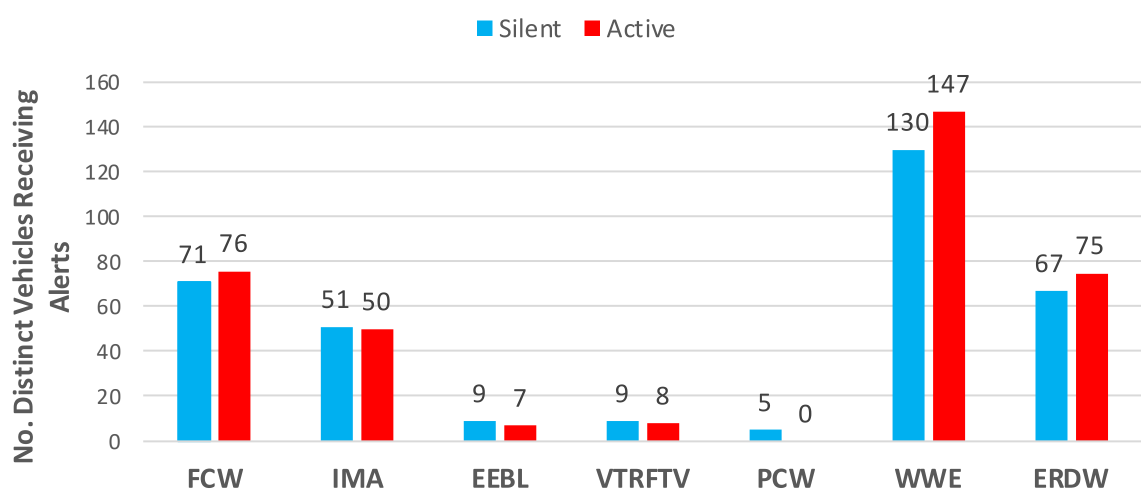

Figure 9. Breakdown of Distinct Vehicles Receiving Silent and Active Alerts by Alert Type

2.4 Data Availability for Alert Analysis

The method of storing data on vehicles before being transferred to the SDC affected the data that were available to the Volpe team for analysis. Specifically, BSM data surrounding alerts were not available for some of the alert event records. The prevailing explanation for missing BSM data for these alert events was that the log files containing certain alert event records were not in the same log files as the BSM data describing vehicle behavior at the time of these events, and the log files containing the BSM data were never uploaded. Consequently, the Volpe team excluded a portion of alert events from the final analysis because there was no information about vehicle movements or vehicle response to these alerts. The final dataset included V2I alert events with available sent BSM data and V2V alert events with available sent and received BSM data. Overall, corresponding BSM data were available for 7,308 or about 91 percent of the alert events in Volpe's database. Figure 10 illustrates the breakdown of the different alert types and the share of alert events by missing and available BSM data. Figure 11 shows the breakdown of distinct alerted vehicles by alert type and HMI status at time of the alert, based on available BSM data. Thus, a total of 322 and 345 distinct vehicles respectively received silent and active alerts.

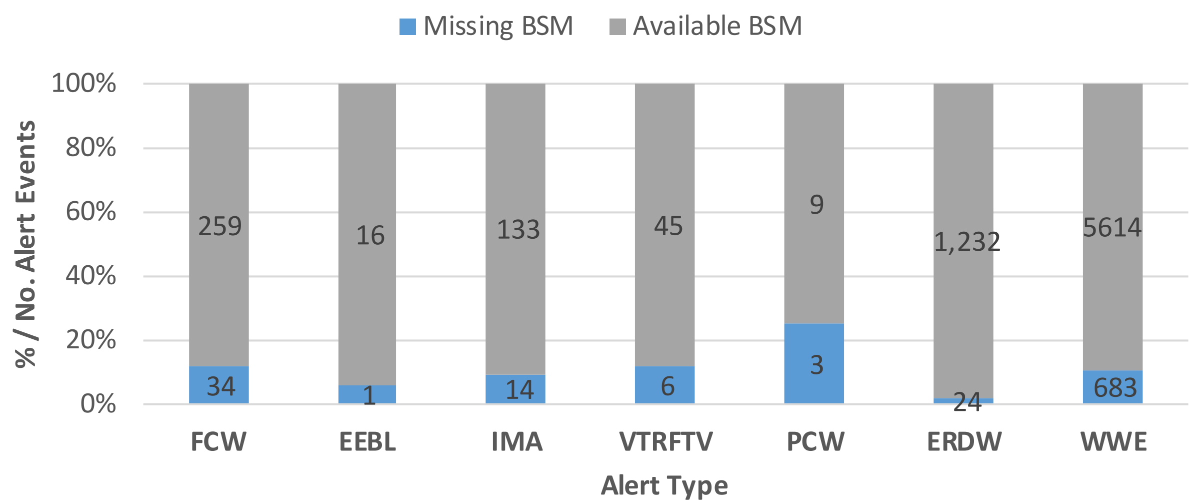

Figure 10. Breakdown of Alert Events by Alert Type and BSM Data Availability

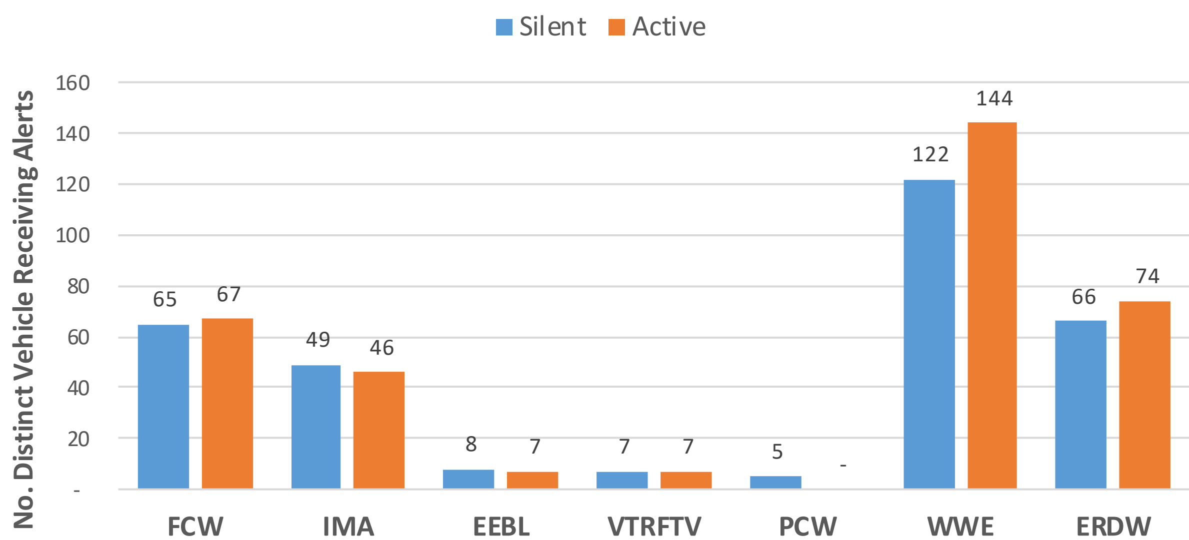

Figure 11. Breakdown of Distinct Alerted Vehicles by Alert Type with Available BSM Data

3 ANALYSIS OF ALERT EVENTS AND DRIVER RESPONSE

The following sections provide details on the alert validity analysis, hazard alert classification, and driver response to alerts in silent and active modes during the THEA CVP deployment period, following the safety assessment approach in Figure 3. The Volpe team performed these analyses specifically for alert events that had corresponding BSM data, as discussed in the previous section. These results are discussed separately for each V2V and V2I safety application.

3.1 Forward Crash Warning

The FCW application warns HV drivers of a stopped or slower RV ahead in the same lane and direction to avoid rear-end crashes. Appendix A describes the FCW application deployed in the THEA CVP.

3.1.1 FCW Alert Validity

The intent of the FCW application is to alert HV drivers to take action (i.e., apply brakes) when an RV is stopped, decelerating, or moving slower than the HV directly ahead in the same lane and direction. The Volpe team categorized FCW alert events by RV location relative to the HV at alert onset as follows:

- <u>RV in path of HV</u>: refers to RVs that are in the same lane of travel (i.e., any part of the RV is in the HV's lane) and in the intended forward path of the HV at alert onset. The Volpe team considered this category of FCW alert events as valid.
- <u>RV in-path of HV but turning or changing lanes</u>: refers to RVs that are in the same lane of travel as the HV, but are turning or changing lanes. Alerts in this category are invalid.
- <u>RV in adjacent lane(s)</u>: refers to RVs that are in the adjacent lane or two lanes over ahead of the HV, and therefore do not pose a crash threat to the HV. Alerts in this category are invalid.
- <u>Other</u>: refers to alerts triggered for RVs that are not ahead of the HV (i.e., RV is behind or adjacent to the HV, or on over/under pass). Alerts in this category are invalid.

The validity analysis of FCW alerts excluded 34 alert events, out of 293 events, which did not have any BSM data. Consequently, the Volpe team examined the remaining 259 FCW alert events that contained BSM data. Figure 12 shows the results of breaking down these alert events by RV location relative to the HV. There were 85 valid FCW alert events where the RV was in the path of the HV, accounting for 33 percent of all FCW alert events with BSM data. The remaining 174 FCW alert events were invalid since they involved an RV that was out of the forward path of the HV, accounting for 67 percent of all FCW alert events with BSM data.

Appendix E describes the validity criteria for FCW alerts and provides an example of an invalid FCW alert event.

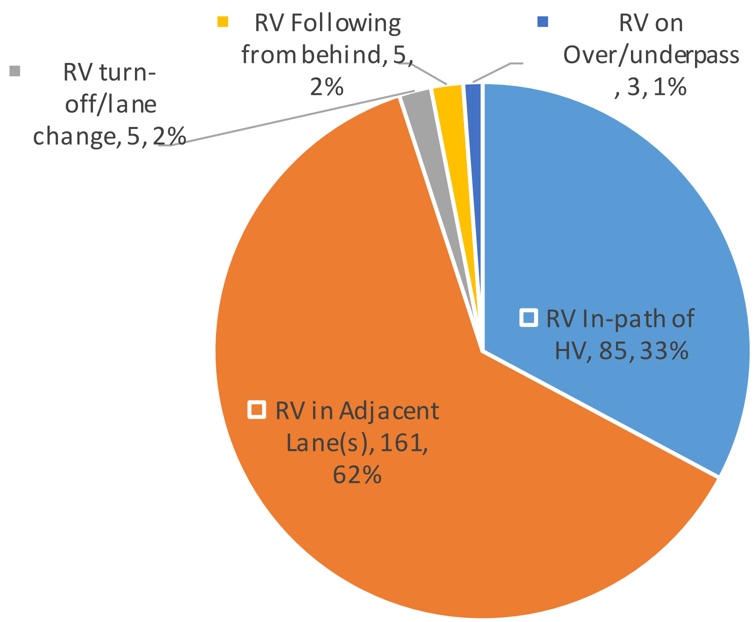

Figure 12. Breakdown of FCW Alert Events by Validation Category

3.1.2 Hazard FCW Alerts

The Volpe team deemed in-path FCW alerts as non hazard and not useful for the safety impact analysis if:

- HV and RV were separating as indicated by a range rate[6] greater than 0.5 m/s, or
- HV had a benign response in the 5-second window after alert onset. A benign response is determined by:
    - no brake flag (i.e., brake pedal not pressed),
    - peak deceleration greater than -0.49 m/s^2,
    - time headway[7] at alert onset greater than 3 seconds, or
    - range rate greater than -2.5 m/s.

The application of these criteria yielded 78 useful FCW alerts for the safety impact analysis, received by 61 distinct vehicles.

3.1.3 Silent and Active FCW Alerts

The Volpe team identified 40 silent and 38 active hazard FCW alerts, received respectively by 30 and 31 distinct vehicles. Figure 13 provides a breakdown of these FCW alerts by HMI status, using bins of initial kinematic conditions of the HV and RV at alert onset. The Volpe team binned these alerts based on the combined initial conditions of:

- HV speed bin: less than or equal to 45 mph and over 45 mph.
- Time headway rounded by 0.5-second increments.
- Range rate rounded to 5 m/s increments.

[6] Range rate = RV speed - HV speed
[7] Time headway = range / HV speed

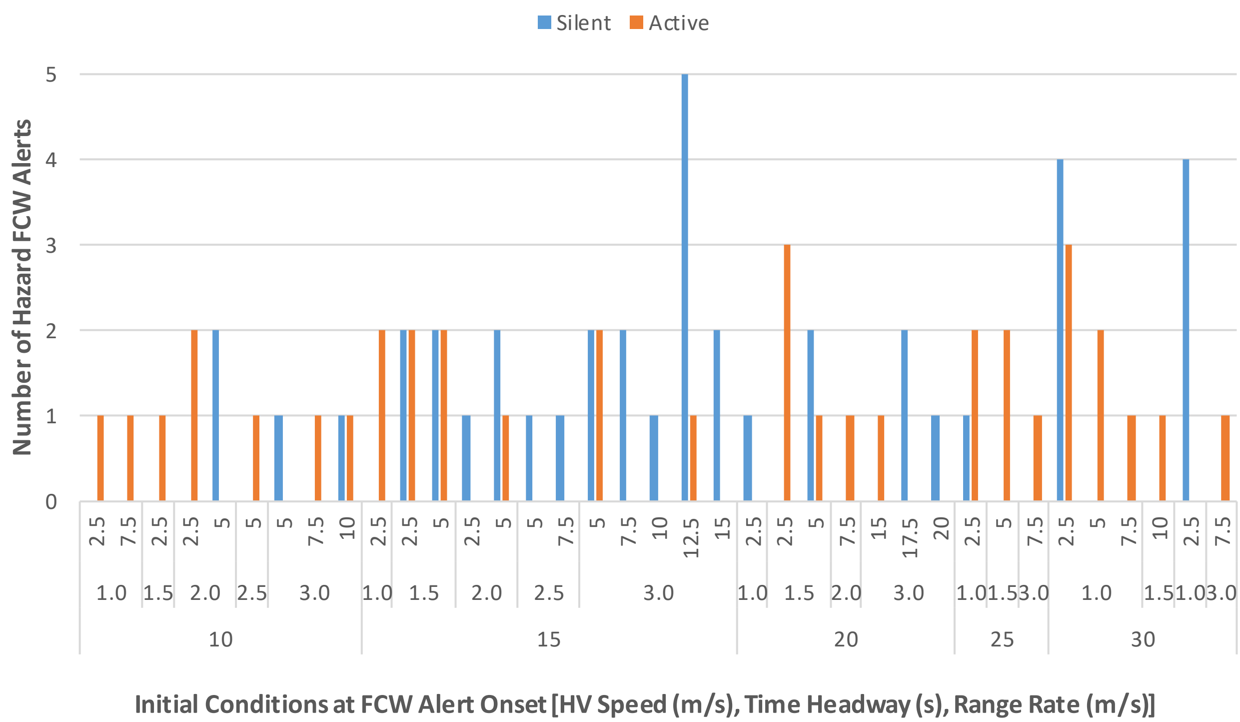

Figure 13. Breakdown of Hazard FCW Alerts by Initial Condition Bins and HMI Status

Figure 13 excluded one active FCW alert event that did not have a speed value. Thus, the Volpe team matched the initial conditions of 40 silent to 37 active hazard FCW alert events. In order to compare driver response to hazard FCW alerts between silent and active events, these events must have similar initial conditions at alert onset. Based on observations in Figure 13, the Volpe team identified 12 matched groups of events that had at least one silent and one active FCW alerts with similar initial condition bins. Table 4 lists these groups, their initial condition bins, and corresponding counts of alert events and distinct FCW-alerted vehicles according to HMI status. In total, 36 silent and 27 active FCW alert events were suitable for further statistical analysis.

The Volpe team used the mean values of various measures for each matched group to perform statistical comparison of vehicle performance between silent and active alert events. Table 5 shows key results of the statistical analysis of the actual time headway at alert onset for silent and active alert events, based on the two-sample two-tail T-test for means assuming unequal variance. As seen in Table 5, the difference in time headway between silent and active alert events was not statistically significant (P = 0.63). Therefore, the Volpe team used the 12 matched groups of FCW alert events to compare driver response to FCW alerts between silent and active alert events.

Table 4. Matched FCW Alert Groups

Speed (mph)	Time Headway (s)	|Range Rate| (m/s)	Alert Count		Distinct Vehicle	
			Silent	Active	Silent	Active
≤ 45	1.0	2.5	1	3	1	3
	1.5	2.5	2	6	2	5
	1.5	5	4	3	4	3
	2.0	2.5	1	2	1	2
	2.0	5	4	1	4	1
	2.5	5	1	1	1	1
	> 3	5	3	2	3	2
	> 3	7.5	2	1	2	1
	> 3	10	2	1	2	1
	> 3	12.5	5	1	4	1
	> 3	15	2	1	2	1
> 45	1.0	2.5	9	5	7	5

Table 5. Statistical Analysis of Time Headway (s) at Onset of Silent and Active Alerts

Statistical Parameter	Silent Alerts	Active Alerts
Mean	2.57	2.29
Variance	2.71	1.43
Observations (Groups)	12	12
P(T ≤ t) two-tail	0.63	

3.1.4 Driver Response to FCW Alerts

The Volpe team compared driver response to FCW alerts between silent and active HMI modes, in matched alert events under similar initial conditions at alert onset. Performance measures of HV driver response included:

- Brake response time from alert onset time until brake pedal activation[8]
- Time to collision (TTC) at brake onset[9]
- Time headway at brake onset
- Mean HV deceleration (Ax) within 5-second time window after alert onset
- Peak HV Ax within 5-second time window after alert onset

The Volpe team focused its analysis on braking response of the HV (i.e., longitudinal response). Based on previous experience evaluating driver response to in-vehicle alerts, if drivers respond to alerts, these

[8] Brake flag was not always available
[9] TTC = range / range rate

responses are usually observable within the first five seconds after the alert is issued. Therefore, the Volpe Team evaluated vehicle dynamics in the first five seconds after an alert was issued to a driver to ensure any response was accounted for. Drivers responded to FCW alerts by steering or changing lanes in only ten hazard events, as observed from the event visualization tool (see Appendix F listing the coding scheme for event visualization analysis). Table 6 shows key results of the statistical analysis of driver response measures for silent and active alert events, based on the two-sample two-tail T-test for means assuming unequal variance. The difference in all five performance measures between silent and active alert events was not statistically significant ($P > 0.05$). Thus, FCW alerts did not change driver response to rear-end driving conflicts based on recorded events in the THEA CVP deployment. Consequently, the crash prevention ratio in Equation (1) is set to one (i.e., no effect in driving conflict resolution).

Table 6. Statistical Analysis of Driver Braking Response Measures to FCW Alerts by HMI Status

Statistical Parameter	**Brake Response Time (s)**		**Mean Ax (m/s^2)**		**Peak Ax (m/s^2)**		**Brake Onset TTC (s)**		**Brake Onset Time Headway (s)**	
	Silent	**Active**	**Silent**	**Active**	**Silent**	**Active**	**Silent**	**Active**	**Silent**	**Active**
Mean	1.2	1.1	-0.8	-0.9	-1.4	-1.5	4.3	4.6	1.8	1.6
Variance	1.8	1.1	0.2	0.2	0.6	0.6	6.1	5.9	1.1	0.6
Observations	7	7	12	12	12	12	7	7	7	7
$P(T \le t)$ two-tail	0.90		0.92		0.68		0.81		0.78	

3.2 Emergency Electronic Brake Light

The EEBL application alerts HV drivers to suddenly decelerating RVs driving in the same direction ahead in the traffic queue.

3.2.1 EEBL Alert Validity

A hard-braking RV directly ahead of the HV or in front of other vehicles, traveling in the same direction in the same or adjacent lane, triggers an EEBL alert. The Volpe team analyzed the EEBL alert validity by using the following categories:

- RV traveling in the same lane ahead of the HV
- RV traveling in adjacent lanes ahead of the HV
- RV in ‘other’ situations.

Figure 14 shows the results of the EEBL alert validity analysis. The Volpe team deemed EEBL alert events to be valid when the RV was traveling ahead of the HV in the same or adjacent lane. Fifteen out of 16, or about 94 percent of, EEBL alert events were valid. An RV traveling on an adjacent road triggered the only invalid EEBL alert event. Appendix E describes the validity criteria for EEBL alerts and illustrates this invalid EEBL alert.

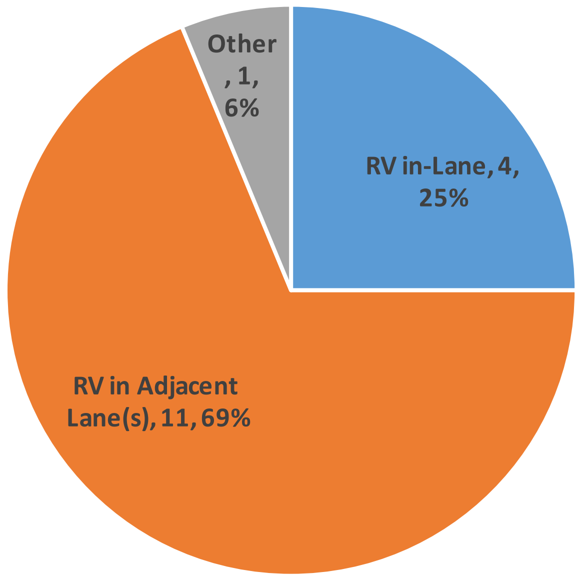

Figure 14. Breakdown of EEBL Event by Validation Category

3.2.2 Hazard EEBL Alerts

The Volpe team considered valid EEBL alert events as hazard alerts when the RV braked hard (i.e., deceleration ≤ -2.5 m/s^2) in the traffic queue ahead of the HV. Thirteen out of 15 valid EEBL alert events in the THEA CVP site were hazard alerts. The deceleration values of the RV at EEBL alert onset in the two excluded valid events were -0.64 and -1.00 m/s^2. All 13 hazard alert events were received by distinct vehicles.

3.2.3 Silent and Active EEBL Alerts

Figure 15 plots silent and active hazard EEBL alerts by their HV speed and time headway at alert onset. There were eight silent and five active hazard EEBL alert events received by eight and five distinct vehicles, respectively.

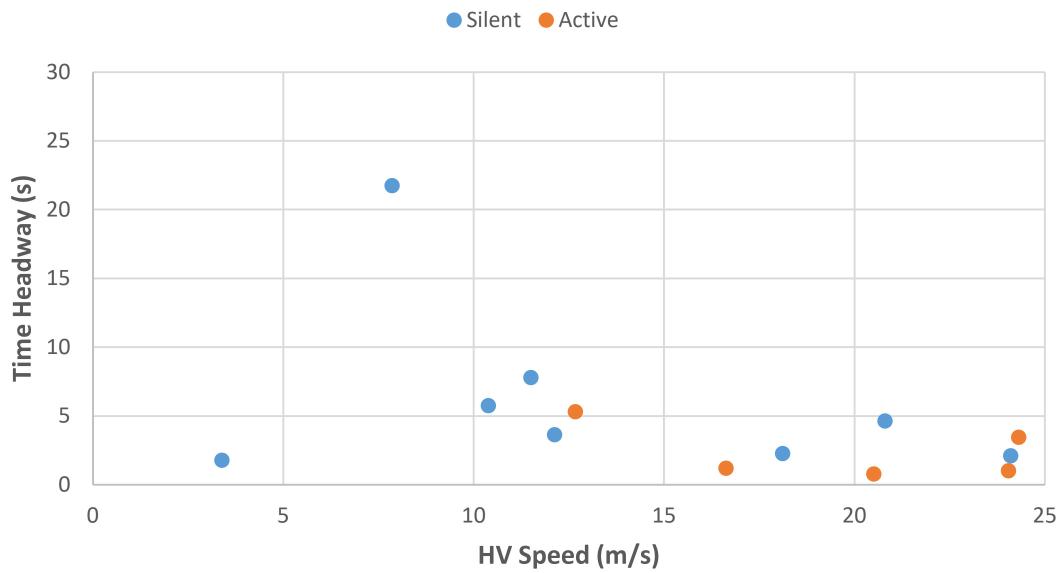

Figure 15. Time Headway versus HV Speed at Onset of Silent and Active Hazard EEBL Alert Events

Table 7 provides the mean values of key kinematic parameters at onset of hazard EEBL alert events for silent and active alerts. The Volpe team did not perform any statistical analysis on these parameters to compare initial conditions between silent and active alert events due to the small sample (5) of active alert events (i.e., < 8 events in each event).[10] As seen in Figure 15, one silent EEBL alert occurred at a time headway of 21.8 seconds at a range of 171 meters. This alert outlier contributed to mean values of range, TTC, and time headway for silent alerts that are larger than active alert values.

Table 7. Mean Values of Kinematic Parameters at Onset of Silent and Active Hazard EEBL Alert Events

Kinematic Parameter	**Alert Events**	
	Silent	**Active**
HV Speed (m/s)	13.5	19.6
Range (m)	70.0	42.5
TTC (s)	25.9	7.2
RV Acceleration (m/s²)	-3.9	-4.0
Time Headway (s)	6.2	2.4

3.2.4 Driver Response to EEBL Alerts

Of the 13 hazard EEBL alert events, only three silent and one active events had data about driver response in the database. One of the three silent alert events (i.e., outlier in Figure 15) did not have brake flag information. The Volpe team did not have sufficient events to perform any statistical analysis to compare driver response between silent and active EEBL alert events. Table 8 provides the values of

[10] Based on statistical rules of thumb and best practice

TTC at alert onset and driver response measures for the two silent and one active alert events. Due to the lower TTC value at alert onset, the vehicle receiving the active EEBL alert braked harder and reached smaller minimum TTC than the two vehicles receiving the silent alert during the response period. Due to insufficient data, the Volpe team was not able to estimate the crash prevention ratio for the EEBL application.

Table 8. Values of Driver Response Variables for Three EEBL Alert Events by HMI Status

Kinematic Parameter	**Alert Events**		
	Silent	**Silent**	**Active**
TTC (s) @ alert onset	29.3	46.6	8.9
Mean HV Ax (m/s^2)	-0.88	-1.06	-2.94
Peak HV Ax (m/s^2)	-1.94	-2.22	-5.59
TTC (s) @ brake onset	9.0	21.1	6.0
Minimum TTC (s)	8.9	7.8	4.7

3.3 Intersection Movement Assist

The IMA application alerts HV drivers of imminent crossing-paths crashes with laterally approaching RVs at intersections.

3.3.1 IMA Alert Validity

The Volpe team assessed the validity of IMA alert events based on:

- HV and RV on intersecting paths at intersections
- RV on over/underpass
- HV following RV from behind or vice versa
- Other (i.e., RV at two intersections away from HV path, HV in a parking lot, HV has already crossed the intersection, etc.)

There were 133 IMA alert events with available BSM data. Figure 16 illustrates the results of the alert validity analysis. The Volpe team deemed IMA alerts as valid if the HV and RV were approaching the same intersection and were on intersecting paths. As a result, 28 IMA alerts or about 21 percent of all IMA alert events with BSM data were valid. Appendix E describes the validity criteria for IMA alerts and illustrates two examples of invalid IMA alert events.

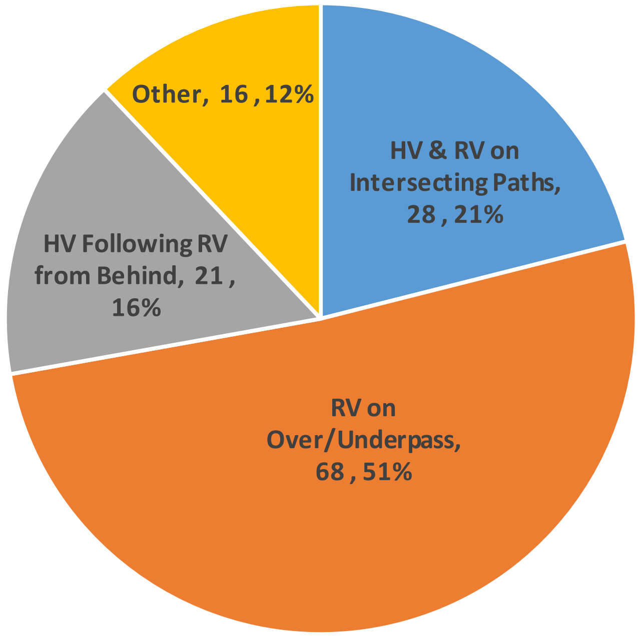

Figure 16. Breakdown of IMA Alert Events by Validation Category

3.3.2 Hazard IMA Alerts

The Volpe team considered all 28 valid IMA alert events as hazard events for further analysis. Figure 17 allocates these events to the following five driving conflict scenarios [7]:

- HV and RV on straight crossing paths (SCP)
- HV making a right turn into the path (RTIP) of the RV
- HV making a left turn into the path (LTIP) of the RV
- HV making a left turn across the path from lateral direction (LTAP/LD) of the RV
- HV making a left turn across the path from opposite direction (LTAP/OD) of the RV

Figure 53 in Appendix F shows the schematics of these scenarios. Figure 17 assigns the 28 hazard IMA alert events to the five scenarios, which were received by 25 distinct vehicles.

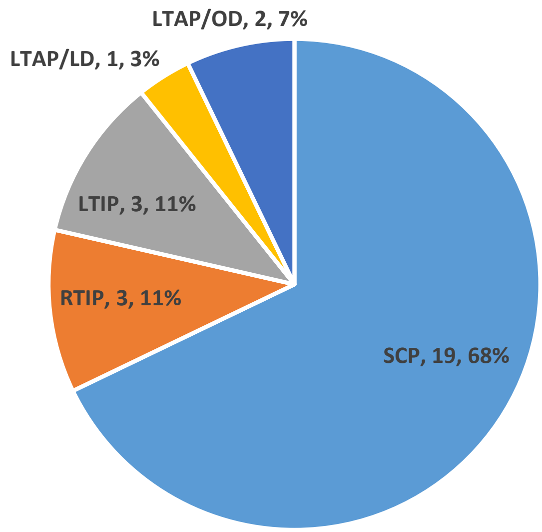

Figure 17. Breakdown of Hazard IMA Alert Events by Crossing-Paths Scenarios

3.3.3 Silent and Active IMA Alerts

Table 9 lists the initial kinematic conditions at the onset of silent and active hazard IMA alerts by driving conflict scenario. There were 17 silent and 11 active IMA alert events, broken down by driving conflict scenario as follows:

- <u>SCP</u>: 14 silent and 5 active IMA alerts
- <u>LTIP</u>: one silent and two active IMA alerts
- <u>RTIP</u>: two silent and one active IMA alerts
- <u>LTAP/LD</u>: one active IMA alert
- <u>LTAP/OD</u>: two active IMA alerts

Kinematic conditions at alert onset include speed, Ax, and time to intersection (TTI)[11] for HV and RV. Obviously, the rarity of available IMA alert events in LTIP, RTIP, LTAP/LD, and LTAP/OD scenarios did not allow the Volpe team to pursue any further analysis of these cases. Two silent alert events in the SCP scenario did not have any available data to compute TTI for HV and all three initial conditions for RV. Moreover, one active alert event in the SCP scenario involved a stopped HV (i.e., HV speed = 0.8 m/s and HV Ax = -0.12 m/s^2). Thus, 12 silent and four active IMA alert events remained in the SCP scenario for further analysis. The HV was accelerating (i.e., HV Ax ≥ ~0.5 m/s^2) at IMA alert onset in all four active alert events and in five silent active alerts in the SCP scenario.

Figure 18 displays TTI of HV and RV at the onset of IMA alerts by HMI status in the SCP scenario, in order to observe any matched cases between silent and active alert events. Only two active IMA alert events appeared to closely match silent events at alert onset.

[11] TTI (s) = range to intersection (m) / speed (m/s)

Table 9. Initial Conditions at Onset of Silent and Active Hazard IMA Alerts

HMI Status	Driving Conflict Scenario	HV Speed (m/s)	HV Ax (m/s^2)	HV TTI (s)	RV TTI (s)	RV Speed (m/s)	RV Ax (m/s^2)
Silent	SCP	6.3	1.31	4.2	1.5	13.4	-0.17
		4.6	4.21	14.7	3.7	11.6	-0.39
		18.8	-1.86	2.7	7.1	8.6	1.03
		15.7	-2.15	2.7	5.8	9.1	0.59
		12.6	-0.12	5.9	6.1	16.6	-0.12
		4.2	0.34	4.4	6.0	13.4	-0.09
		17.2	-0.40	9.1	2.2	5.2	-1.12
		10.8	0.90	3.8	3.5	3.5	-1.36
		4.4	-0.15	3.5	4.3	10.4	-0.26
		6.8	0.32				
		1.1	0.95	8.7	7.2	11.8	-0.12
		7.3	0.81	4.7	4.7	13.9	0.72
		3.6	-0.87	3.8	2.1	10.5	0.16
		6.0	-0.15				
	LTIP	4.4	2.62	9.5	6.4	11.2	0.64
	RTIP	5.2	2.54	16.1	6.8	10.3	0.65
		7.8	2.12	9.2	4.8	11.4	0.76
Active	SCP	4.9	1.15	1.0	2.1	17.2	-1.06
		5.1	2.89	3.0	4.5	14.5	-1.18
		2.5	1.75	9.7	7.4	11.1	-0.77
		0.8	-0.12	32.8	7.3	10.5	-0.47
		4.1	0.49	1.1	6.7	10.8	1.20
	LTIP	8.4	0.49	2.7	4.1	10.3	-1.63
		12.7	-0.21	3.5	2.2	11.5	-1.32
	RTIP	2.2	1.00	3.6	0.0	10.2	0.76
	LTAP/LD	3.1	1.84	5.3	3.0	13.1	0.00
	LTAPOD	5.1	1.97	5.2	6.9	11.1	-0.31
		1.7	0.69	3.3	0.1	10.1	1.17

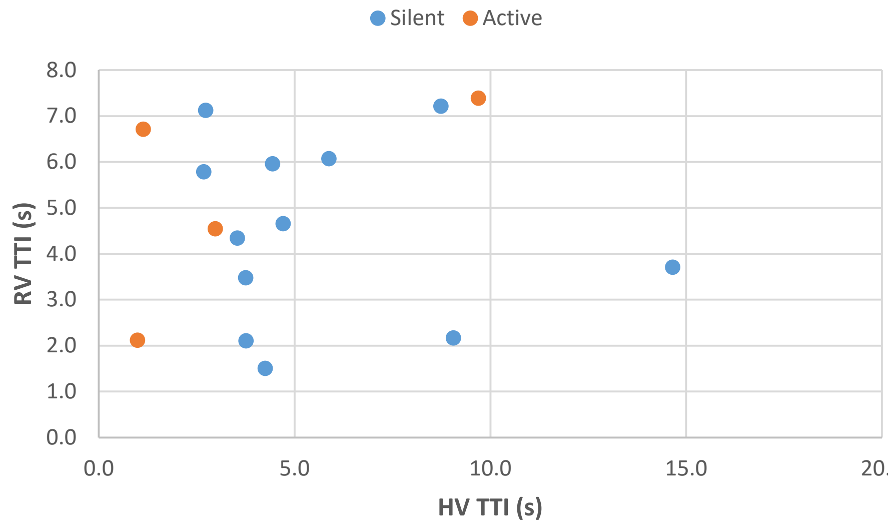

Figure 18. RV versus HV TTI at Onset of Silent and Active IMA Alerts in SCP Scenario

3.3.4 Driver Response to IMA Alerts

Information about brake pedal activation in the HV was only available for three silent and two active IMA alert events in the SCP scenario. However, the Volpe team was able to compute HV Ax during a 5-second time window after IMA alert onset for ten silent and three active alert events in the SCP scenario. The HV decelerated (i.e., Peak Ax ≤ -0.5 m/s^2) in seven silent and three active alert events. In these events, the average peak Ax was -2.94 m/s^2 in silent alert events and -1.04 m/s^2 in active alert events. Moreover, the average mean Ax was -1.63 m/s^2 in silent alert events and -0.52 m/s^2 in active alert events. Unfortunately, statistical conclusions could not be gleaned from these driver response results due to small and unmatched samples between silent and active IMA alert events. Consequently, the Volpe team was not able to estimate the crash prevention ratio for the IMA application.

3.4 Vehicle Turning Right in Front of a Transit Vehicle

The VTRFTV application alerts transit vehicle drivers of other vehicles that are turning right in front of them, and alerts other vehicles about the presence of a transit vehicle when intending to turn right.

3.4.1 VTRFTV Alert Validity

THEA's VTRFTV application alerts trolley drivers about RVs attempting to take a right turn in front of them at intersections between the roadway and trolley tracks. The Volpe team classified the VTRFTV alert events by the following categories using the location and motion of the RV relative to the HV at alert onset:

- RV on intersecting path with HV: refers to RVs that were turning right in the intended path of the HV.
- RV on adjacent but not intersecting path with HV: refers to RVs that were in the adjacent lane or two lanes over, going straight or turning left away from the intended path of the HV.
- RV turning right but not on intersecting path with HV: refers to RVs that turned right but not on the intended path of the HV.
- RV on over/underpass: refers to RV location over or under the intended path of the HV.

- Other: refers to RVs approaching the HV on a parallel path from the opposite direction, or at parking lots.

Figure 19 classifies 45 VTRFTV alert events with available BSM data into the five categories listed above. The Volpe team considered the nine alert events where the HV and RV were on intersecting paths as valid, accounting for 20 percent of all 45 VTRFTV alert events. Other categories contained invalid VTRFTV alert events. Appendix E describes the validity criteria for VTRFTV alerts and illustrates two examples of invalid VTRFTV alert events.

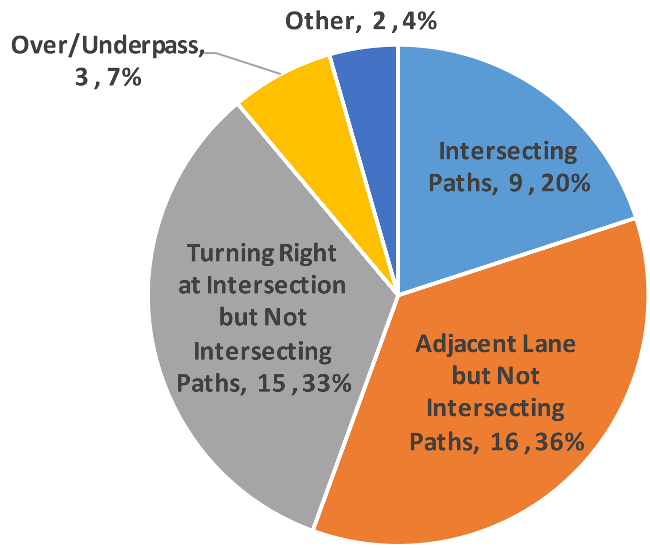

Figure 19. Breakdown of VTRFTV Alert Events by Validation Category

3.4.2 Hazard VTRFTV Alerts

The Volpe team examined the nine valid VTRFTV alert events and found that:

- One passenger vehicle experienced two successive alerts while slowing down and yielding to the trolley.
- One trolley received four successive alerts while continuing to move along the track.
- One trolley received two successive alerts while continuing to move along the track.
- One trolley received one alert while continuing to move along the track.

3.4.3 Silent and Active VTRFTV Alerts

The passenger car with two alerts and the trolley with four alerts were operating in the silent mode. The other two trolleys were operating in the active mode when they received the three VTRFTV alerts. Table 10 lists the initial kinematic conditions at the onset of the six silent and three active VTRFTV alerts. Kinematic conditions at alert onset include speed, Ax, and TTI for HV and RV. As seen in the last two rows of Table 10, the RV was stopped when the trolley received an active VTRFTV alert. There was no such an event in the silent alert events. Figure 20 displays TTI of HV and RV at the onset of VTRFTV alerts by HMI status for the remaining seven events, in order to observe any matched cases between silent and active alert events. Unfortunately, the one active alert event did not match any in the silent alert sample. The rarity of available VTRFTV alert events did not allow the Volpe team to pursue any further statistical analysis of these cases.

Table 10. Initial Conditions at Onset of Silent and Active Hazard VTRFTV Alerts

HMI Status	Vehicle Type	HV Speed (m/s)	HV Ax (m/s²)	HV TTI (s)	RV Speed (m/s)	RV Ax (m/s²)	RV TTI (s)
Silent	Passenger car	7.7	-2.4	4.7	5.6	0.3	5.1
		6.4	-0.8	4.5	5.6	0.0	3.7
	Trolley	4.7	-0.6	10.2	16.0	-1.1	4.1
		4.6	-0.6	7.1	15.8	-1.0	4.4
		4.0	-0.5	7.6	13.4	-2.6	4.2
		3.9	-0.4	7.1	12.6	-3.4	4.3
Active	Trolley	6.0	0.5	4.2	13.1	-1.1	0.5
		6.1	-0.1	0.4	0.2	0.1	28.0
		7.0	0.7	5.1	0.0	0.0	Null

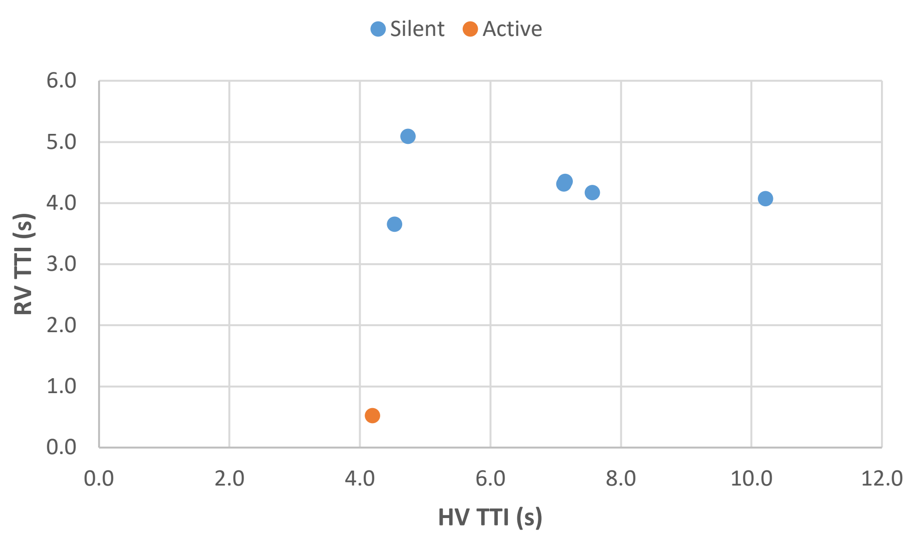

Figure 20. RV versus HV TTI (s) at Onset of Silent and Active VTRFTV Alerts

3.4.4 Driver Response to VTRFTV Alerts

Information about brake pedal activation in the HV was not available in any of the nine VTRFTV alert events. The Volpe team was able to compute HV Ax during a 5-second time window after VTRFTV alert onset for six silent and two active alert events. The HV decelerated (i.e., Peak Ax ≤ -0.5 m/s^2) in the six silent alert events and none of the active alert events. In these six events, the average peak Ax was -1.20 m/s^2 and the average mean Ax was -0.60 m/s^2. Statistical conclusions could not be gleaned from these driver response results due to very small and unmatched samples between silent and active

VTRFTV alert events. Consequently, the Volpe team was not able to estimate the crash prevention ratio for the VTRFTV application.

3.5 Pedestrian Collision Warning

The PCW application alerts drivers to the presence of pedestrians in a crosswalk.

3.5.1 PCW Alert Validity

The Volpe team assessed the validity of PCW alert events by whether or not the HV was on a collision course with a pedestrian crossing the equipped crosswalk. This validity assessment classified these events by the following three validity categories:

- HV approaching equipped crosswalk while pedestrian crossing
- HV approaching equipped crosswalk while pedestrian not crossing but standing on the sidewalk
- Other - HV not approaching equipped crosswalk or premature alert (HV was at least one block away)

Figure 21 shows the breakdown of all PCW alert events with available BSM data (i.e., nine events) by the three categories listed above. The Volpe team considered PCW alert events as valid when the HV approached the equipped crosswalk while the pedestrian was crossing or present on the sidewalk next to the crosswalk. Thus, five cases or 56 percent of PCW alert events were valid. Appendix E describes the validity criteria for PCW alerts and illustrates two examples of invalid PCW alert events.

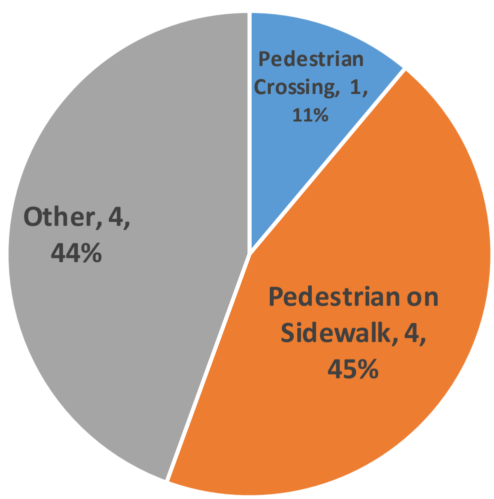

Figure 21. Breakdown of PCW Alert Events by Validation Category

3.5.2 Hazard PCW Alerts

The Volpe team deemed valid PCW alert events as hazard events if the pedestrian was crossing the sidewalk and the HV was approaching. There was one hazard event where the HV was accelerating from a low speed while a pedestrian was crossing the sidewalk at PCW alert onset. In the other four valid cases, a pedestrian was not crossing the sidewalk.

3.5.3 Silent and Active PCW Alerts

Three distinct vehicles received the five valid PCW alerts, all in silent mode. Table 11 lists the kinematic conditions of the HV and pedestrian at the onset of these silent, valid PCW alerts. The hazard event (1^{st}

numerical row) shows the pedestrian was crossing the sidewalk at a speed of 1.9 m/s, while the HV was accelerating at 1.69 m/s^2 from a speed of 3.1 m/s. In other events, the speed of the pedestrian was zero or very close to zero.

Table 11. Initial Kinematic Conditions of HV and Pedestrian at Valid PCW Alert Onset

HV Speed (m/s)	HV Ax (m/s^2)	TTC (s)	Pedestrian Speed (m/s)
3.1	1.69	1.9	1.9
9.9	0.12	5.2	0.0
8.8	-0.22	5.3	0.0
12.8	0.49	3.0	0.0
8.5	-0.75	3.8	0.1

3.5.4 Driver Response to PCW Alerts

The one hazard PCW alert event did not have available data to quantify driver response within the 5-second time window from alert onset. In other four non-hazard valid events, the HV decelerated slightly (peak Ax ≤ -0.5 m/s^2) in three cases at an average mean Ax of -0.30 m/s^2 and an average peak Ax of -0.65 m/s^2.

Given the lack of any active PCW alert events and only one silent, hazard PCW alert event, the Volpe team was not able to estimate the crash prevention ration of the PCW application.

3.6 End of Ramp Deceleration Warning

The ERDW application provides advisory speed limit information to HV drivers who are approaching or are on the curve leading to the REL exit, based on their speed and the traffic queue build-up ahead at the end of the REL ramp.

3.6.1 ERDW Alert Validity

The Volpe team assessed the validity of ERDW alert events based on:

- HV traveling above advisory speed
- HV traveling below advisory speed
- HV no longer on REL ramp
- HV traveling on over/underpass

Figure 22 shows the breakdown of the 1,232 ERDW alert events with available BSM data by the four validity categories listed above. The Volpe team deemed ERDW alert events as valid where the HV was approaching or traveling on the REL above the advisory speed. Thus, 628 or 51 percent of all ERDW alert events with available BSM data were valid. Appendix E describes the validity criteria for ERDW alerts and illustrates two examples of invalid ERDW alert events.

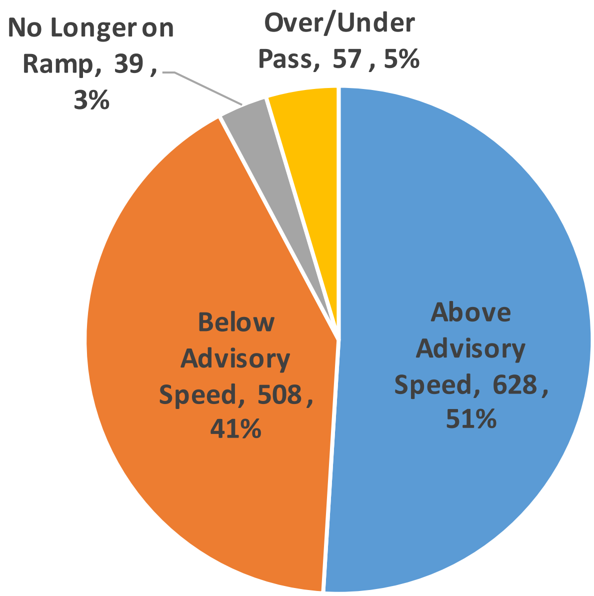

Figure 22. Breakdown of ERDW Alert Events by Validation Category

3.6.2 Hazard ERDW Alerts

The Volpe team deemed all 628 valid ERDW alert events as hazard events. However, the Volpe team pursued the analysis of 619 ERDW alert events and eliminated from the analysis nine events that did not have any HMI status information. The initial analysis of these 619 events revealed that some HVs received multiple ERDW alerts during the same ramp approach. The Volpe team decided to evaluate the driver response to the first alert of its kind (i.e., speed advisory). Thus, the Volpe team did not analyze consecutive ERDW alerts for the same driver receiving the same speed advisory alert within a five-minute period after the first alert. Based on this criterion, the Volpe team further eliminated consecutive 35 ERDW alerts and retained 584 hazard ERDW alerts for further analysis.

3.6.3 Silent and Active ERDW Alerts

The Volpe team identified 232 silent and 352 active hazard ERDW alert events. Figure 23 shows the distribution of these alert events by HMI status, ERDW advisory speed, and HV over-speed bin at ERDW alert onset. There were no matches between silent and active alert events for two of the HV over-speed bins in the 40 mph ERDW advisory speed.

Table 12 provides the number of hazard ERDW alert events, the number of ERDW-alerted distinct vehicles, and the average values of HV speed at alert onset for each of the 13 combinations of ERDW advisory speed and HV over-speed bin, by HMI status. This table excludes the two unmatched active ERDW alert events with over-speed greater than 30 mph in the 40 mph EDRW advisory speed group.

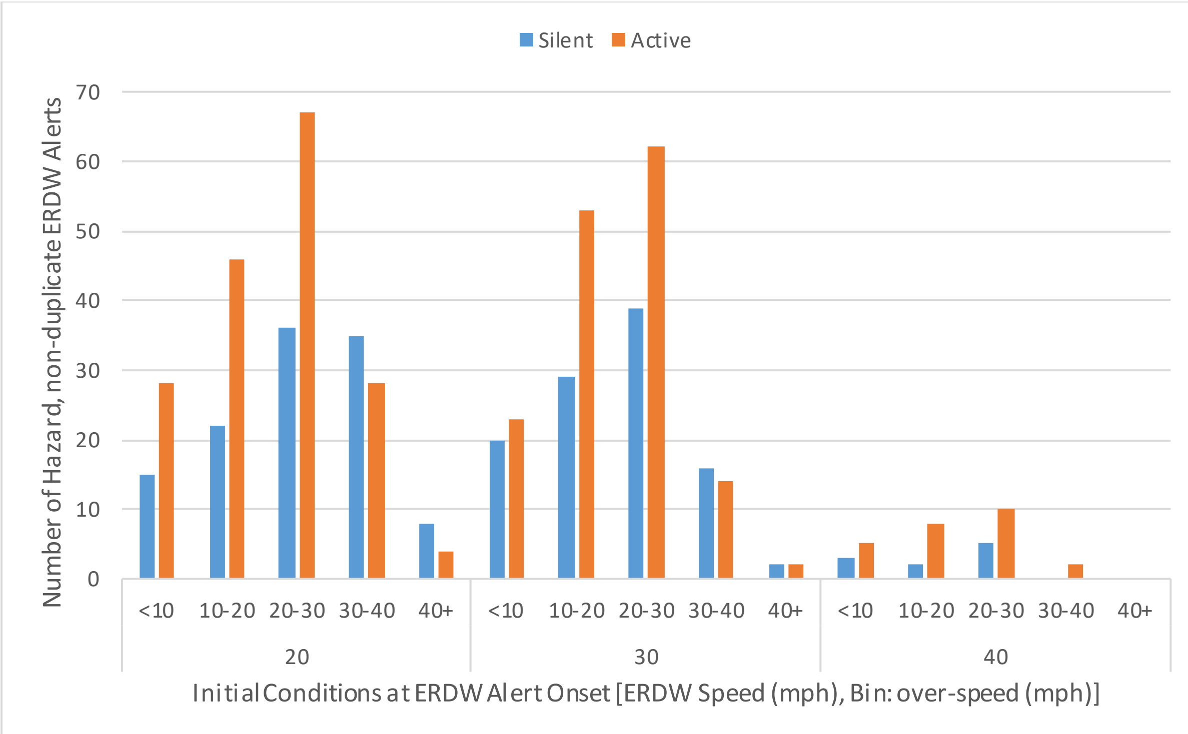

Figure 23. Breakdown of Hazard ERDW Alert Events by Initial Speed Condition and HMI Status

Table 12. Hazard ERDW Alert Groups by HMI Status

ERDW Advisory Speed (mph)	Over-speed bin (mph)	Alert Count		Distinct Vehicle		Mean Values HV Speed (mph)	
		Silent	Active	Silent	Active	Silent	Active
20	<10	15	28	12	19	24.0	24.2
	10-20	22	46	19	29	36.7	36.3
	20-30	36	67	21	37	45.2	45.4
	30-40	35	28	22	22	54.6	53.7
	40+	8	4	7	4	63.5	62.2
30	<10	20	23	14	17	37.3	37.1
	10-20	29	53	18	32	46.8	45.8
	20-30	39	62	25	40	54.8	54.2
	30-40	16	14	12	12	63.6	62.3
	40+	2	2	2	2	72.3	72.1

ERDW Advisory Speed (mph)	Over-speed bin (mph)	Alert Count		Distinct Vehicle		Mean Values HV Speed (mph)	
		Silent	Active	Silent	Active	Silent	Active
40	<10	3	5	3	5	47.0	45.0
	10-20	2	8	2	8	55.6	55.4
	20-30	5	10	5	10	62.1	64.7

In order to determine whether silent hazard ERDW alert events match with active events, the Volpe team performed a statistical analysis on the mean values of HV speed at alert onset in the 13 combinations (i.e., groups) using the two-sample T-test for means assuming unequal variance. Table 13 displays the results of this test showing that the silent and active ERDW alert events are not statistically different (i.e., P > 0.05). Therefore, the Volpe team continued with its statistical analysis to compare driver response between silent and active alert events.

Table 13. Summary of Statistical Analysis of Mean HV Speed at ERDW Alert Onset by HMI Status

Statistical Parameter	**Mean HV Speed (mph)**	
	Silent	Active
Mean	51.0	50.6
Variance	79.4	79.9
No. Observations (Groups)	13	13
P(T ≤ t) two-tail	0.94	

3.6.4 Driver Response to ERDW Alerts

The Volpe team compared driver response to ERDW alerts between silent and active HMI modes, in matched alert events under similar initial conditions at alert onset. Performance measures of HV driver response, within 5-second time window after ERDW alert onset, included:

- Maximum HV over-speed
- Maximum HV speed
- Minimum HV speed
- Mean HV speed
- Mean HV Ax
- Peak HV Ax
- Brake response time from ERDW alert onset until brake pedal activation

Table 14 shows key results of the statistical analysis of driver response measures for silent and active ERDW alert events, based on the two-sample two-tail T-test for means assuming unequal variance. It should be noted that some events did not have values and thus did not contribute to the group's mean calculation. There were no statistically-significant differences in all seven performance measures between silent and active ERDW alert events (P > 0.05). Thus, ERDW alerts did not change driver response to over-speeding based on recorded events in the THEA CVP deployment. Consequently, the crash prevention ratio is set to one (i.e., no effect in driving conflict resolution).

Table 14. Statistical Analysis of Driver Response Measures in ERDW Alert Events by HMI Status

Statistical Parameter	Max HV Over-speed (m/s)		Max HV Speed (m/s)		Min HV Speed (m/s)		Mean HV Speed (m/s)		Mean HV Ax (m/s^2)		Peak HV Ax (m/s^2)		Brake Response Time (s)	
	Silent	Active	Silent	Active	Silent	Active	Silent	Active	Silent	Active	Silent	Active	Silent	Active
Mean	10.09	9.92	22.97	22.72	20.31	19.33	21.69	21.13	(0.62)	(0.75)	(1.09)	(1.26)	0.06	0.08
Variance	76.31	75.25	34.70	34.66	41.01	34.69	37.62	34.71	0.06	0.04	0.16	0.07	0.00	0.00
Observations	13	13	13	13	13	13	13	13	13	13	13	13	12	13
P(T≤t) two-tail	0.94		0.92		0.69		0.81		0.14		0.22		0.18	

3.7 Wrong-Way Entry

The WWE application is designed to prevent drivers from entering and traveling outbound on the REL when going the wrong way, and to warn legal inbound drivers when the wrong-way violation occurs. In addition, the WWE application alerts drivers when they enter the outbound or inbound closed section of the REL.

3.7.1 WWE Alert Validity

Participants in the THEA CVP deployment experienced a total of 6,297 WWE alert events. The Volpe team analyzed the validity of 5,614 (≈ 89%) alert events with available BSM data. The lack of BSM data for the remaining 683 alert events did not allow the Volpe team to obtain any information about HV location and movement during these events. The Volpe team constructed and applied four automatic filters, using programmatic SQL and geographic information system (GIS) tools, to determine the validity of WWE alert events as detailed in Appendix E. The four filters and their results are:

1. Filter 1, HV location and heading at alert onset, eliminated 3,433 WWE alert events as invalid and applied the second filter to the remaining 2,181 alerts (39% of 5,614 WWE alert events).
2. Filter 2, southbound alerts during closed gate and wrong-way driver alerts, yielded 495 invalid WWE alerts and applied the third filter to the remaining 1,686 alerts (77% of 2,181 alerts).
3. Filter 3, HV location and heading 3 seconds after alert, deemed 489 WWE alerts (29% of 1,686 alerts) as potentially valid for further filtering, eliminating 1,197 invalid WWE alerts.
4. Filter 4, southbound vehicles with heading errors at alert onset, determined that 130 WWE alert events were invalid and the remaining 359 alerts (73% of 489 alerts) would require manual visualization to assess their validity.

Consequently, the four automatic filters removed 5,255 invalid WWE alert events (about 94% of 5,614 total alerts). Considered potentially valid, the remaining 359 WWE alert events (about 6% of total alerts) required further manual analysis using the event visualization tool. This analysis determined:

1. HV location within the intersection area at WWE alert onset
2. Trajectory of HV travel over the course of 30 seconds before and after alert onset
3. HV response to WWE alerts

Table 15 lists the results of the first step to locate the HV at alert onset for the 359 WWE alert events, based on eight locations as depicted in Figure 54 in Appendix F. These events comprised 237 silent alerts and 122 active alerts. Figure 24 illustrates the location of individual HVs at WWE alert onset in each of the eight locations.

Table 15. HV Locations and Concomitant WWE Numbers at Alert Onset

HV Location	Number
Southbound RELs (0)*	147
Northbound RELs (1)	79
Quadrant 1 (2)	43
Quadrant 2 (3)	2
Quadrant 3 (4)	11
Quadrant 4 (5)	1
E Twiggs St (6)	44
N Meridian Ave (7)	5
Ramp (8)	27

*: Number in parentheses corresponds to the location codes in Figure 24

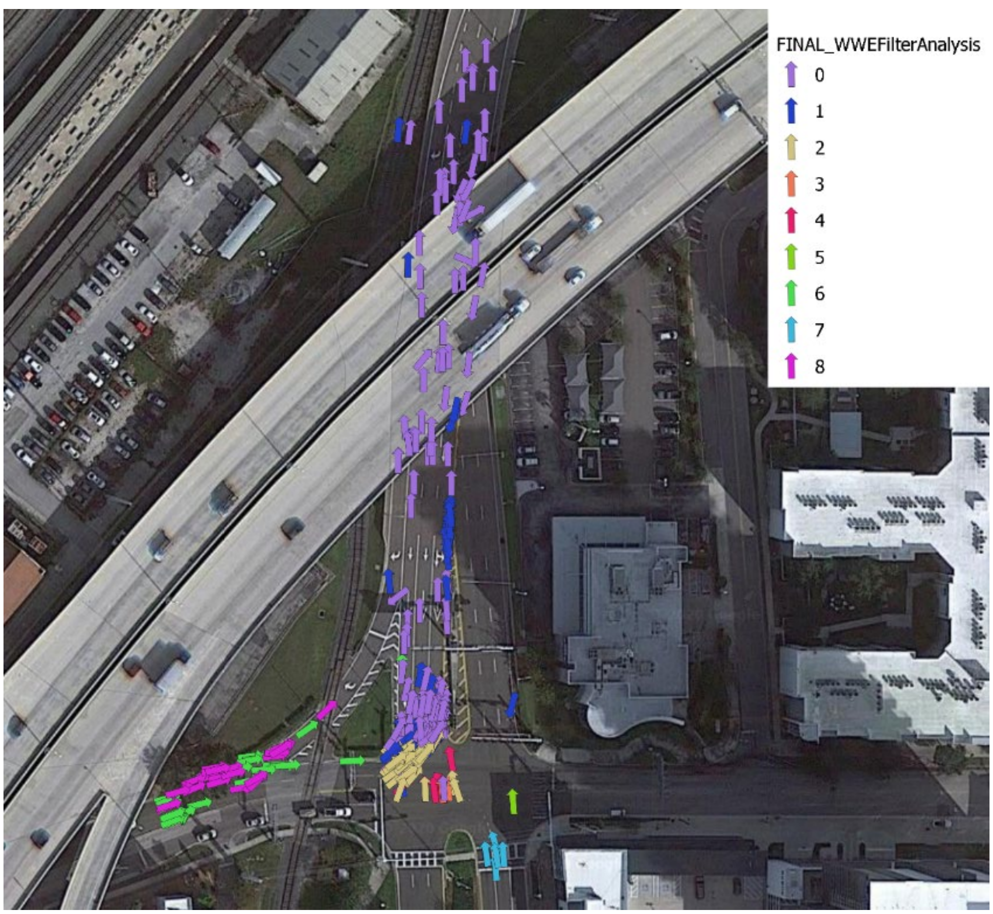

Figure 24. HV Location Results from Manual WWE Alert Analysis

Table 16 provides analysis results that described the HV direction of motion at the time and location of WWE alert onset. Figure 25 illustrates the direction of motion of individual HVs at WWE alert onset.

Table 16. HV Direction of Motion and Concomitant WWE Numbers at Alert Onset

HV Direction of Motion	Number
None (0)*	1
HV approaching/entering REL northbound on ‘Do-Not-Travel' lanes (1)	6
HV approaching/traveling on 'Do-Not-Enter' lane (2)	271
HV traveling southbound on REL and alerted for an RV on 'Do-Not-Enter' lanes (3)	7
HV approaching/traveling southbound on 'Do-Not-Travel’ Lanes (4)	4
HV approaching 'Do-Not-Enter’ ramp (5)	70

*: Number in parentheses corresponds to the location codes in Figure 25

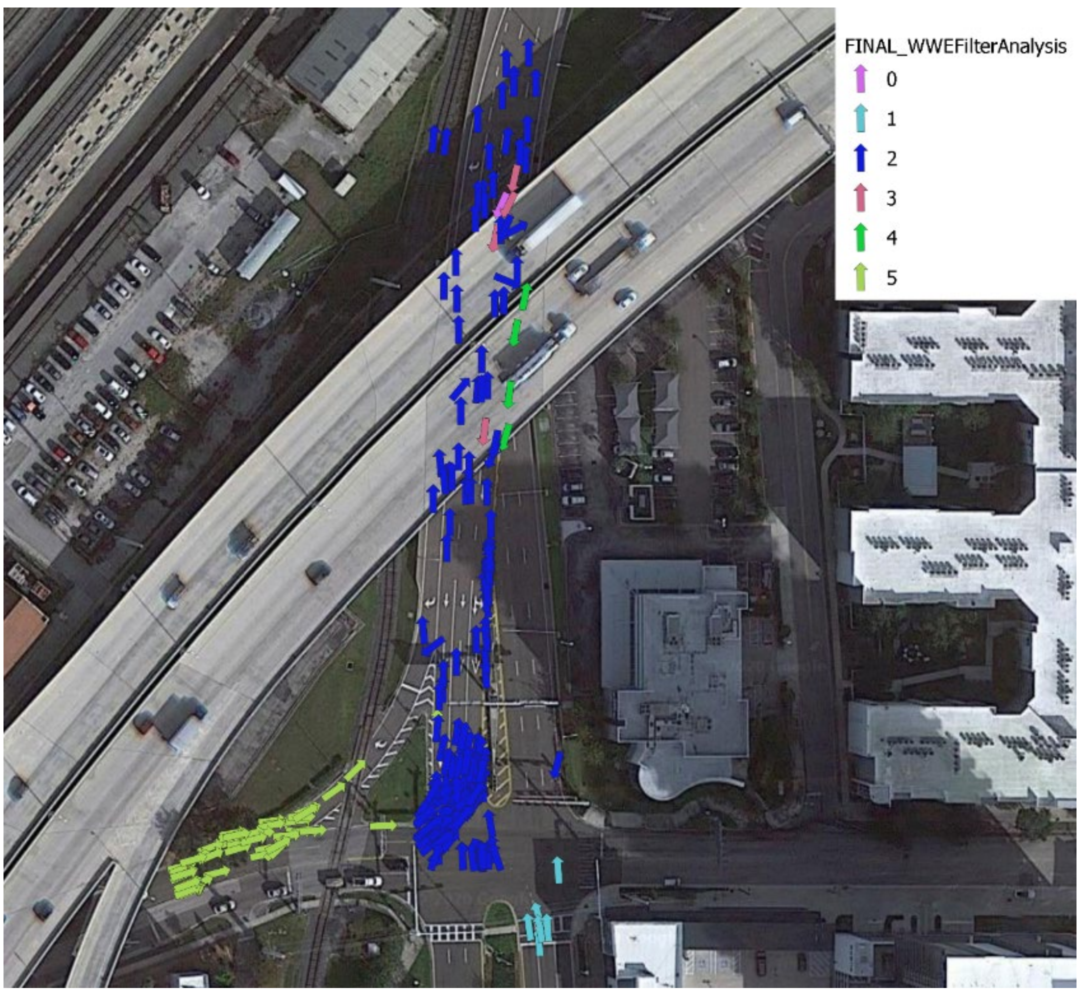

Figure 25. HV Direction of Motion Results from Manual WWE Alert Analysis

The Volpe team observed certain patterns during the manual assessment of HV trajectory in WWE alert events. Specifically, inaccuracies in GPS coordinates in the OBUs of HVs clearly caused the WWE application to issue a false-positive alert in many events. These WWE alerts were marked as having clear GPS offsets from the actual HV locations when examining the alerts and HV trajectories manually. One pattern involved HVs turning left onto the REL from East Twiggs Street, which were geo-located to northwest in the intersection of where they actually were. This inaccuracy increased the likelihood that the WWE application would issue an alert to the HV driver because the location and heading were measured as being toward the "Do Not Enter" lane. In reality, most of these vehicles were simply turning left onto the outbound lane of the REL, a legal maneuver. Another pattern involved vehicles entering downtown Tampa during morning commute hours. The WWE application issued a large number of alerts during these hours due to vehicle headings pointed directly north. Upon examining the actual HV trajectories and responses, it became clear that it was possible for vehicle headings to be reset to 0 degree in cases where the vehicle was stopped for a long period of time in the REL inbound lane. This happened often during morning commutes when there were large traffic jams and traffic queues for vehicles exiting the REL. The Volpe team counted 288 WWE alert events that had HV GPS offset when entering REL outbound, and 56 WWE alert events that had HVs with heading inaccuracy. Figure 26 depicts these results (1 and 2 codes refer respectively to GPS offset and heading inaccuracy, while code 0 indicates remaining alerts).

In summary, the Volpe team did not see any evidence of drivers altering their vehicle maneuver or travel path in response to the alert, based on vehicle trajectory and kinematics, in all 359 WWE alert events. Thus, the Volpe team was not able to assess the safety impact of the WWE application based on the alert events captured during the THEA CVP deployment.

Figure 26. Results of Manual WWE Alert Validity Analysis

4 VEHICLE EXPOSURE

This section derives and analyzes information regarding the exposure of equipped vehicles to other equipped vehicles (i.e., V2V interactions) and to equipped infrastructure locations (i.e., V2I interactions), which allows the safety applications to issue alerts to HVs as designed. This analysis addresses the driving conflict exposure ratio in Equation (1) that projects the crash avoidance effectiveness of the safety applications. This section computes V2V interactions in minutes and V2I interactions in crossing counts for each safety application, and estimates the alert rates[12] for the all-silent and all-active vehicle groups. Vehicles in the all-silent group only received silent alerts and vehicles in the all-active group only received active alerts throughout the duration of the deployment. The Volpe team did not use other vehicle groups in this analysis that had an alternating HMI status during the deployment period. This section also includes the results of the statistical analysis that compared these measures between all-silent and all-active groups. Appendix G provides the criteria that the Volpe team used to compute the exposure measures.

The Volpe team used the 10-Hz 'Received' BSM data from the THEA CVP deployment to quantify HV exposure to other OBU-equipped vehicles (i.e., V2V communication time) and to RSU-equipment roadside locations (i.e., crossing count). Figure 27 shows the total V2V interaction time (in minutes) per vehicle when equipped vehicles were in communication range, sorted by vehicle with the highest (1,273.2 minutes) to lowest (0.1 minute) communication time. A total of 484 equipped vehicles communicated with at least another vehicle, with a mean interaction time of 86.6 minutes and a standard deviation of 152.5 minutes.

[12] V2V alert rate = number of alerts / minutes of exposure; V2I alert rate = number of alerts / crossing counts

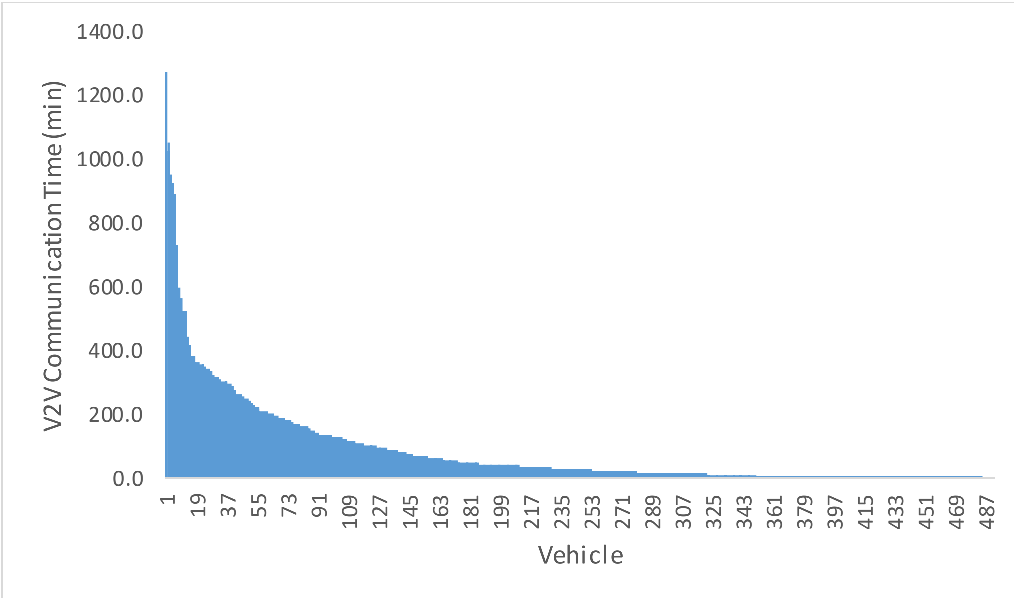

Figure 27. Overall V2V Communication Time per Vehicle

4.1 Vehicle-Vehicle and Vehicle-Infrastructure Interactions

Table 17 shows some descriptive statistics of V2V interactions in minutes for each of the four V2V safety applications, and displays the P value of the two-sample T-test for means assuming unequal variance comparing the performance of all-silent to all-active vehicle groups. As seen in Table 17, there was no statistically-significant difference (i.e., P > 0.05) between the all-silent and the all-active vehicle groups in terms of exposure.

Table 17. V2V Exposure (Minutes) Results by Safety Application

Statistical Parameter	**FCW**		**IMA**		**EEBL**		**VTRFTV**	
	All Silent	All Active	All Silent	All Active	All Silent	All Active	All Silent	All Active
Mean	2.99	3.67	2.18	2.19	10.15	11.38	1.54	1.17
Variance	14.77	21.18	7.34	7.16	147.18	154.74	20.41	9.39
No. of Vehicles	121	131	130	139	121	130	22	21
P(T ≤ t) two-tail	0.21		0.99		0.43		0.75	

Table 18 shows some descriptive statistics of V2I interactions in crossing counts for each of the three V2I safety applications, and displays the P value of the two-sample T-test for means assuming unequal variance comparing the performance of all-silent to all-active vehicle groups. As seen in Table 18, there was no statistically-significant difference (i.e., P > 0.05) between the all-silent and the all-active vehicle groups in terms of exposure to locations of V2I safety applications.

Table 18. V2I Exposure (Crossing Counts) Results by Safety Application

Statistical Parameter	PCW		ERDW		WWE	
	All Silent	All Active	All Silent	All Active	All Silent	All Active
Mean	14.05	11.40	36	37	69	66
Variance	713.65	323.24	1,059.7	1,222.0	2,975.68	3,354.56
No. of Vehicles	81	99	94	111	74	90
P(T ≤ t) two-tail	0.45		0.90		0.68	

4.2 Alert Rates by Exposure

The Volpe team determined the alert rates by exposure based on the number of observed valid V2V and V2I alerts, as described in Section 3, against the corresponding total exposure time (V2V) or total exposure crossing count (V2I) by vehicle reported for each alert type as appropriate. Table 18 provides some descriptive statistics of valid alert rates for the FCW and IMA V2V applications (i.e., number of valid alerts / minutes of exposure) and for the ERDW V2I application (i.e., number of valid alerts / number of crossings). This table also displays the P value of the two-sample T-test for means assuming unequal variance, comparing the performance of all-silent to all-active vehicle groups. The statistical analysis did not include the remaining EEBL and VTRFTV V2V safety applications and the remaining PCW and WWE V2I safety applications due to the very low count of valid alerts received by the two experimental groups.

The mean values in Table 19 quantify $EM_{without}$ for the all-silent group and EM_{with} for the all-active group, which estimate the driving conflict exposure ratio as expressed in Equations (1) and (2). These values clearly show that the all-active group experienced lower valid alert rates than the all-silent group, which would yield positive safety effectiveness for all three applications. However, there was no statistically-significant difference (i.e., $P > 0.05$) between the all-silent and the all-active vehicle groups in terms of alert rates by exposure based on the statistical test results in Table 19. As a result, the driving conflict exposure ratio parameter would be set to one (i.e., no effect).

Table 19. Valid Alert Rates by Exposure Results

Statistical Parameter	FCW*		IMA*		ERDW**	
	All Silent	All Active	All Silent	All Active	All Silent	All Active
Mean	1.43	1.08	2.28	0.49	0.20	0.17
Variance	5.40	3.05	38.80	0.33	0.11	0.03
No. of Vehicles	30	31	10	10	43	54
P(T ≤ t) two-tail	0.51		0.39		0.60	

*: Alert rate = number of alerts / minutes

**: Alert rate = number of alerts / crossings

5 CONCLUSIONS

The Volpe team assessed the safety impact of four V2V and three V2I safety applications that THEA deployed on 806 passenger vehicles and 17 transit vehicles in Tampa, as part of the U.S. DOT CVP program. This assessment was based on naturalistic driving data that were collected at the vehicle level from the deployed vehicles, with their HMI turned on or off during a limited time or throughout the deployment period. The Volpe team analyzed the data with dates ranging from March 1, 2019 until June 30, 2020, which THEA has posted on the SDC. A total of 503 equipped vehicles, or about 61 percent of all deployed vehicles, did not have any alert events, including the 10 transit busses deployed by THEA. No alerts were reported in the dataset from the transit busses during the deployment, so they were not included in this analysis. The Volpe team was unable to determine if vehicles that did not receive any alerts belonged to the silent or active group, because this information was stored in event records and not in BSM records. As these vehicles did not record any event records, the data fields that would indicate the experimental group to which the vehicles belonged to were unavailable for the 503 vehicles that received no alerts during the deployment. The remaining 320 equipped vehicles received 8,073 total alert events from the seven safety applications combined. There were 508 V2V alert events (about 6% of all alerts) and 7,565 V2I alert events (about 94% of all alerts). The V2I WWE application alone generated 6,297 alerts or about 78% of all alert events.

The first step of the safety impact assessment was to determine the validity of all alert events received during the 16-month deployment period. From the start, the Volpe team was not able to determine the validity of 765 alert events (about 9% of all alert events) due to missing BSM data. As a result, the Volpe team examined the validity of 453 V2V and 6,855 V2I alert events. There were 137 valid V2V alert events (about 30% of all 453 V2V alerts), broken down by each application as follows:

- FCW: 85 valid alerts (33% of all 259 alerts)
- EEBL: 15 valid alerts (94% of all 16 alerts)
- IMA: 28 valid alerts (21% of all 133 alerts)
- VTRFTV: nine valid alerts (20% of all 45 alerts)

Considerable improvement in the validity of V2V alerts might occur with better accounting of relative elevation and relative heading between the HV and RV. The validity assessment of the three V2I safety applications determined that 992 V2I alerts (14% of all 6,855 V2I alerts) could potentially be valid:

- PCW: five valid alerts (56% of all 9 alerts)
- ERDW: 628 potentially valid alerts (51% of all 1,232 alerts)
- WWE: 359 potentially valid alerts (6% of all 5,614 alerts)

The validity of V2I alerts might improve with more accurate relative positioning, relative heading, and travel path prediction of the HV. It is noteworthy that THEA has deployed three novel V2I safety applications in a challenging driving environment (i.e., under and over pass roadways). The results of this deployment would certainly provide to THEA alternative solutions to improve the technical performance of these applications.

The second step of the safety impact assessment involved the determination of a potential driving hazard in valid alert events. This determination was based on TTC or TTI at alert onset and on observed vehicle response after alert onset. Some alert event files did not contain any data on brake pedal activation, which hindered the analysis for these events. There were 128 hazard V2V alert events (about 93% of all 137 valid V2V alerts), broken down by each application as follows:

- FCW: 78 hazard alerts (92% of all 85 valid alerts)
- EEBL: 13 hazard alerts 87% of all 15 valid alerts)
- IMA: 28 hazard alerts (100% of all 28 valid alerts)
- VTRFTV: nine hazard alerts (100% of all 9 valid alerts)

The FCW and EEBL applications issued an alert too early in a few alert events. For the PCW and ERDW V2I applications, the Volpe team determined that one valid PCW alert event and 584 valid ERDW alert events (excluding 9 events without HMI information and 35 consecutive events from a total of 628 events) were potentially hazardous. This was not the case for all 359 WWE alert events, as the Volpe team did not see any evidence of drivers altering their vehicle maneuver or travel path after alert onset based on vehicle trajectory and kinematics.

The third step of the safety impact assessment separated hazardous alert events between silent and active alerts for each application. The fourth step matched groups of silent and active alert events by similar initial conditions at alert onset. As a result, only the V2V FCW and V2I ERDW applications had sufficient numbers of alert events in silent and active modes (≥ 8 alert events in each mode) in order to perform a statistical comparison of driver/vehicle response between the two modes. There were 36 silent and 27 active matched FCW alerts, and 232 silent and 352 active ERDW alerts. Using various performance measures, the Volpe team did not find any statistically-significant difference in driver/vehicle response after alert onset between silent and active alert events.

The Volpe team also analyzed valid alert rates for the FCW and IMA applications (i.e., number of valid alerts / minutes of exposure) and for the ERDW application (i.e., number of valid alerts / number of crossings), and statistically compared these rates between all-silent and all-active vehicle groups. This statistical analysis did not include the EEBL, VTRFTV, PCW, and WWE applications due to the very low count of valid alerts received by the two vehicle groups. The Volpe team did not find any statistically-significant difference in valid FCW, IMA, and ERDW alert rates between all-silent and all-active vehicle groups.

Finally, the Volpe team was not able to estimate the crash avoidance effectiveness of EEBL, IMA, VTRFTV, PCW, and WWE due to insufficient valid alert events in silent and active alert groups. Moreover, the Volpe team did not observe any statistically-significant effect on driver/vehicle performance in response to FCW and ERDW applications because truly hazardous alert events were rare during the THEA CVP deployment period.

6 REFERENCES

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Appendix A. Description of THEA CVP Safety Applications

Table 20. V2V Safety Applications – Functions, Alert Criteria, and Visual Displays

Application	Function and Alert Criteria	Visual Display
FCW	Warns the HV driver of a slower or stopped RV ahead in the same lane if the HV is within pre-specified time and distance behind the RV. Minimum operating speed is 10 m/s (22.4 mph).	
EEBL	Warns the HV driver of heavy braking (≥ 4 m/s^2) by an RV traveling in the same or adjacent lane ahead. There is no minimum speed of the HV to issue this alert.	
IMA*	Warns both drivers when RV and HV are on a collision course, approaching the intersection from lateral directions. Minimum operating speed of HV is 1 m/s (2.2 mph) and of RV is 10 m/s (22.4 mph). RV is considered a crash threat if it is on a perpendicular heading of ±15 degree delta heading with the HV.	
VTRFTV	Warns streetcar operator and HV driver if they are on a collision course approaching same intersection, and HV intending to make a right turn across the streetcar tracks. When the HV turns on its right-turn signal, driver receives a "Streetcar" pre-warning and streetcar operator receives "Vehicle on Track" pre-warning. When the HV begins the right turn in front of the streetcar, driver receives a "Streetcar" warning and the streetcar operator receives "Vehicle on Track" warning. Minimum operating speed of the streetcar is 1 m/s (2.2 mph) and of the HV is 2 m/s (4.5 mph).	"Streetcar" Warning  "Vehicle on Track" Warning 

*: IMA will also issue a warning to both vehicles if one vehicle is attempting to turn left at an intersection across the path of another oncoming vehicle from the opposite direction.

Table 21. V2I Safety Applications – Functions, Alert Criteria, and Visual Displays

Application	Function and Alert Criteria	Visual Display
PCW	Warns HV driver about the presence of pedestrians in a crosswalk. LiDAR units, installed at each end of the crosswalk, identify pedestrians within the defined area of the crosswalk and measure their location, heading, and speed. LiDAR creates and sends a message containing this information to the RSU near the crosswalk, which broadcasts the message to oncoming HV. If PCW determines the HV and pedestrian are on a collision course, it will trigger an audiovisual alert within the HV displaying in rearview mirror a symbol depicting a pedestrian in a crosswalk and a warning symbol. Alert is issued at any HV travel speed and only applies to designated mid-block crosswalk for pedestrian access to and from the main parking garage at George E. Edgecomb Hillsborough County Courthouse in downtown Tampa.	 
ERDW	Provides speed advice to HVs based on longest queue length of any lane, which are approaching or are in the curve leading to REL exit. RSU calculates queue length of each lane and determines longest queue and safe stopping distance from the end of this queue to the physical curve speed limit sign. Using a lookup, RSU determines and broadcasts to HVs recommended speed advice based on calculated distance. Within range of RSU, HV receives recommended speed advice, calculates specific speed advice based on vehicle type, and displays it to HV driver regardless of HV travel speed.	
WWE	Issues DO NOT ENTER warning to HV driver if WWE determines that the HV is advancing to enter the REL going the wrong way.	
	Issues WRONG WAY warning to HV driver if WWE determines the HV has continued up the REL the wrong way.	
	Issues WRONG WAY VEHICLE warning to the legal inbound driver after the wrong way violation occurs.	
	Issues NO TRAVEL LANE warning to HV driver if HV enters the Outbound or Inbound closed section of REL.[13]	

[13] REL scheduled times and diagram details are available at https://www.tampa-xway.com/reversible-express-lanes/

Appendix B. Safety Impact Database Structure

Connected Vehicle Pilot

Database Structure - Tampa (THEA)

Last Updated: 04/28/2020

VOLPE- THEA DATA STRUCTURE

Volpe_Thea_SentBsm	DataType	Units	Source
HostVehID	Varchar	PK	DOT
HV_ID	int		DOT
Time	Datetime	PK	DOT
Latitude	float	deg	DOT
Longitude	float	deg	DOT
Elevation	int	m	DOT
Transmission	varchar		DOT
Speed	float	m/s	DOT
Heading	int	deg	DOT
WheelAngle	float	deg	DOT
Ax	float	m/s^2	DOT
Ay	float	m/s^2	DOT
Az	float	m/s^2	DOT
Yaw	float	deg/s	DOT
Brake	tinyint		DOT
Width	float	m	DOT
Length	float	m	DOT

Volpe_Thea_ReceivedBsm	DataType	Units	Source
HostVehID	Varchar	PK	DOT
RV_ID	int	PK	DOT
Time	Datetime	PK	DOT
Latitude	float	deg	DOT
Longitude	float	deg	DOT
Elevation	int	m	DOT
Transmission	varchar		DOT
Speed	float	m/s	DOT
Heading	int	deg	DOT
WheelAngle	float	deg	DOT
Ax	float	m/s^2	DOT
Ay	float	m/s^2	DOT
Az	float	m/s^2	DOT
Yaw	float	deg/s	DOT
Brake	tinyint		DOT
Width	float	m	DOT
Length	float	m	DOT

Volpe_Thea_ReceivedSpat	DataType	Units	Source
HostVehID	Varchar	PK	DOT
Time	Datetime	PK	DOT
MessageID	int		DOT
IntersectionID	bigint		DOT
IntersectionRevision	int		DOT
IntersectionStatus	int		DOT

Volpe_Thea_ReceivedMap	DataType	Units	Source
HostVehID	varchar	PK	DOT
Time	datetime	PK	DOT
LayerID	tinyint		DOT
IntersectionID	int		DOT
Latidute	float	deg	DOT
Longitude	float	deg	DOT
Lanewidth	float	m	DOT

Volpe_Thea_ReceivedPsm	DataType	Units	Source
HostVehId	varchar	PK	DOT
Time	datetime	PK	DOT
Ped_ID	int	PK	DOT
Latitude	float	deg	DOT
Longitude	float	deg	DOT
Speed	float	m/s	DOT
Heading	int	deg	DOT
PathPredictCurve	int	m	DOT
PathPredictConf	int	%	DOT

Volpe_Thea_SentSrm	DataType	Units	Source
HostVehId	varchar	PK	DOT
Time	datetime	PK	DOT
SequenceNo	bigint		DOT
RequestID	bigint		DOT
RequestType	varchar		DOT
RequestInboundLane	bigint		DOT
RequestOutboundLane	bigint		DOT
RequestMininute	bigint		DOT
RequestSecond	bigint		DOT
RequestDuration	bigint		DOT
RequestorEntityID	bigint		DOT
RequestorTypeRole	varchar		DOT
RequestorTypeRequest	varchar		DOT
RequestorPositionLatitude	bigint	deg	DOT
RequestorPositionLongitude	bigint	deg	DOT
RequestorPositionHeading	bigint	deg	DOT
RequestorPositionElevation	bigint	m	DOT

Volpe_Thea_Veh_Kinematics	DataType	Units	Source
HostVehID	Varchar	PK	DOT
RV_ID	Varchar	PK	DOT
Time	Datetime	PK	DOT
Range	Float	m	VOLPE
RangeRate	Float	m/s	VOLPE
TTC	Float	s	VOLPE
LongRange	Float	m	VOLPE

Volpe_Thea_All_Warning	DataType	Units	Source
EventID	Int		VOLPE
HostVehID	Varchar	PK	DOT
HV_ID	Bigint		DOT
StartTime	Datetime	PK	DOT
RV_ID	Varchar	PK	DOT
ParticipantGroup	Varchar		VOLPE
WarningType	Varchar		VOLPE

Volpe_Thea_Veh_Event_Kinematics	DataType	Units	Source
EventID	Int		VOLPE
HostVehID	Varchar	PK	DOT
RV_ID	Varchar	PK	DOT
Time	Datetime	PK	DOT
WarningType	Varchar		DOT
Range	Float	m	VOLPE
RangeRate	Float	m/s	VOLPE

LatRange	Float	m	VOLPE
RV_RelLongLocation	Varchar		VOLPE
RV_RelLatLocation	Varchar		VOLPE
RV_ApplicationLocation	Varchar		VOLPE
HV_TTI	Float	s	VOLPE
RV_TTI	Float	s	VOLPE
HV_TTI_Dist2X	Float	s	VOLPE
RV_TTI_Dist2X	Float	s	VOLPE
Distance	Float	m	VOLPE
TTPOI	Float	s	VOLPE

LocalTime	Datetime		VOLPE
Latitude	Float	deg	DOT
Longitude	Float	deg	DOT
RV_Latitude	Float	deg	DOT
RV_Longitude	Float	deg	DOT
DriverWarn	Tinyint		DOT
IsControl	Tinyint		DOT
IsDisabled	Tinyint		DOT

TTC	Float	s	VOLPE
LongRange	Float	m	VOLPE
LatRange	Float	m	VOLPE
RV_RelLongLocation	Varchar		VOLPE
RV_RelLatLocation	Varchar		VOLPE
RV_ApplicationLocation	Varchar		VOLPE
HV_TTI	Float	s	VOLPE
RV_TTI	Float	s	VOLPE
HV_TTI_Dist2X	Float	s	VOLPE
RV_TTI_Dist2X	Float	s	VOLPE
Distance	Float	m	VOLPE
TTPOI	Float	s	VOLPE

Volpe_Thea_Veh_ImaLogger	DataType	Units	Source
EventID	int	PK	VOLPE
WarningType	varchar	PK	VOLPE
BsmData_Available	tinyint		VOLPE
HV_onCollisionPath	tinyint		VOLPE
PreCrashScenario	tinyint		VOLPE
HV_Maneuver	tinyint		VOLPE
HV_Position	tinyint		VOLPE
RV_Maneuver	tinyint		VOLPE
RV_Location	tinyint		VOLPE
Comment	varchar		VOLPE
Staff	varchar		VOLPE

Volpe_Thea_Veh_FcwLogger	DataType	Units	Source
EventID	int	PK	VOLPE
WarningType	varchar	PK	VOLPE
BsmData_Available	tinyint		VOLPE
HV_onCollisionPath	tinyint		VOLPE
PreCrashScenario	tinyint		VOLPE
HV_Maneuver	tinyint		VOLPE
HV_RoadPosition	tinyint		VOLPE
RV_RelativeLocation	tinyint		VOLPE
RV_Maneuver	tinyint		VOLPE
RV_RoadPosition	tinyint		VOLPE
SteeringResponse?	tinyint		VOLPE
Comment	varchar		VOLPE
Staff	varchar		VOLPE

Volpe_Thea_Veh_EeblLogger	DataType	Units	Source
EventID	int	PK	VOLPE
WarningType	varchar	PK	VOLPE
BsmData_Available	tinyint		VOLPE
HV_onCollisionPath	tinyint		VOLPE
PreCrashScenario	tinyint		VOLPE
HV_Maneuver	tinyint		VOLPE
HV_RoadPosition	tinyint		VOLPE
RV_RelativeLocation	tinyint		VOLPE
RV_Maneuver	tinyint		VOLPE
RV_RoadPosition	tinyint		VOLPE
SteeringResponse?	tinyint		VOLPE
Comment	varchar		VOLPE
Staff	varchar		VOLPE

Volpe_Thea_Veh_ImaLogger	DataType	Units	Source
EventID	int	PK	VOLPE
WarningType	varchar	PK	VOLPE
BsmData_Available	tinyint		VOLPE
HV_onCollisionPath	tinyint		VOLPE
PreCrashScenario	tinyint		VOLPE
HV_Maneuver	tinyint		VOLPE
RV_Maneuver	tinyint		VOLPE
TTI?	tinyint		VOLPE
Comment	varchar		VOLPE
Staff	varchar		VOLPE

Volpe_Thea_Veh_PcwLogger	DataType	Units	Source
EventID	int	PK	VOLPE
WarningType	varchar	PK	VOLPE
BsmData_Available	tinyint		VOLPE
HV_onCollisionPath	tinyint		VOLPE
PreCrashScenario	tinyint		VOLPE
HV_Maneuver	tinyint		VOLPE
Comment	varchar		VOLPE
Staff	varchar		VOLPE

Volpe_Thea_Veh_WweLogger	DataType	Units	Source
EventID	int	PK	VOLPE
WarningType	varchar	PK	VOLPE
BsmData_Available	tinyint		VOLPE
HV_onCollisionPath	tinyint		VOLPE
PreCrashScenario	tinyint		VOLPE
HV_Maneuver	tinyint		VOLPE
HV_Position	tinyint		VOLPE
Comment	varchar		VOLPE
Staff	varchar		VOLPE

Appendix C. Event Visualization Tool

The Volpe team developed an event visualization tool that animated the motion of HV and RV using their instantaneous locations before and after an alert event, overlaid on a satellite image map. The development of this tool involved two stages:

1. Develop the ability to perform queries on Volpe's database through a Python connection.
2. Present the results of this query on a web-based interface that allows the user to choose a specific event from a list of indexed alert events and view a controllable animation of the motion of vehicle(s) involved in that event.

Python Backend

The python program serves as the backend of the event visualization tool. This program runs in an anaconda environment that has the following python libraries installed:

1. Flask: a server implementation engine in python that provides HTTP communication functionalities.
2. Pandas: a data manipulation and analysis engine for python, which provides access to dataframe functionality that makes working with large datasets simpler and more efficient.
3. SQLAlchemy: a SQL server connection and query interface that allows for communication between the Python program and the SQL server housing the CVP data.

The python backend implements a number of functions that are made accessible through an HTTP server that is created using the flask application. The functions in this backend rely on a configuration file that stores specific information about the data in the database specific to the CVP site being analyzed. Storing this information in a configuration file, instead of using this information directly in the backend codes of the event visualization tool, makes it easier to make adjustments and makes it useful for all of the CVP pilot sites, instead of just one.

The functions accessible via the HTTP server in the python backend are detailed below:

1. Home ("/"): the Home directory path returns the main HTML page for the visualization tool.
2. Get_site_info: returns the configuration file in a JSON formatted string of data relevant to the information on all sites.
3. Get_events (site_name, event_type): returns all of the warning ID strings for the specified CVP site and the specified type of event. Return format is a JSON data string.
4. Get_event_data (site_name, event_type, event_id): returns the location data for all vehicles relevant to the specified event ID for the specified event type at the specified CVP site. Return format is a JSON data array containing data retrieved from the database for latitude and longitude locations for all vehicles.
5. From_sql (query): returns the results directly from the Volpe SQL server based on the query passed to the function.

Web Browser-Based User Interface

The tool's user interface is written using HTML and JavaScript, which is accessed through a web browser after the python backend program is run. Figure 28 displays the web interface.

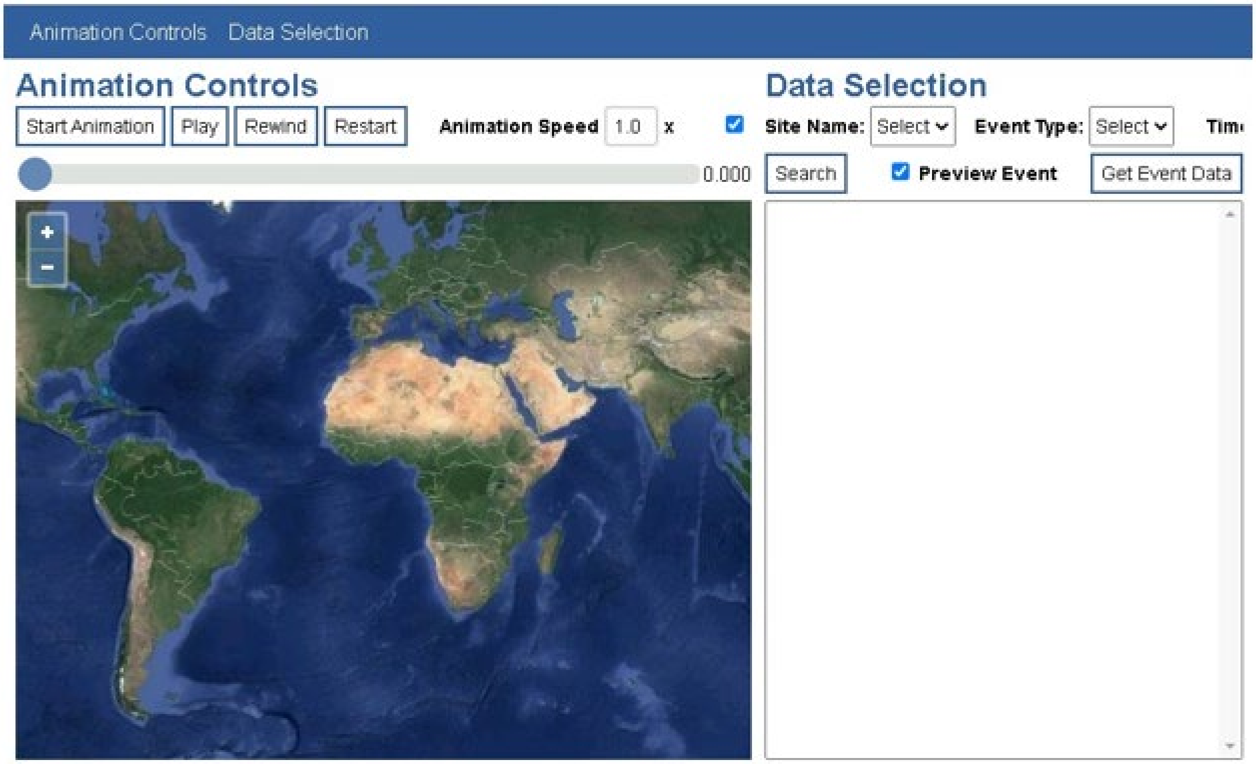


Figure 28. Event Visualization Tool's User Interface

As seen in Figure 28, there are two key controls in the user interface:

1. "Data Selection" controls allow users to choose the CVP site from which they would like to visualize events and specify the exact event type that they would like to analyze. After site and event types are specified using the dropdown boxes, users can scroll through the resulting list of events to select one to animate on the map (left side of the screen). There is also a search functionality built into the tool that allows users to search for a specific vehicle ID, date, and time. Once an event is chosen (right side of the screen), the "Get Event Data" button can be used to return the relevant data from the SQL database for that specific event. As shown in Figure 29, the tool provides a preview of the vehicles' paths overlaid on the satellite map background.
2. "Animation Controls" enable users to start, pause, play, rewind, or restart the animation. Users can also control the animation speed by modifying the Animation Speed input above the map.

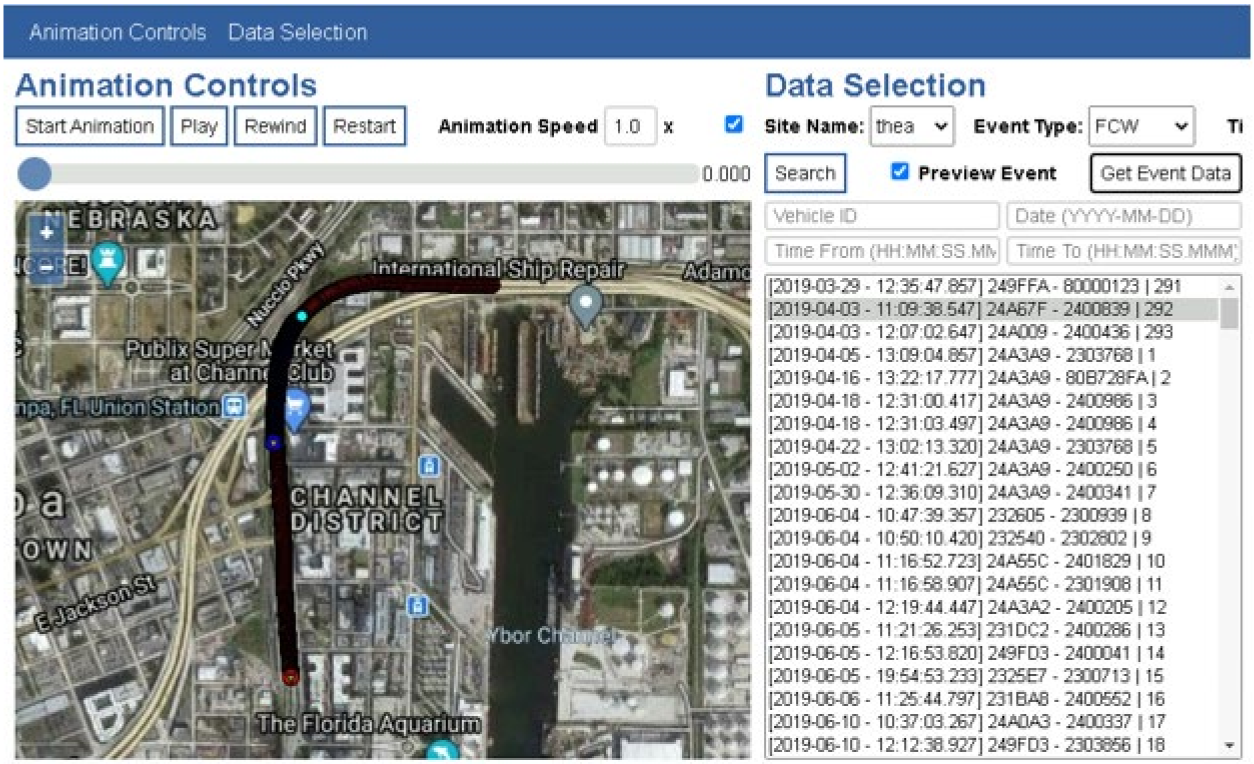


Figure 29. Event Visualization Tool Showing Vehicle Data of FCW Alert Number 292

Appendix D. Relative Position Data Processing

The Volpe team calculated different vehicle kinematic parameters from the sent and received BSM data to conduct the safety evaluation for THEA CVP safety applications, as listed in Table 22. This table also indicates whether each data element is provided as part of the BSM data or needs to be calculated from the BSM data. Each of the calculated parameters in Table 22 has a corresponding equation number or section provided in this appendix.

Table 22. THEA CVP Vehicle Kinematic Data Needs

Data Need	Provided in BSM	Calculated	Equation # or Section
Date/Time	X		
Latitude	X		
Longitude	X		
Heading	X		
Speed	X		
Longitudinal Acceleration	X		
Lateral Acceleration	X		
Range		X	D1
Range Rate		X	D2
Time-To-Collision (TTC)		X	D3
Longitudinal Range		X	D4
Latitudinal Range		X	D5
Relative RV location (Front, back, side)		X	Relative Latitudinal and Longitudinal Positions
Relative RV lane position (in lane, adjacent)		X	RV Precise Relative Location
Time-To-Intersection (TTI) (for perpendicularly approaching vehicles)		X	D6 – D9
Relative Distance to Point of Interest (e.g., crosswalk or intersection)		X	D10

Time To Point of Interest		X	D11

Range

Equation (D1) calculates the distance between two vehicles based on their GPS coordinates:

$$Range = \sqrt{\mathrm{NorthOffset}^2 + \mathrm{EastOffset}^2} \quad \text{(D1)}$$

Where:

- NorthOffset = Northing_RV - Northing_HV
- EastOffset = Easting_RV - Easting_HV

Range Rate

Equation (D2) calculates the change in range between two vehicles over time, also known as closing speed:

$$RangeRate = \frac{ScaledDRange}{dT} \text{ (D2)}$$

Where:

- ScaledDRange = 0.65 × [Range(i) - Range(i-1)] + 0.25 × [Range(i-1) - Range(i-2)] + 0.1 × [Range(i-2) - Range(i-3)]
- dT is the time difference between data points
- i is an individual time-series record of the value range

Time-to-Collision (TTC)

Equation (D3) calculates the number of seconds until a vehicle comes into contact with another vehicle, based on the current vehicle kinematics:

$$TTC = \frac{Range}{|RangeRate|} \text{ (D3)}$$

Where RangeRate < 0

Longitudinal and Latitudinal Ranges

Equation (D4) computes the longitudinal range, relative to vehicle heading and the center point of the vehicle:

$$LongRange = \sqrt{\mathrm{x}^2 + \mathrm{y}^2} \text{ (D4)}$$

$$LongRange = NorthOffset\ WHEN\ HV\_Heading = 0\ OR\ 180 \text{ (D4a)}$$

$$LongRange = EastOffset\ WHEN\ HV\_Heading = 90\ OR\ 270 \text{ (D4b)}$$

Where:

- $x = \frac{b}{(HVSlope - RVSlope)}$
- $y = HVSlope \times x$

And where:

- *HVSlope* is computed as follows:
  - If 0 < HV_Heading < 90 then HVSlope = Tan[Deg2Rad × (90 - HV_Heading)]
  - If 90 < HV_Heading < 180 then HVSlope = 0 – Tan[Deg2Rad × (HV_Heading - 90)]
  - If 180 < HV_Heading < 270 then HVSlope = Tan[Deg2Rad × (270 - HV_Heading)]
  - If 270 < HV_Heading < 360 then HVSlope = 0 – Tan[Deg2Rad × (HV_Heading - 270)]
- $RVSlope = -\frac{1}{HVSlope}$
- $b = NorthOffset + \frac{EastOffset}{HVSlope}$

Equation (D5) computes the vertical range, relative to vehicle heading and the center point of the vehicle:

$$LatRange = \sqrt{\text{Range}^2 - \text{LongRange}^2} \quad \text{(D5)}$$

$$LatRange = EastOffset\ WHEN\ HV\_Heading = 0\ OR\ 180\ \text{(D5a)}$$

$$LatRange = NorthOffset\ WHEN\ HV\_Heading = 90\ OR\ 270\ \text{(D5b)}$$

Figure 30 illustrates the longitudinal and latitudinal ranges.

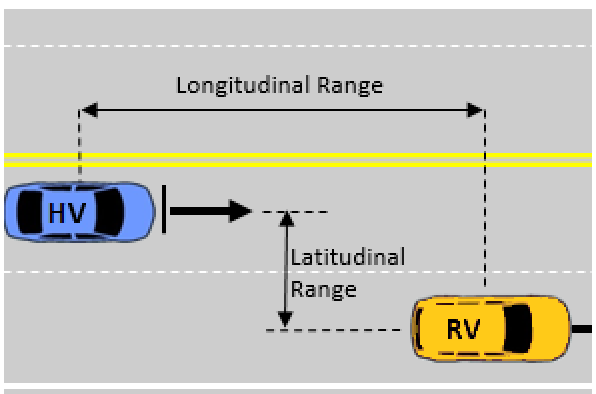


Figure 30. Schematic Illustrating Latitudinal and Longitudinal Ranges

Adjusts longitudinal and latitude offset for RV being to left/right or front/back of HV:

```
If 0 < HVHeading < 90 Then
   If y < 0 Then
      LongRange = -1 × LongRange
   End If
   If NorthOffset > y Then
      LatRange = -1 × LatRange
   End If
ElseIf 90 < HVHeading < 180 Then
   If y > 0 Then
      LongRange = -1 × LongRange
   End If
   If NorthOffset > y Then
```

```
      LatRange = -1 × LatRange
    End If
  ElseIf 180 < HVHeading < 270 Then
    If y > 0 Then
      LongRange = -1 × LongRange
    End If
    If NorthOffset < y Then
      LatRange = -1 × LatRange
    End If
  ElseIf 270 < HVHeading < 360 Then
    If y < 0 Then
      LongRange = -1 × LongRange
    End If
    If NorthOffset < y Then
      LatRange = -1 × LatRange
    End If
  End If
```

Relative Latitudinal and Longitudinal Positions

The relative location/position between two equipped vehicles is determined as follows:

- RV_RelativeLongLocation:
  - Behind = LongRange < minLongThreshold
  - Side = minLongThreshold ≤ LongRange ≤ maxLongThreshold
  - Front = maxLongThreshold < LongRange

Where: (*assuming GPS antenna is located at the center of a vehicle or truck; if truck with trailer, add trailer length*)

minLongThreshold = - (0.5 × HV_carlength + 0.5× RV_carlength)

maxLongThreshold = (0.5× HV_carlength + 0.5 × RV_carlength)

The three possible outputs of Relative Longitudinal Location are illustrated in Figure 31.

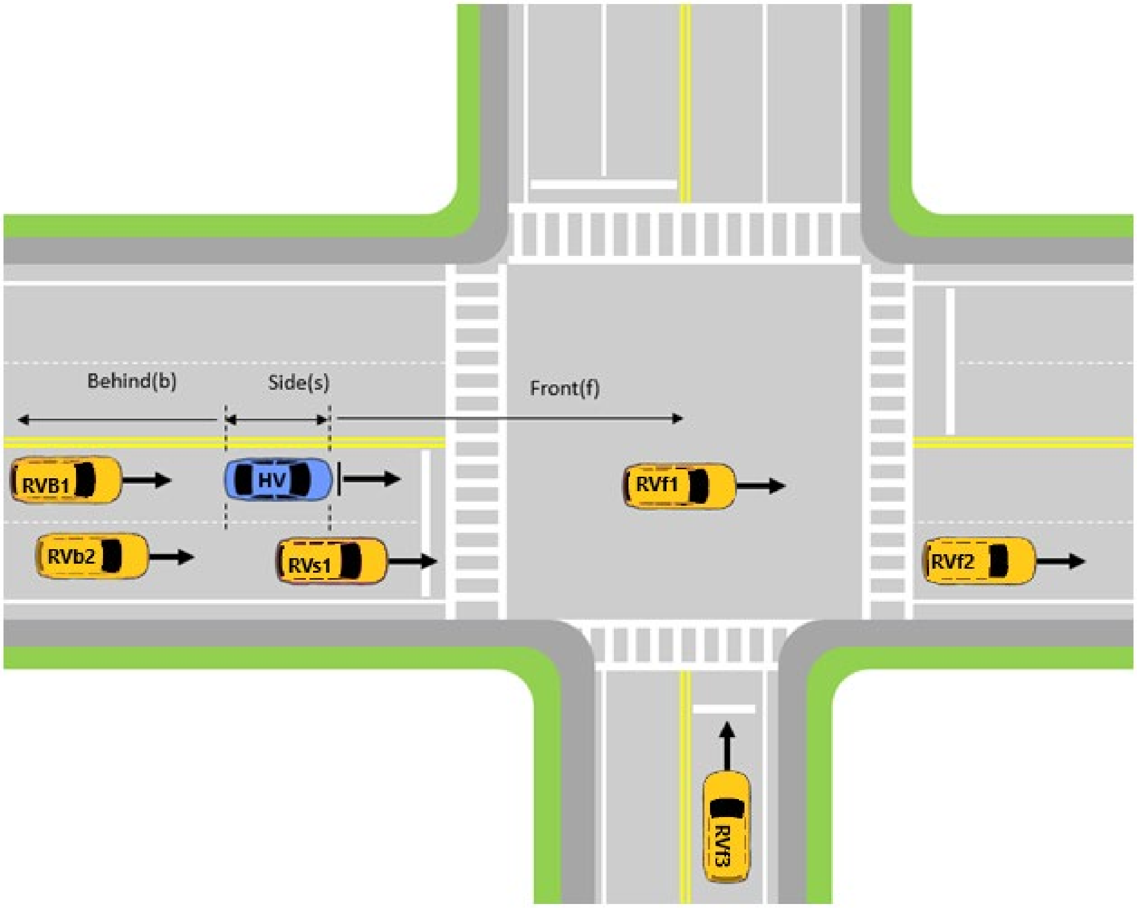


Figure 31. Schematic Illustrating Relative Longitudinal Location

- RV_RelativeLatLocation:
  - Left = LatRange < minLatThreshold
  - Center = minLatThreshold ≤ LatRange ≤ maxLatThreshold
  - Right = maxLatThreshold < LatRange

Where: (*assuming GPS antenna is located at the center of a vehicle or truck; if truck with trailer, add trailer length*)

- *minLatThreshold = - (0.5× HV_carwidth + 0.5 × RV_carwidth + 0.15)*
- *maxLatThreshold = (0.5× HV_carwidth + 0.5 × RV_carwidth + 0.15)*

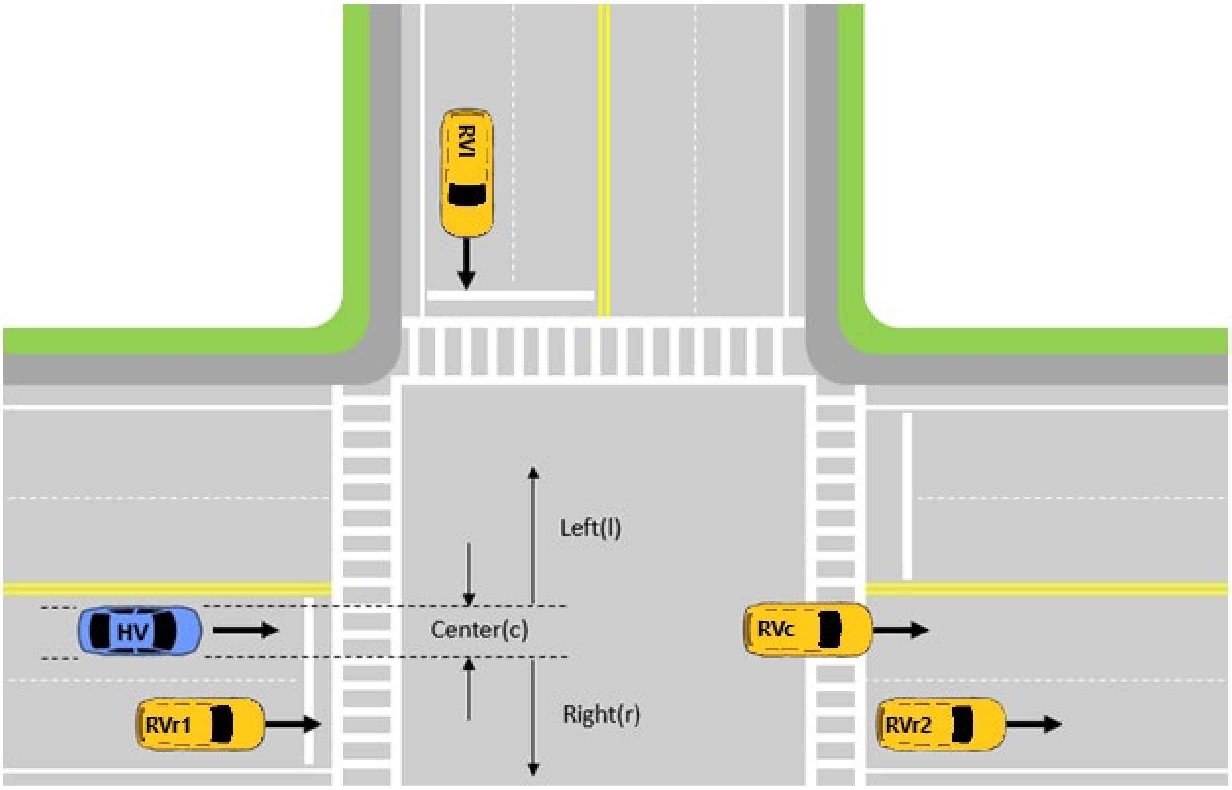


Figure 32. Schematic Illustrating Relative Latitudinal Location

RV Precise Relative Location

The following determines the lane-level positioning, applied to specific driving scenarios, to confirm the appropriateness of warnings:

- FCW/EEBL (in-path target)
  - |HV_heading – RV_heading| < 10 deg AND
    RV_RelativeLongLocation = 'Front' AND
    RV_RelativeLatLocation = 'Center'

- IMA (intersecting left and right)
  - RV_RelativeLongLocation = 'Front' AND
    - RV_RelativeLatLocation = LEFT:
      - (0 ≤ HV_Heading ≤ 60) AND (HV_Heading + 60 ≤ RV_Heading ≤ HV_Heading + 120) OR
      - (HV_Heading > 60 AND HV_Heading < 120) AND (HV_Heading + 60 ≤ RV_Heading ≤ HV_Heading + 120) OR
      - (120 ≤ HV_Heading ≤ 240) AND (HV_Heading + 60 ≤ RV_Heading ≤ HV_Heading + 120) OR
      - (HV_Heading > 240 AND HV_Heading < 300)
        AND (HV_Heading + 60 ≤ RV_Heading ≤ 360 OR HV_Heading-HV_Heading ≤ RV_Heading ≤ HV_Heading -270 + 30) OR
      - (300 ≤ HV_Heading ≤ 360) AND (HV_Heading+60-360 ≤ RV_Heading ≤ HV_Heading+120-360)

- RV_RelativeLatLocation = RIGHT
  - (0 ≤ HV_Heading ≤ 60) AND (HV_Heading-120+360 ≤ RV_Heading ≤ HV_Heading-60+360) OR
  - (HV_Heading > 60 AND HV_Heading < 120) AND (HV_Heading-120+360 ≤ RV_Heading ≤ 360 OR HV_Heading-HV_Heading < RV_Heading ≤ HV_Heading-90+30) OR
  - (120 ≤ HV_Heading ≤ 240) AND (HV_Heading-120 ≤ RV_Heading ≤ HV_Heading-60) OR
  - (HV_Heading > 240 AND HV_Heading < 300) AND (HV_Heading-120 ≤ RV_Heading ≤ HV_Heading-60) OR
  - (300 ≤ HV_Heading ≤ 360) AND (HV_Heading-120 ≤ RV_Heading ≤ HV_Heading-60)

- VTRFT (Blind-spot zone)
  - RV_RelativeLongLocation IN('Beside', 'Behind')
    AND – (3 + 0.5 × HV_carlength) < LongRange < 0

    AND |HV_heading – RV_heading| < 6 deg

    AND 3.2m ≤ |LatRange – (0.5 × HV_carwidth + 0.5 × RV_carwidth)|

    3.0m ≤ |LongRange – (0.5 × HV_carlength + 0.5 × RV_carlength)|

HV Time-To-Intersection (TTI) Based on Latitude and Longitudinal Ranges

Equation (D6) determines the number of seconds until the HV reaches the intersection point with the RV, based on current vehicle dynamics. This equation is used when vehicle headings are roughly perpendicular to each other. To use this equation, the GPS location of the intersection point does not need to be known.

$$TTI\_HV\_Perpendicular = \frac{LongRange}{Speed\_HV} \quad \text{(D6)}$$

RV TTI Based on Latitude and Longitudinal Ranges

Equation (D7) determines the number of seconds until the RV reaches the intersection point with the HV, based on current vehicle dynamics. This equation is used when vehicle headings are roughly perpendicular to each other. To use this equation, the GPS location of the intersection point does not need to be known.

$$TTI\_RV\_Perpendicular = \frac{LatRange}{Speed\_RV} \quad \text{(D7)}$$

Figure 40 illustrates the scenario where the HV and RV TTI equations are used. In this scenario, the intersection point is calculated based on the current trajectories of the vehicles.

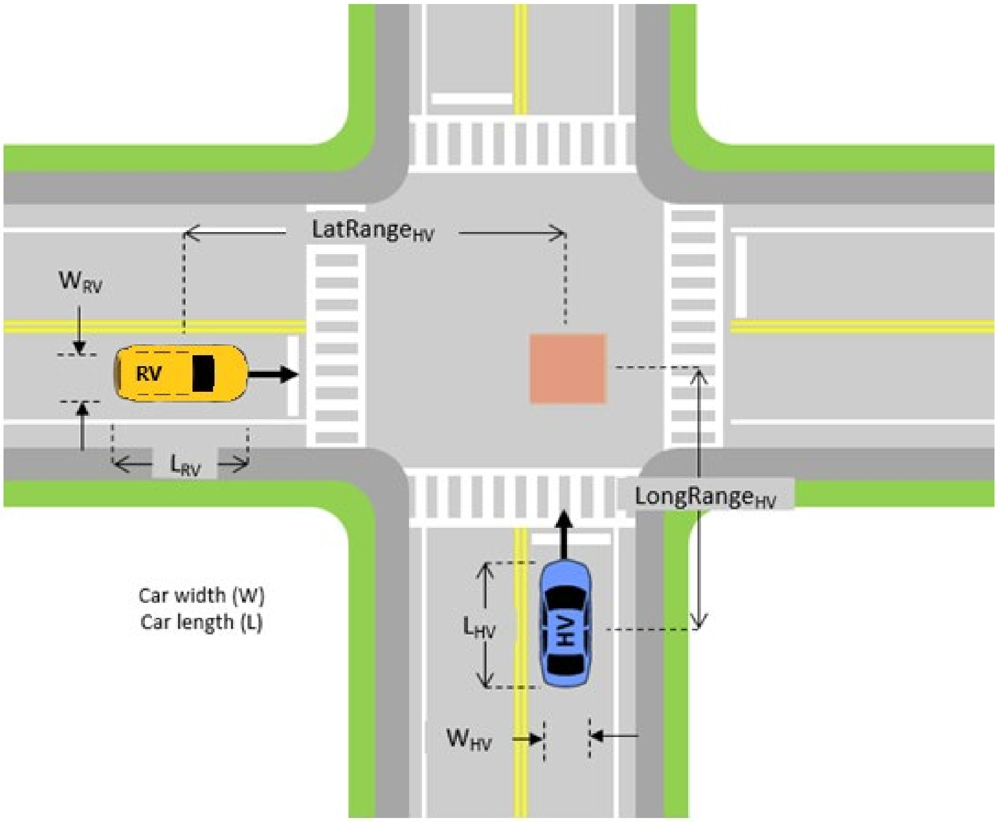


Figure 33. Intersection Diagram Showing Latitudinal and Longitudinal Range to an Intersection Point

HV TTI Based on Distance to Intersection

Equation (D8) determines the number of seconds until the HV reaches the intersection point with the RV, based on current vehicle dynamics. To use this equation, the GPS location of the point of intersection needs to be known, but it can be used regardless of vehicle heading.

$$TTI\_HV\_Dist2X = \frac{HVDist2X}{Speed\_HV} \quad \text{(D8)}$$

Where: $HVDist2X = \sqrt{\mathrm{x}^2 + \mathrm{y}^2}$

RV TTI Based on Distance to Intersection

Equation (D9) determines the number of seconds until the RV reaches the intersection point with the HV, based on current vehicle dynamics. To use this equation, the GPS location of the point of intersection needs to be known, but it can be used regardless of vehicle heading.

$$TTI\_RV\_Dist2X = \frac{RVDist2X}{Speed\_RV} \quad \text{(D9)}$$

Where: $RVDist2X = \sqrt{(\mathrm{EastOffset} - \mathrm{x})^2 + (\mathrm{NorthOffset} - \mathrm{y})^2}$

Figure 34 shows a scenario in which the HV and RV TTI equations are used. In this scenario, the vehicles are not traveling perpendicularly; however, location of the intersection point is known.

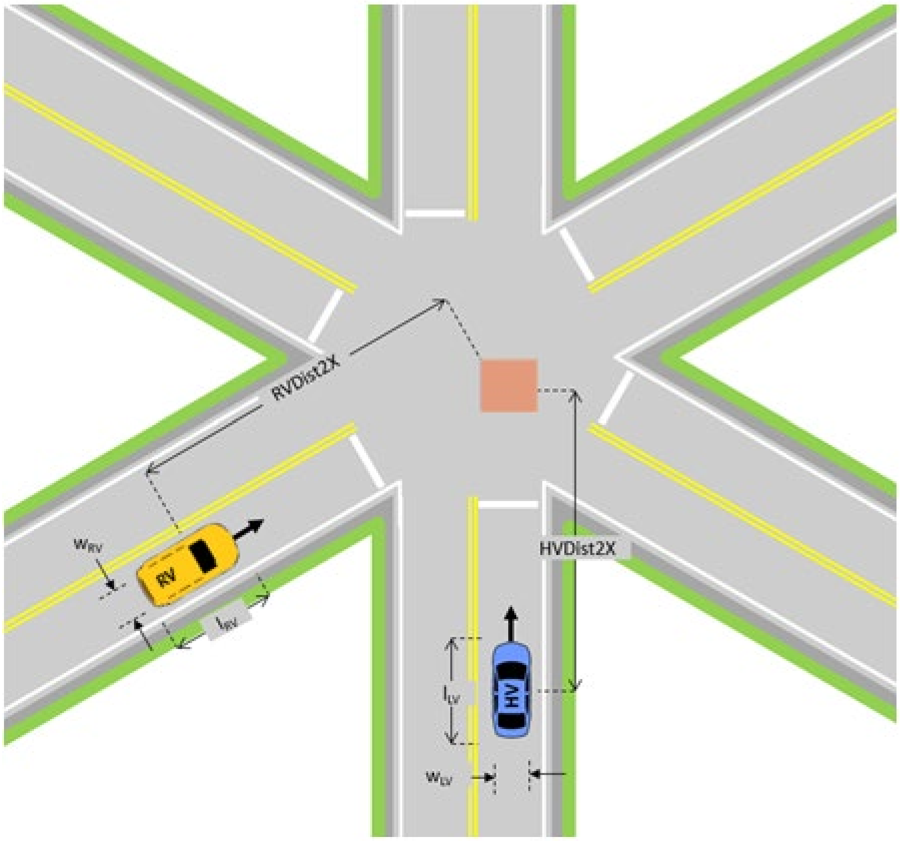


Figure 34. Intersection Diagram Showing Distances to an Intersection Point

Distance to Point of Interest

The following determines the distance between the HV and a landmark with a known GPS location (for example, a curve apex, a bridge with low clearance, or a crosswalk):

Distance(m) = 111.045 × DEGREES(ACOS(COS(RADIANS(HV_Latitude)) × COS(RADIANS(xx_Latitude)) × COS(RADIANS(HV_Longitude) - RADIANS(xx_Longitude)) + SIN(RADIANS(HV_Latitude))× SIN(RADIANS(xx_Latitude))))×1000 (D10)

Time to Point of Interest

Equation (D11) determines the number of seconds until the HV reaches a landmark with a known GPS location, based on current vehicle dynamics.

$$TTPOI = \frac{Distance}{Speed} \quad \text{(D11)}$$

Appendix E. Alert Validity Criteria

The Volpe team analyzed a total of 7,308 alerts that had BSM information using event visualization, SQL, and/or QGIS Tools. The alert validity analysis using the event visualization tool focused on a 30-second time window of the alert event: 15 seconds before alert onset to assess the driving scenario and 15 seconds after alert onset to gauge the HV driver response to the event. The Volpe team assessed the validity of all FCW, EEBL, IMA, VTRFTV and PCW alert events using the event visualization tool. Due to the very large number of ERDW and WWE alert events recorded during the THEA CVP deployment (6,846), the Volpe team performed SQL and QGIS numerical queries to validate those events. Table 23 shows the breakdown of alert events analyzed by the event visualization tool or SQL/QGIS tools.

Table 23. Breakdown of Number of Alerts by Analysis Tool

Alert Type	Event Visualization	SQL/QGIS	Total
FCW	259	-	259
EEBL	133	-	133
IMA	16	-	16
VTRFTV	45	-	45
PCW	9	-	9
ERDW	-	1,232	1,232
WWE	359	5,255	5,614
Total	821	6,487	7,308

The following sub-sections present the validity criteria for the different types of alert events and provide examples of invalid (i.e., false positive) alert events.

FCW Validity Criteria

The validity analysis of FCW alerts involved the use of the visualization tool to view the path history of HV and RV prior to alert onset, in order to confirm HV and RV vehicle dynamics and relative positions. The Volpe team considered an FCW alert event to be valid if:

- RV is traveling in the same direction ahead of the HV in the same lane (relative position of HV and RV), and
- HV is approaching or closing in on RV (range rate between the two vehicles is negative)

Figure 35 illustrates an example of an invalid FCW alert event in which the HV (red symbol) approached an RV (blue symbol) that was stopped in an adjacent lane, both on the REL curved lanes.

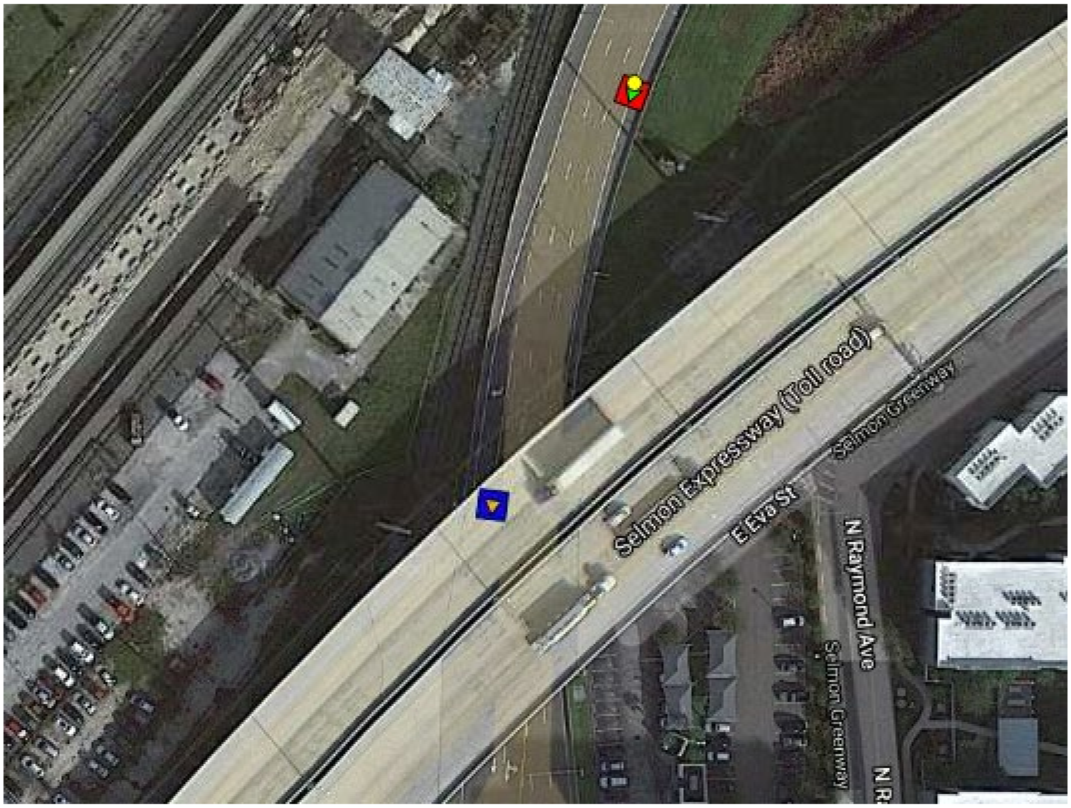


Figure 35. HV Approaching a Stopped RV on an Adjacent Lane

EEBL Validity Criteria

The validity analysis of EEBL alerts involved the use of the visualization tool to view the path history of HV and RV prior to alert onset, in order to confirm HV and RV vehicle dynamics and relative positions. The Volpe team considered an EEBL alert event to be valid if:

- RV is slowing down ahead of the HV by examining vehicle speed profile, and
- RV is traveling in the same direction ahead of the HV in the same or adjacent lanes by examining relative position between the HV and RV.

Figure 36 illustrates an example of an invalid EEBL alert event in which the RV (blue symbol) was decelerating on an adjacent road, not in the path of the HV (red symbol).

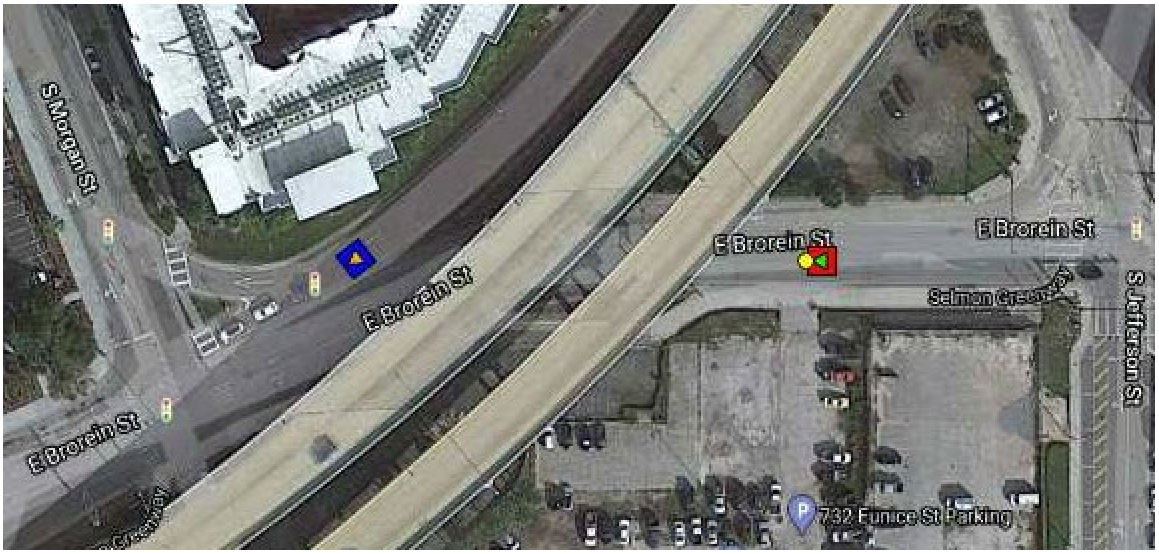


Figure 36. RV Decelerating on an Adjacent Road

IMA Validity Criteria

Similar to FCW and EEBL alert validity assessment, the validity analysis of IMA alerts involved the use of the visualization tool to view the path history of HV and RV prior to alert onset. The Volpe team considered an IMA alert event to be valid if:

- HV is approaching or proceeding from an intersection (not an overpass, rotary, or another road geometry configuration where approaching vehicles will not cross paths), and
- RV is approaching the same intersection as the HV from a lateral direction.

The IMA alert is also valid if the HV is proceeding from an intersection by turning right while the RV is approaching the intersection from HV's left. The IMA alert is considered invalid for a right-turning HV if the RV is approaching from HV's right (not a traffic hazard in this situation).

Figure 37 illustrates an example of an invalid IMA alert event in which the RV is traveling on an overpass above the road that the HV was on. Figure 38 shows another invalid IMA alert event where the HV was turning left at an intersection and following an RV ahead.

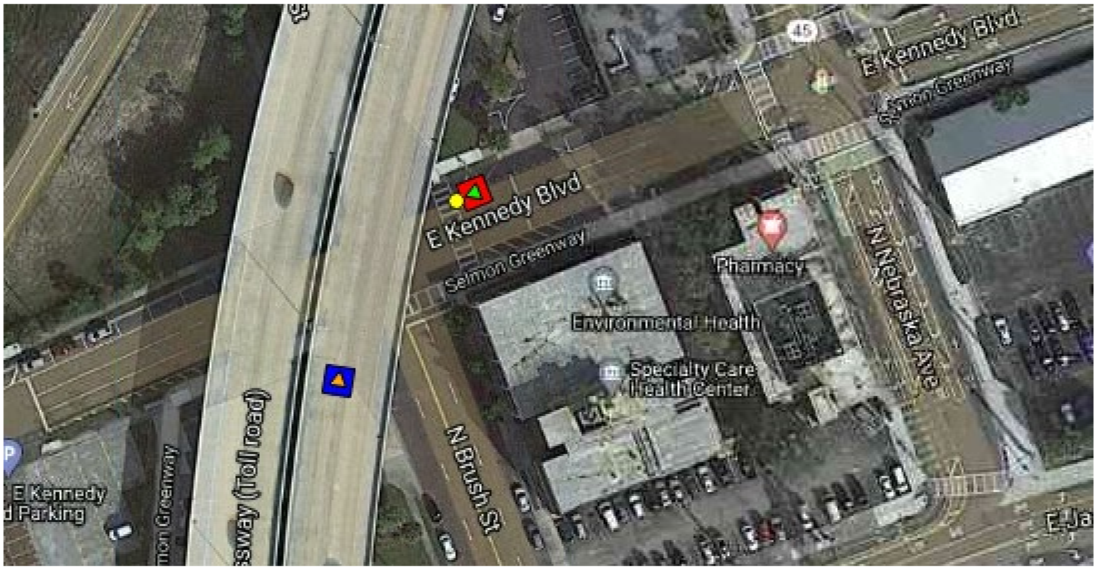


Figure 37. RV Traveling on Overpass above HV Path

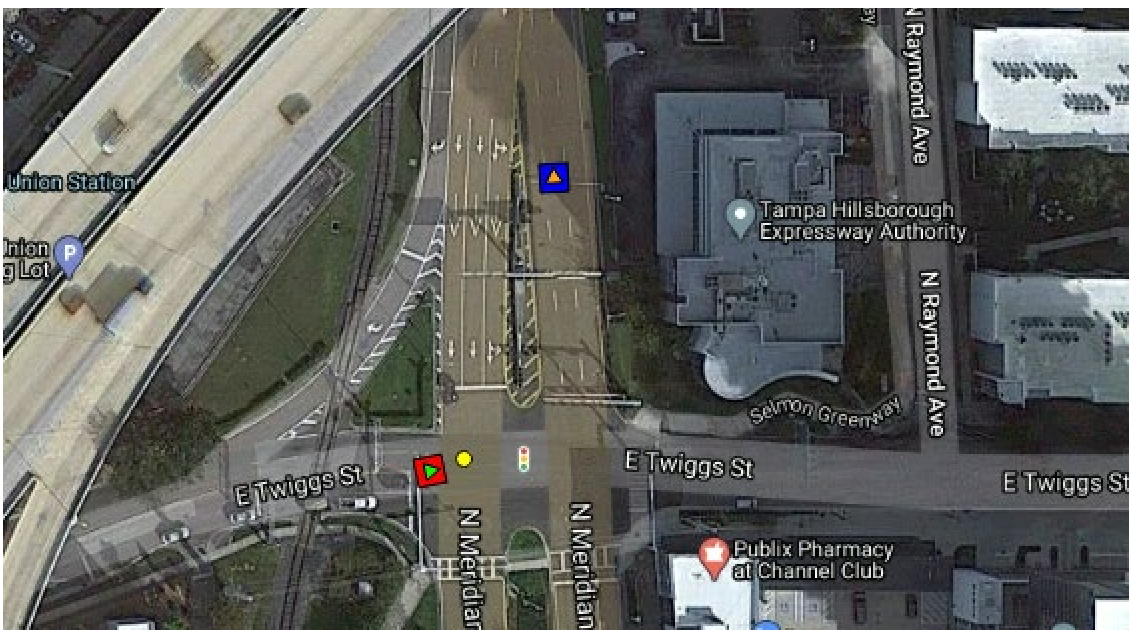


Figure 38. HV Turning Left at Intersection and Following an RV ahead

VTRFTV Validity Criteria

The Volpe team utilized the vehicle visualization tool to view the path history of the HV and trolley prior to and post alert onset, and considered a VTRFTV alert event to be valid if:

- Trolley is approaching an intersection where an HV can make a right turn across the trolley tracks, using the location and heading of the trolley, and
- HV is turning right across the trolley tracks, using the location and heading of the HV.

Figure 39 illustrates an example of an invalid VTRFTV alert event in which the HV (blue symbol) is seen initially traveling on a parallel path with the trolley (red symbol) and later turned left away from the trolley tracks. Figure 40 shows another example of an invalid VTRFTV alert event in which the HV (red symbol) was initially on a lateral path relative to the trolley (blue symbol), and later turned right on a parallel path with the trolley.

Figure 39. HV Turning Left Away from Trolley Tracks

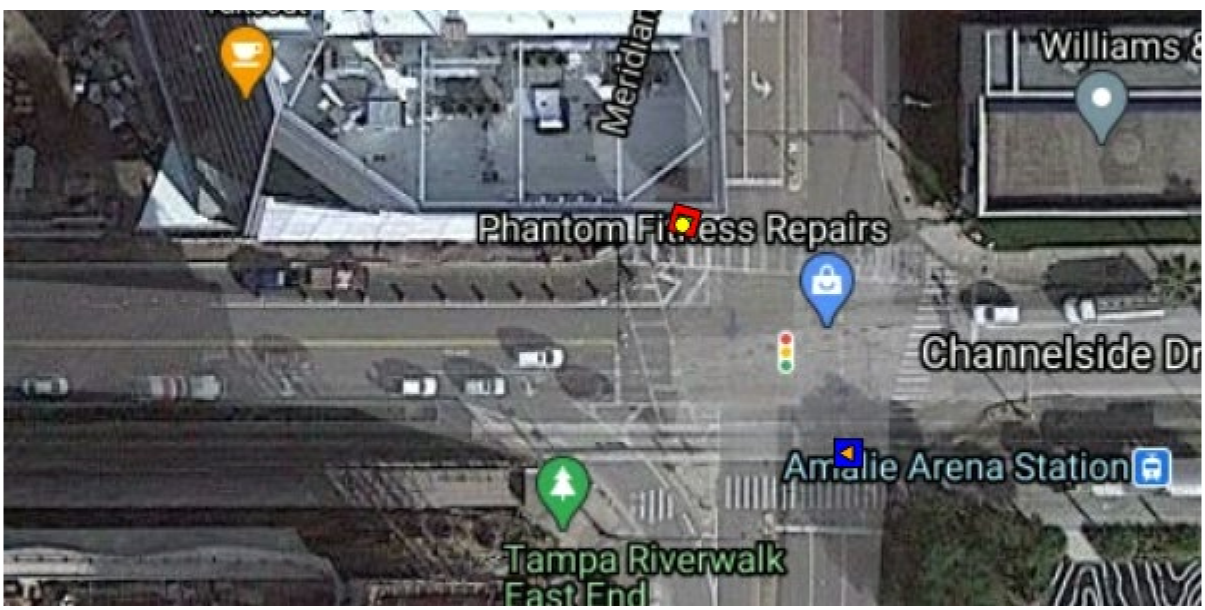


Figure 40. HV Turning Right from an Initial Lateral Direction with Trolley

PCW Validity Criteria

The Volpe team utilized the vehicle visualization tool to view the path history of the HV and pedestrian prior to alert onset, and considered a PCW alert event to be valid if:

- HV is approaching the crosswalk at the courthouse from either direction, using the location and heading of the HV, and
- Pedestrian is in the crosswalk, using the location and heading of the pedestrian.

Figure 41 illustrates an example of an invalid PCW alert event in which the HV received an alert two blocks way from the courthouse crossing. Figure 42 provides another example of an invalid PCW alert event where the HV was not approaching the courthouse crossing.

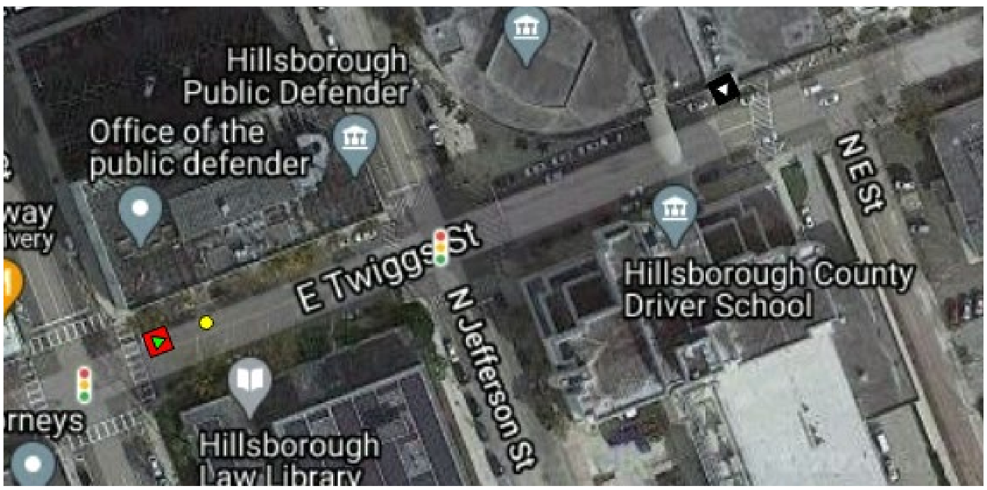


Figure 41. HV Alerted to Pedestrian Crossing Two Blocks Away from the Courthouse

Figure 42. HV Not Approaching Courthouse Crossing

ERDW Validity Criteria

The Volpe team used the SQL/QGIS tool to assess the validity of ERDW alert events based on the location and heading of the HV. An ERDW alert is considered valid if the HV is approaching, but not yet crossed, the end of the REL while heading inbound.

Figure 43 illustrates an example of invalid ERDW events where the HV is not traveling on the REL ramp. Red markers represent HVs at ERDW alert onset. Figure 44 shows instances of HVs that received ERDW alerts after they crossed the end of REL ramp.

Figure 43. HV Not Approaching REL Ramp

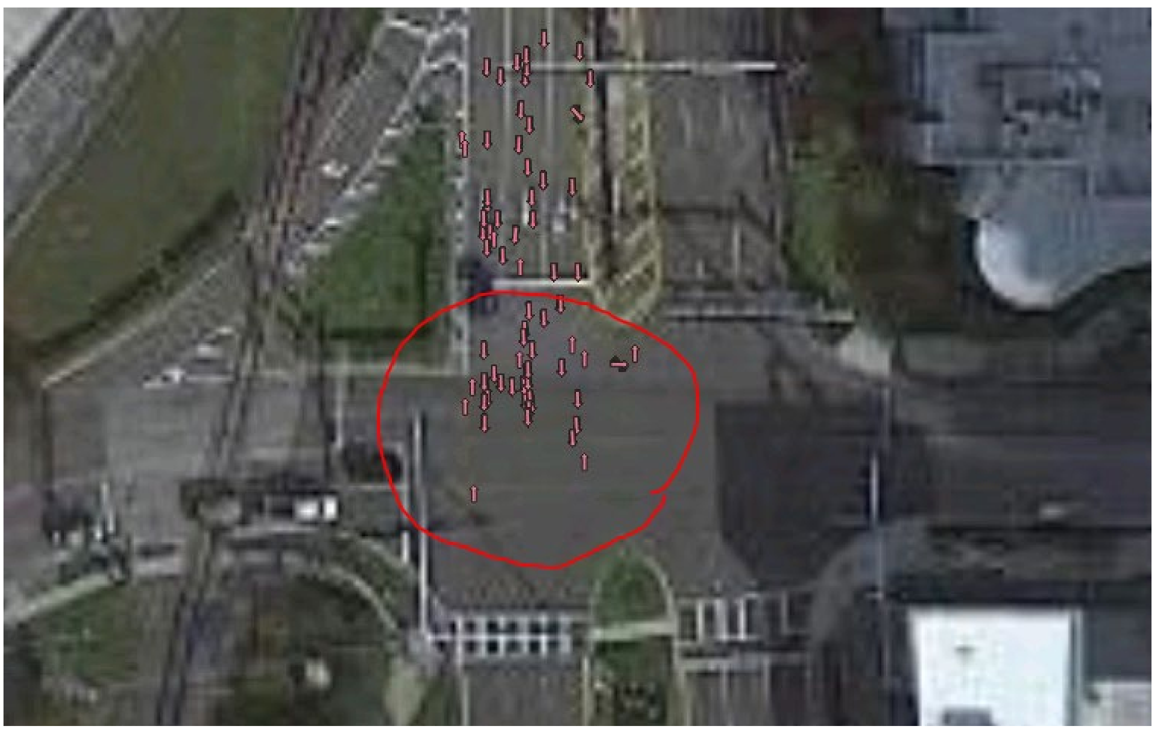


Figure 44. HV after Crossing REL Ramp

WWE Validity Criteria

The following sections describe the four filtering steps used to validate WWE alerts and the numbers and types of alerts that passed or did not pass each filter. The Volpe team excluded 683 WWE alert events without BSM data in the database from further steps of the analysis, which accounted for 10.8 percent of 6,297 total WWE alerts.

Filter 1: Vehicle Location and Heading at Alert Onset

Filter 1 involved plotting WWE alerts on a map of the area around the intersection of Twiggs Street and Meridian Avenue in Tampa. The Volpe team categorized these alerts by where they occurred within the intersection, based on polygons drawn using GIS software tools, as shown in Figure 45.

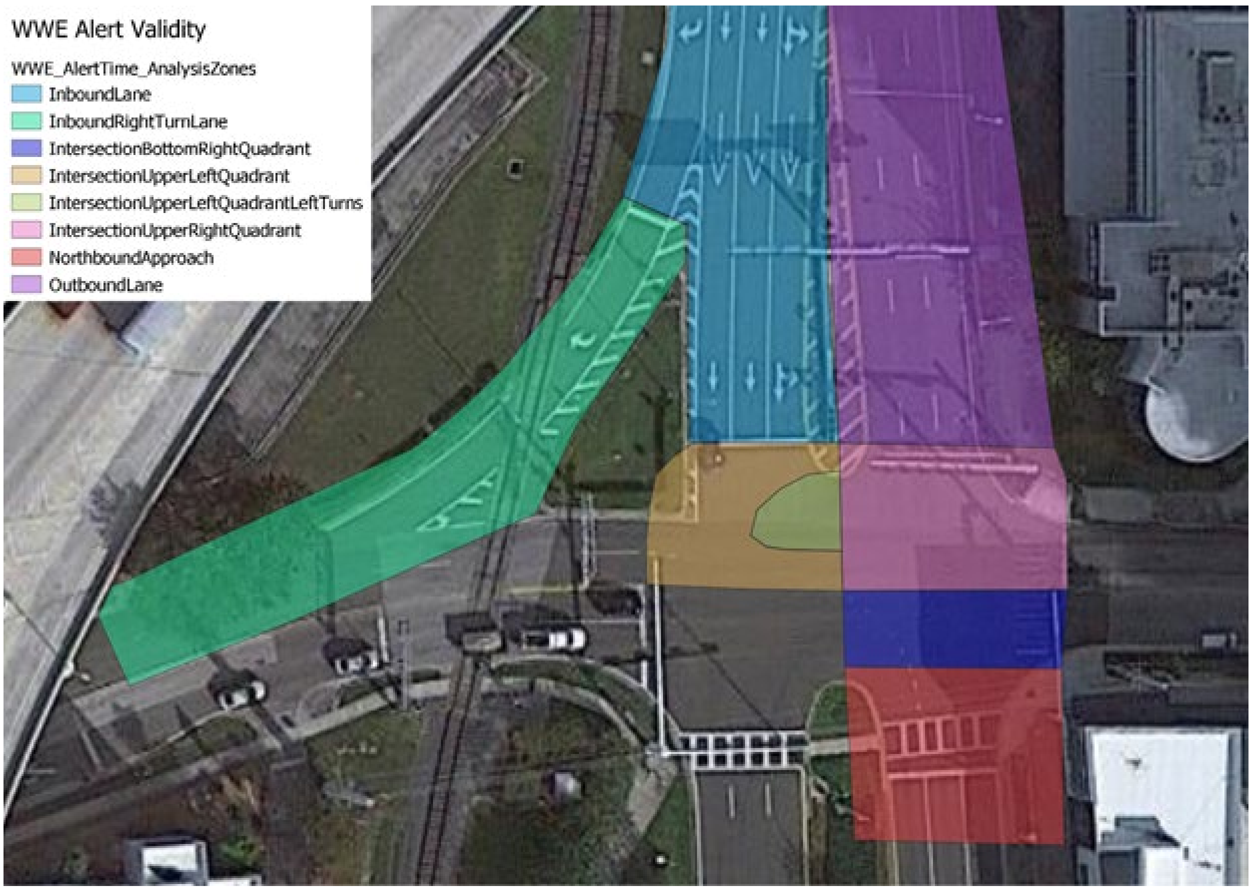


Figure 45. WWE Geographic Filtering Zones

Figure 46 denotes all WWE alerts on the map with different color codes that indicate the zone category they belong to. The arrowhead indicates the heading of the vehicle at the time of the alert.

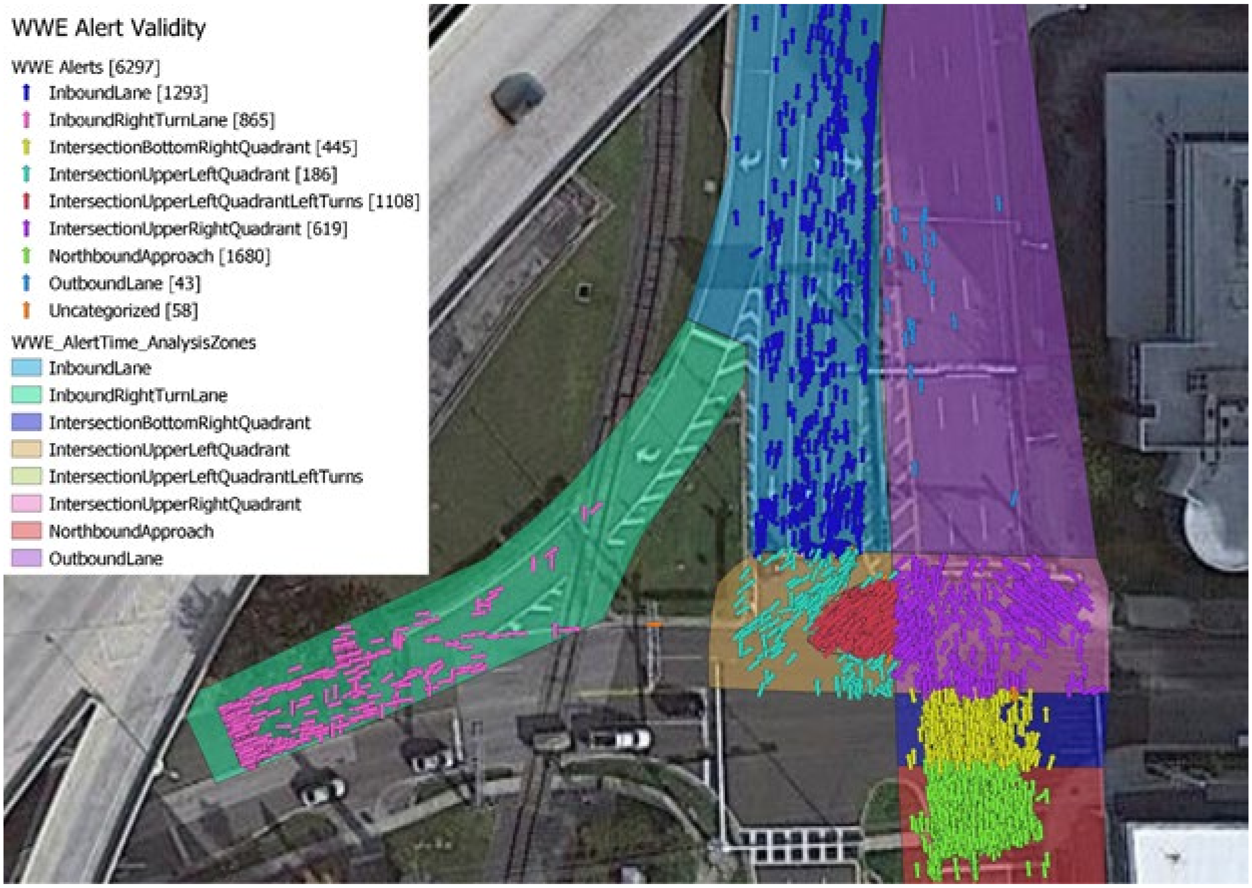


Figure 46. WWE Alert Locations

The Volpe team used Filter 1 to categorize invalid WWE alerts if HVs were traveling toward the Outbound Lane of the REL when the gate is open. While "Do Not Enter" advisories may be issued to HV drivers to warn them not to enter the inbound lane of the REL, a large number of the WWE alerts in the THEA CVP database were issued when the gate was open or were too early. Therefore, the Volpe team considered these alert events to be invalid. Figure 47 provides the mapped results of Filter 1.

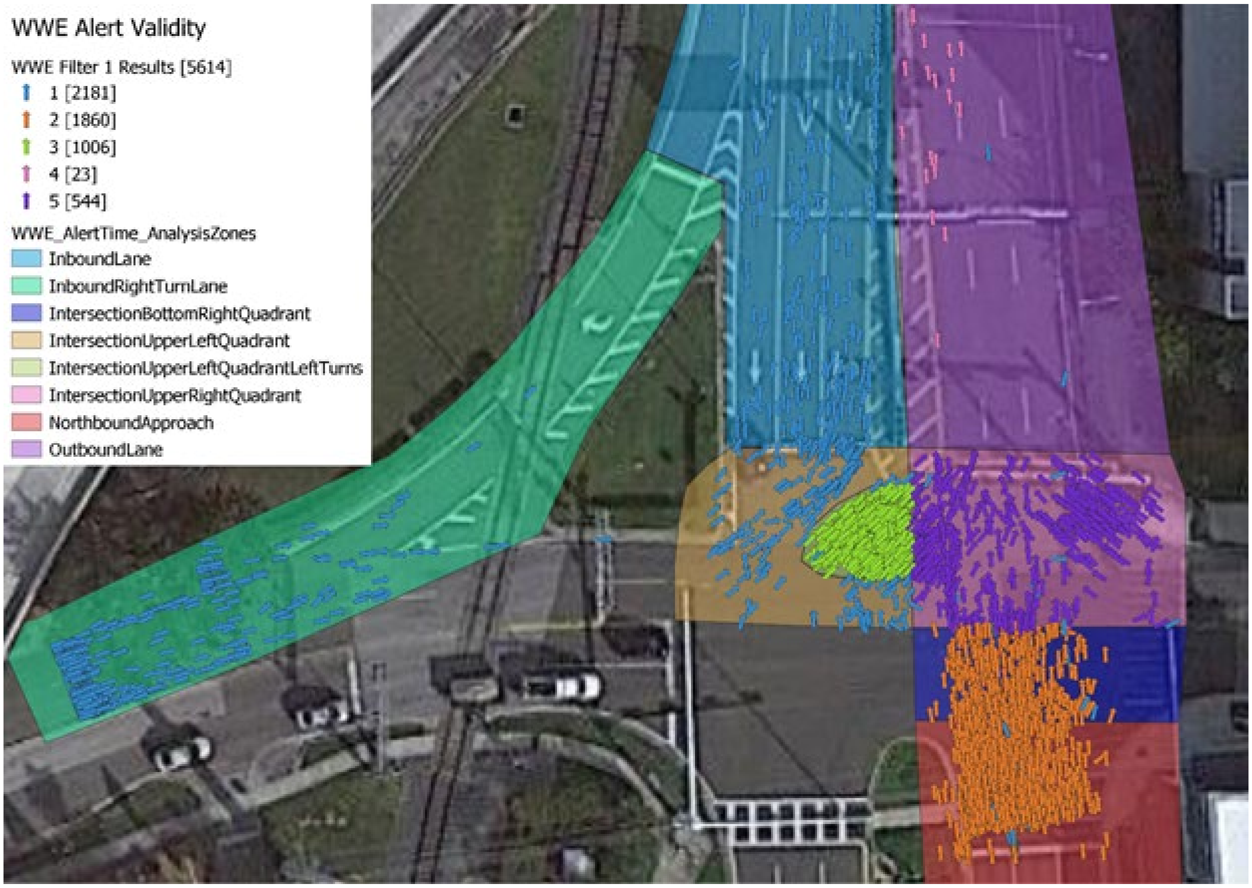


Figure 47. Results of WWE Automatic Filter Step 1

The Volpe team identified a number of categories based on the heading of HVs and their location in various zones of the intersection at WWE alert onset. Table 24 lists the description of each category along with corresponding number of WWE alerts. Based on the results of Filter 1, the Volpe team deemed 2,181 WWE alerts (about 39% of 5,614 total alerts) to be valid and 3,433 alerts to be invalid.

Table 24. Filter 1 Results of WWE Alert Validation

Category	**Alert Validity**	**Number**
Passed Filter 1 (1)*	Potentially valid	2,181
Northbound approach, gate open, early alert (2)	Invalid	1,860
Left turn from eastbound approach, gate open (3)	Invalid	1,006
Northbound in outbound lane, gate open (4)	Invalid	23

Right turn from westbound approach, gate open (5)	Invalid	544

*: Number in parentheses corresponds to the filter codes in Figure 54

Filter 2: Southbound Alerts when Gate Was Closed and Wrong-Way Driver Alerts

The second filter categorized WWE alerts issued to HVs that were traveling southbound in the inbound lane of the REL (the correct direction) while the gate was closed. The Volpe team considered these alerts as invalid because there is no explainable reason or potential driving conflict scenario that would arise in these situations when HVs are going in the correct direction. One exception is when another equipped vehicle receives a wrong-way entry warning for entering the inbound lane when the gate is closed. In these situations, other equipped vehicles traveling southbound in the inbound lane may receive alerts to prevent possible conflict scenarios with vehicles travelling in the wrong direction. Filter 2 first categorizes southbound alerts in the inbound lane when the gate is closed as invalid, and then searches for instances where there is a northbound alert in the inbound lane within 5 seconds of the southbound alert. The map in Figure 48 shows the results of this filter.

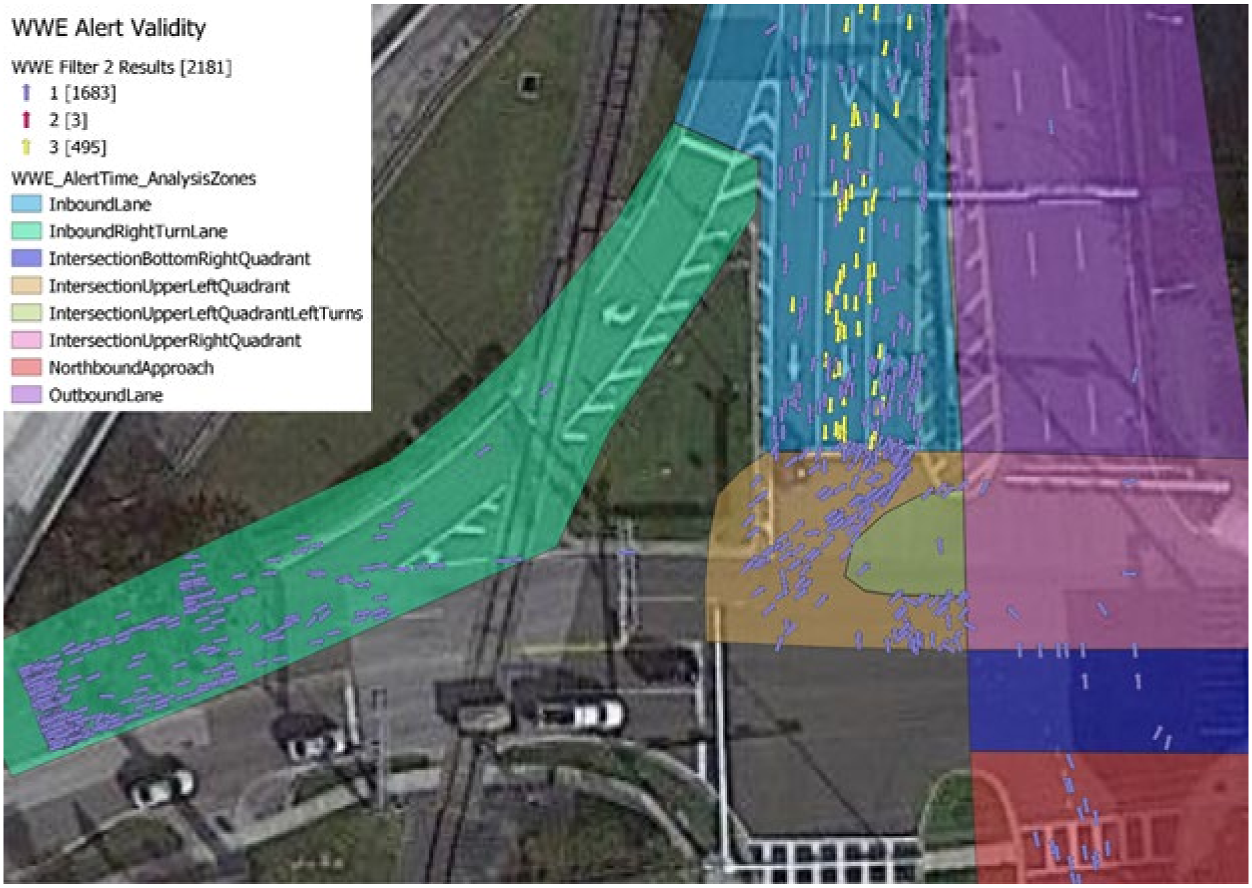


Figure 48. Results of WWE Filtering Step 2

Table 25 shows the descriptions of the categories of Filter 2 and the numbers of alerts that fall under those categories. Overall, a total of 1,686 alerts (about 77% of total 2,181 alerts) remained potentially valid after the application of Filter 2.

Table 25. Filter 2 Results of WWE Alert Validation

Category	**Alert Validity**	**Number**
Not southbound in inbound lane, gate closed (1)*	Potentially Valid	1,683
Southbound in inbound lane, gate closed, northbound alert pair found (2)	Potentially Valid	3

Southbound in Inbound lane, gate closed (3)	Invalid	495

*: Number in parentheses corresponds to the filter codes in Figure 48

Filter 3: Vehicle Location and Heading 3 Seconds after Alert

The third filter used in assessing the validity of WWE alerts involved looking at the locations and headings of HVs 3 seconds after alert onset. The Volpe team modified the geographic zones of the intersection used to categorize alerts for Filter 3 slightly from the zones used in Filter 1, as depicted in Figure 49.

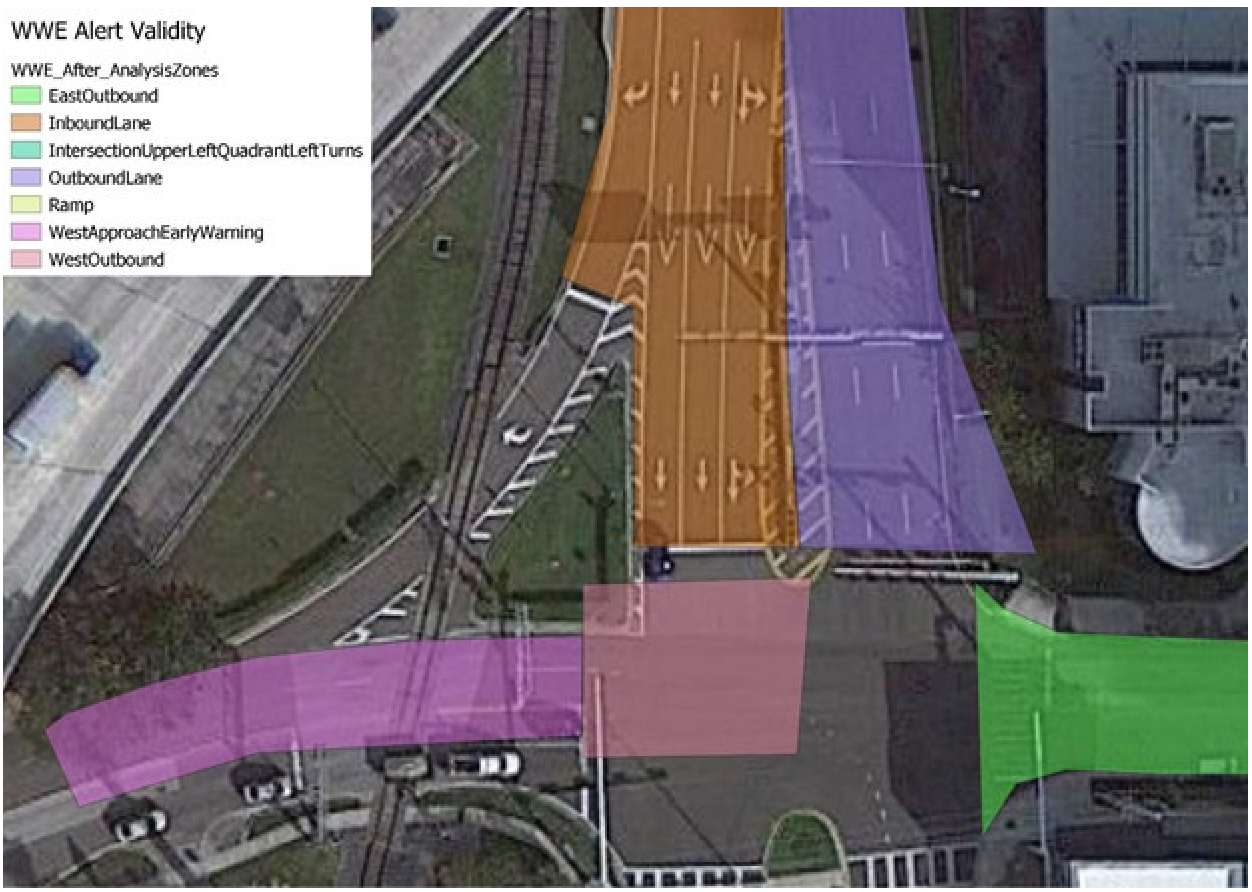


Figure 49. Modified Analysis Zones for Filter 3

A number of WWE alerts did not fall into these categories, as HV locations were simply not in any one of these zones 3 seconds after the alert. Figure 50 overlays HV locations and headings, 3 seconds after the alert, on the map with various color codes that show their analysis zone after the alert.

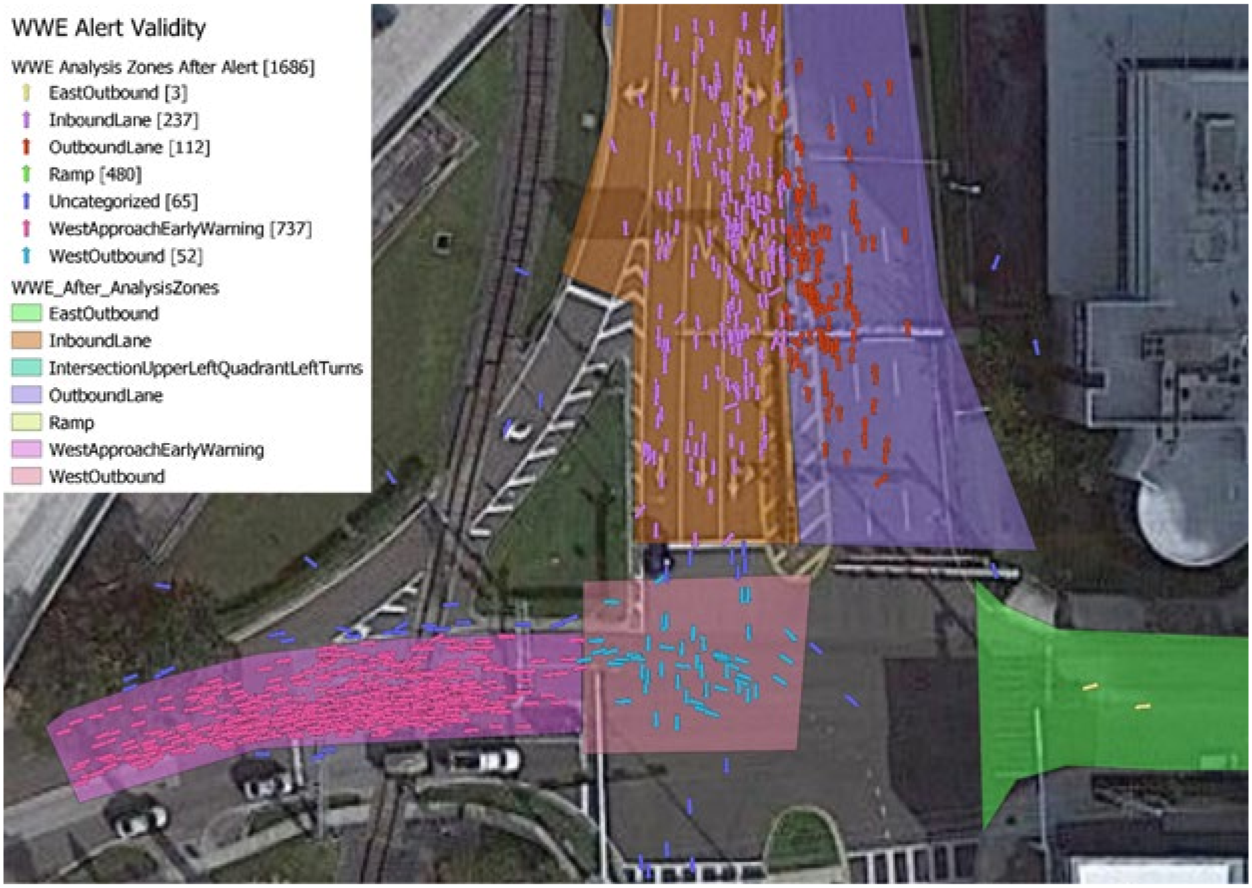


Figure 50. WWE Alerts Categorized by Modified Filter 3 Regions

Filter 3 looked specifically for situations where the HV location and heading after the alert indicated that there was no potential conflict. In these cases, the HV path showed that the driver was not making a dangerous maneuver toward the "Do Not Enter" lane or the closed gate. Additionally, this filter looked for alerts where the HV remained in the intersection approach after 3 seconds, indicating the WWE application issued the alert too early to have any safety impact.

Figure 51 shows the results of Filter 3. Table 26 lists the description of each category along with corresponding number of WWE alerts. The Volpe team identified 489 WWE alerts (about 29% of 1,686 total alerts) as potentially valid after applying Filter 3.

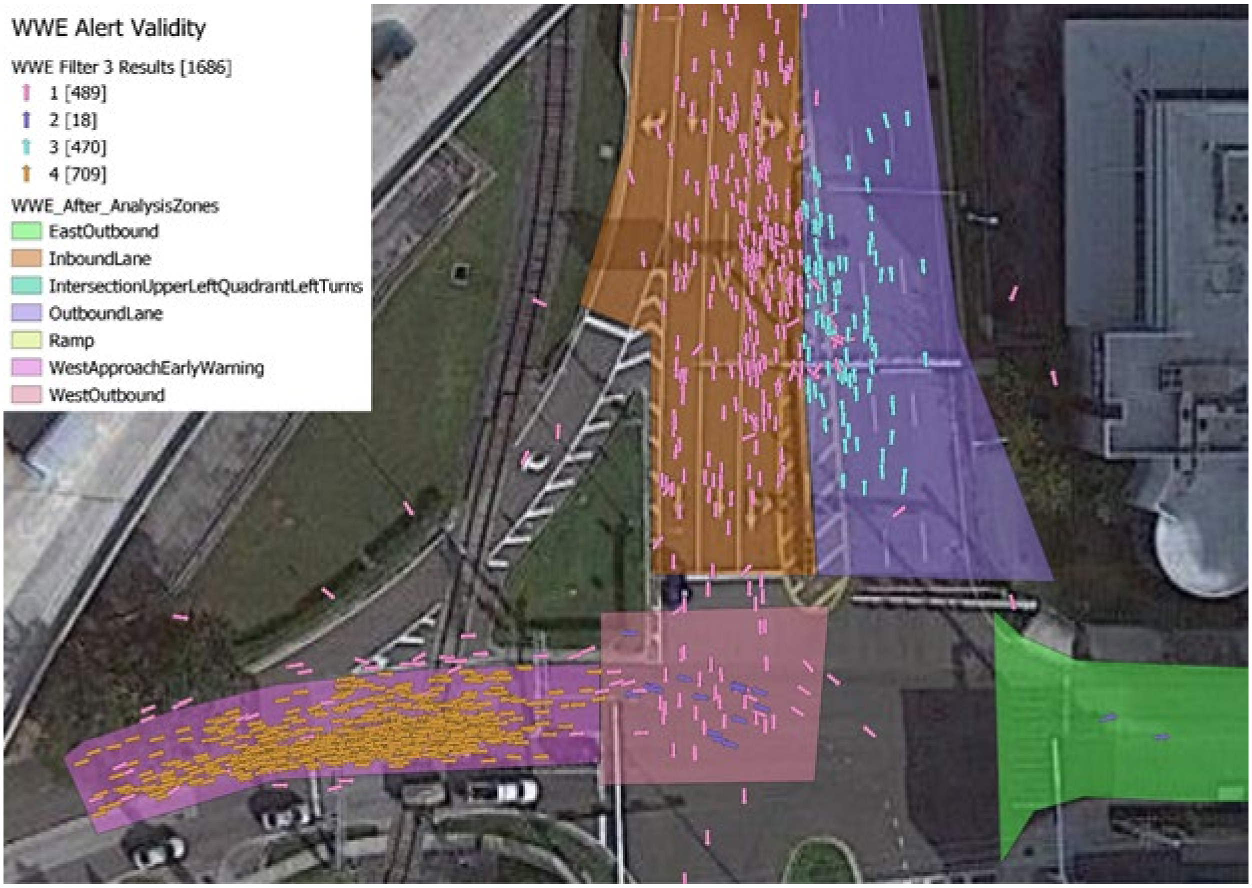


Figure 51. Results of WWE Alert Filtering Step 3

Table 26. Filter 3 Results of WWE Alert Validation

Category	**Alert Validity**	**Number**
Passed Filter 3 (1)*	Potentially Valid	489
Eastbound or westbound, leaving intersection (2)	Invalid	18
Northbound in outbound lane when gate is open (3)	Invalid	470
Eastbound in eastbound approach, early alert (4)	Invalid	709

*: Number in parentheses corresponds to the filter codes in Figure 58

Filter 4: Southbound Vehicles with Heading Errors at Alert Onset

The final filter examined HV paths 3 seconds before and after the alert. This filter specifically categorized WWE alerts where HV headings were erroneously 0 degree (North) in the inbound lane when the gate was closed. During the THEA CVP deployment, it was possible for alerts to be issued to drivers if they were stopped when entering downtown Tampa from the REL. In these situations, the heading of the vehicle was sometimes reset to 0 degree. Thus, the conditions for issuing a WWE alert were met and the application was triggered. This filter identified situations where HVs received WWE alerts, even though their overall path was southbound in the inbound lane when the REL gate was closed.

Figure 52 shows the results of Filter 4, indicating invalid WWE alerts in light blue color and potentially valid alerts in dark purple. The lines shown in the figure represent HV paths 3 seconds before and after an alert, with the arrows on the lines indicating the HV direction of travel. The application of Filter 4 resulted in 359 potentially valid WWE alerts (about 73% of 489 total alerts) and 130 invalid WWE alerts.

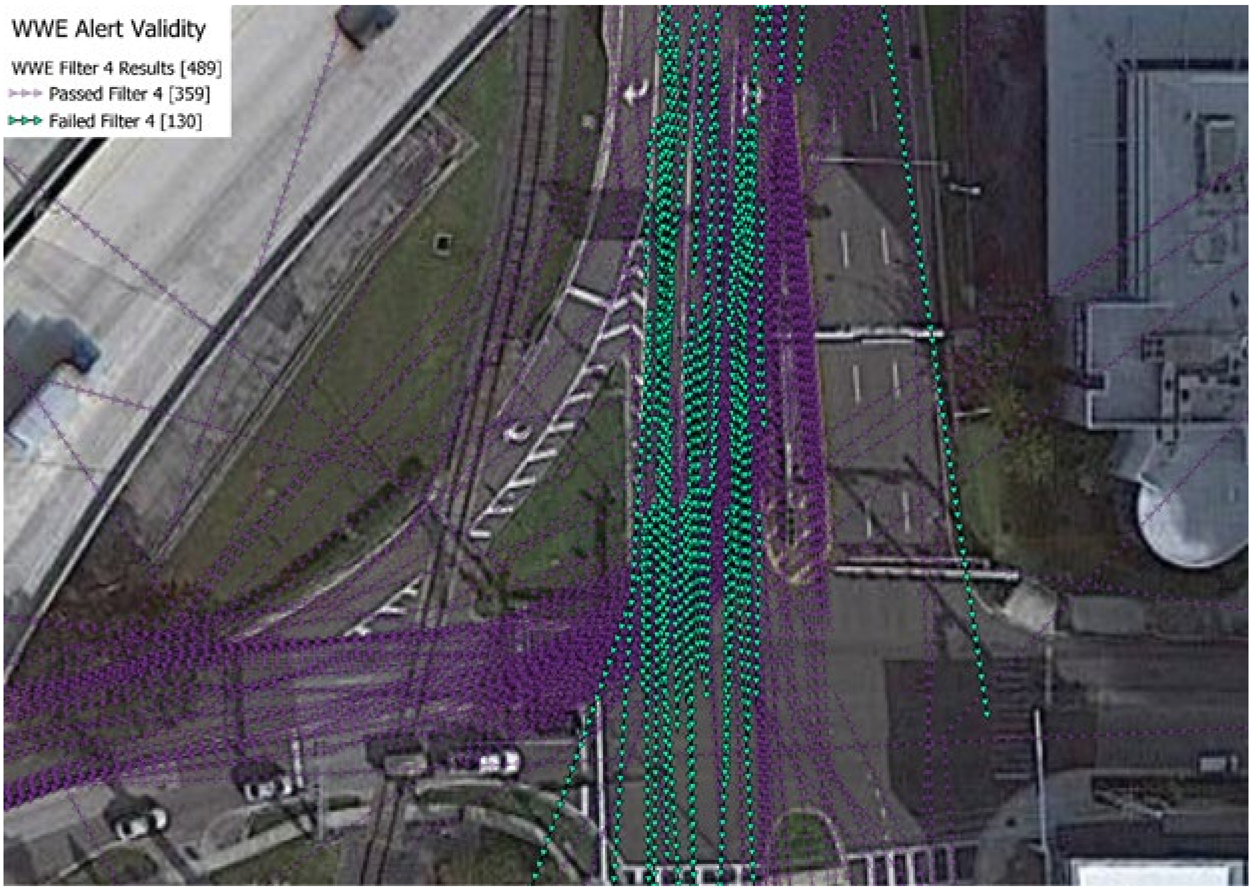


Figure 52. Results from Filter 4, Invalid Alerts Only

After applying automatic Filters 1-4, the Volpe team used the event visualization tool to assess the validity of the remaining 359 potentially valid WWE alerts, and to analyze HV responses to these alerts.

Appendix F. Coding Scheme for Event Visualization Analysis

The Volpe team coded alert events using the event visualization tool in order to collect information that is not available in the numerical database for alert validity and usefulness analyses. Table 27 lists vehicle positions and maneuvers during alert events for each alert type.

Table 27. Coded Vehicle Positions and Maneuvers from Visualization of Alert Events

Variable	**FCW/EEBL**	**IMA**	**VTRFTV**	**PCW**	**ERDW**	**WWE**
HV maneuver	Going straight	Going straight	Going straight	Going straight		
	Turning	Turning	Turning right	Stopped		
	Stopped	Stopped and proceeded	Other	Other		
	Changing lanes/merging	Merging				
	Other	Other				
HV road position	Straight road	Figure 53	In intersection		Unknown	Figure 54
	Curved road		Approaching intersection		On REL ramp	
	Approaching intersection		Stopped at intersection		Over/under pass	
	Stopped at intersection		other		No longer on ramp	
	Other					
RV maneuver	No RV	No RV	No RV			
	Going straight	Traversing intersection	Going straight			

	Turning	Turning (not on crash path)	Turning right			
	Changing lanes/merging	Approaching intersection	Stopped			
	Other	Stopped and proceeded	Other			
		Stopped				
		Traveling over/under pass				
		Other				
RV road position	No RV	Figure 53	Adjacent left lane			
	Straight road		Adjacent right lane			
	Curved road		Intersection 90 left			
	Other		Intersection 90 right			
			Other			

For the FCW/EEBL alert event analysis, the Volpe team also identified the following attributes for RV location relative to the HV:

- No RV
- In same lane as HV
- One or more lanes over
- Other

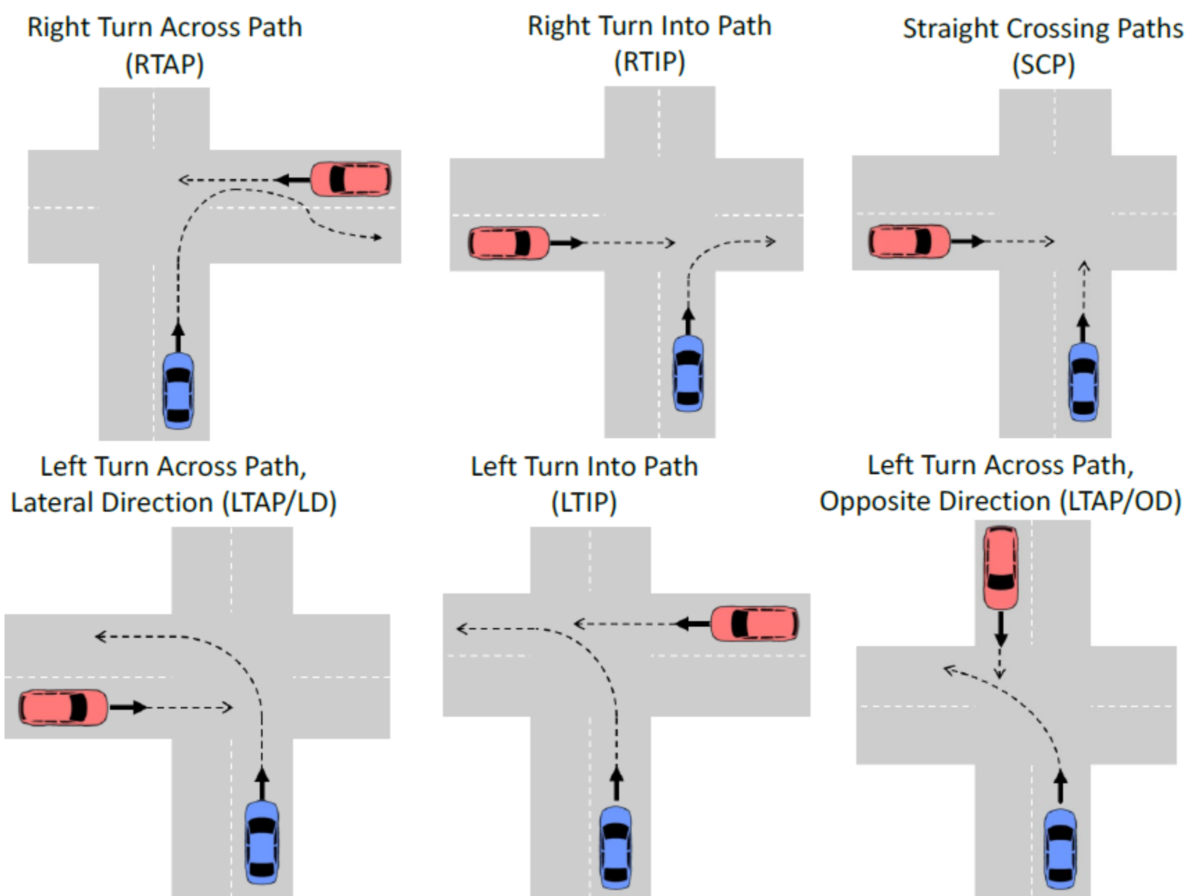


Figure 53. Crossing-Paths Driving Scenarios

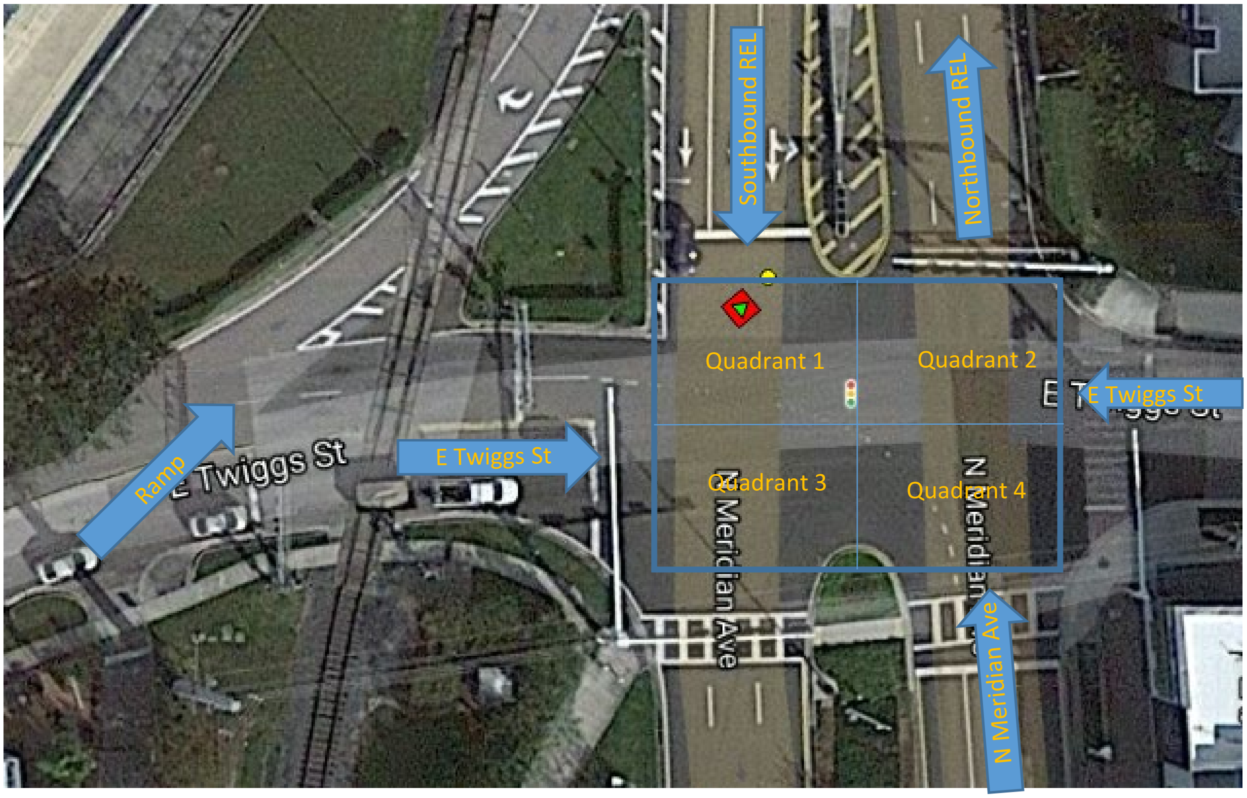


Figure 54. HV Position at WWE Alert Onset

Table 28 presents the coding of the hazard and driving conflict of alert events using the event visualization tool. In addition, the Volpe team coded whether the HV steered in response to FCW and EEBL alerts (i.e., no, yes, or unsure) and whether the HV stayed on its course or altered its travel path in response to WWE alerts.

Table 28. Coded Alert Event Hazard and Driving Conflicts from Visualization of Alert Events

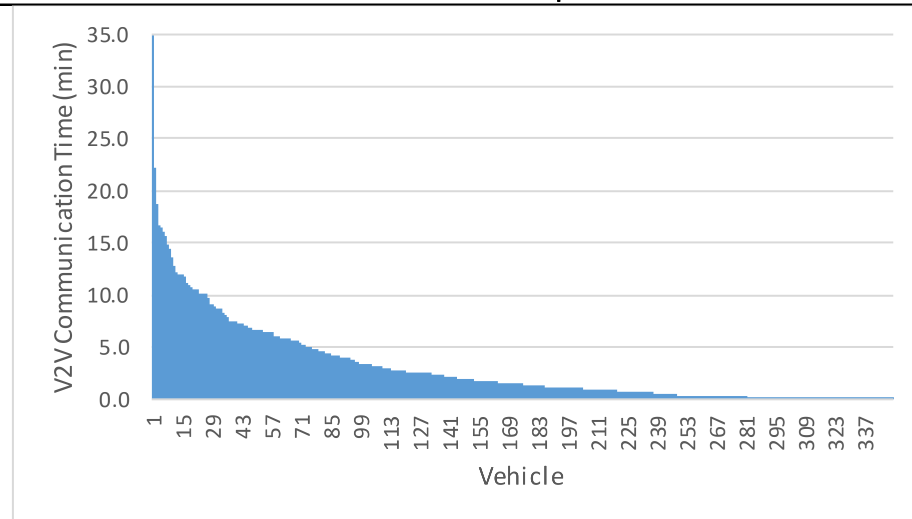
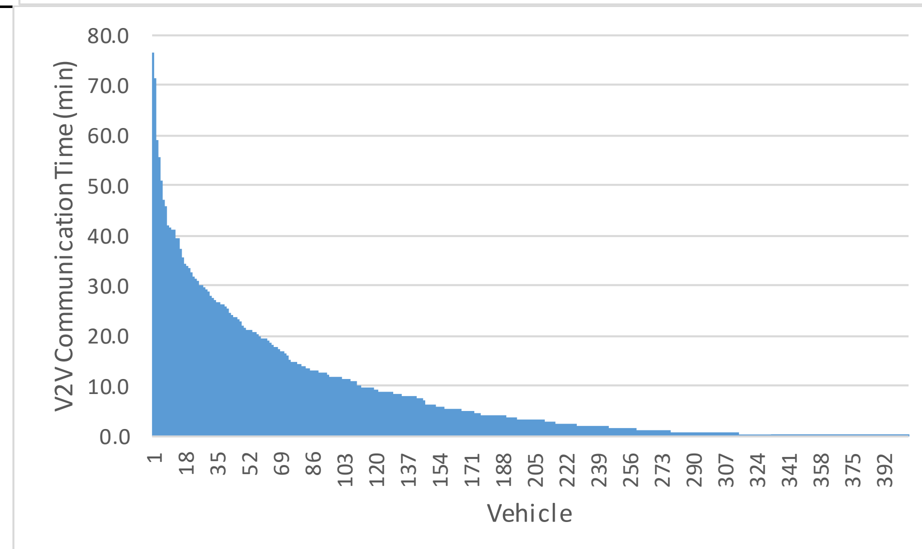
Variable	FCW/EEBL	IMA	VTRFTV	PCW	ERDW	WWE
HV on collision path with RV	No	No	No	No		
	Yes	Yes	Yes	Yes		
	Unsure	Unsure	Unsure	Unsure		
Driving conflict	None	None	None	None		None
	RV Stopped	Figure 53	Streetcar approaching intersection, RV turning right from adjacent lane	Vehicle going straight & pedestrian crossing the road		HV approaching wrong-way entrance (gates closed)
	RV Moving		Streetcar approaching intersection, RV going straight from adjacent lane	Vehicle going straight & pedestrian in the road		HV approaching do-not-enter entrance (gates opened)

			Other	Vehicle going straight & pedestrian adjacent to the road		HV was approaching the RV was on do not enter lanes (gates closed)
				Other		HV entering do-not-enter lanes (gates closed)
						HV was travelling/approaching southbound on 'do not travel lanes (gates closed)
						HV approaching do-not-enter ramp

Appendix G. Vehicle Exposure Criteria and Statistics

Table 29 provides the V2V exposure criteria and a graph of V2V communication time per vehicle, meeting these criteria that would trigger an alert, for each V2V safety application. Table 30 lists the V2I exposure criteria and displays graphs of the calculated crossing count per vehicle by each V2I safety application.

Table 29. V2V Exposure Criteria and Calculated Communication Time per Vehicle by Safety Application

Application	Criteria	V2V Communication Time per Vehicle
FCW	HV follows RV that is in front and on same travel lane, within a range of 120 m. Both vehicles have similar headings within |10| degrees and elevations within |4.3| m.	
EEBL	RV travels in front of HV in the same direction, regardless of its lane position, within a range of 120 m. Both vehicles have similar headings within |10| degrees and elevations within |4.3| m.	

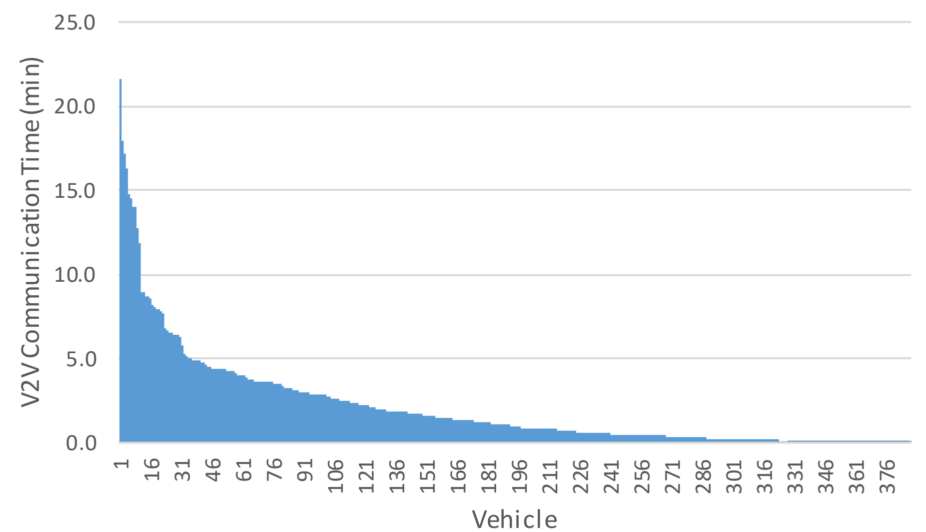
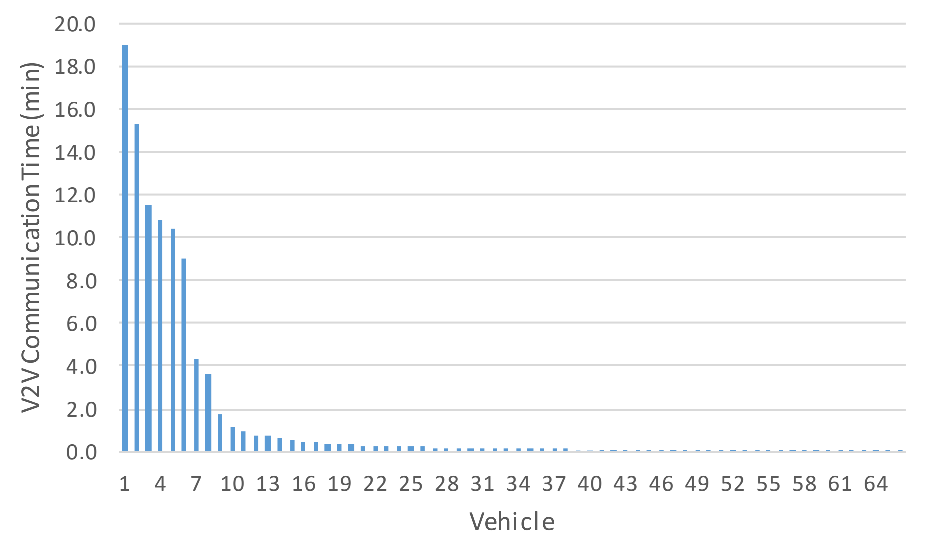
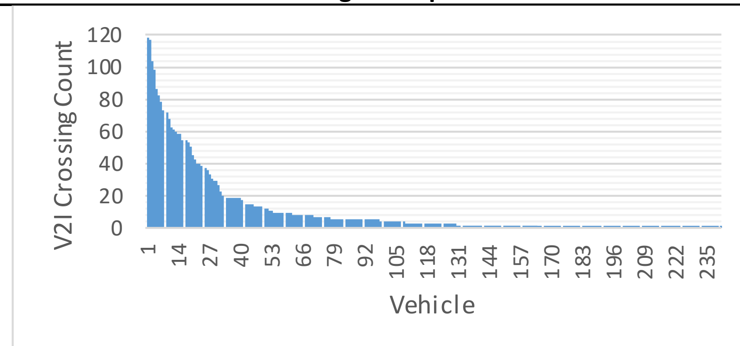
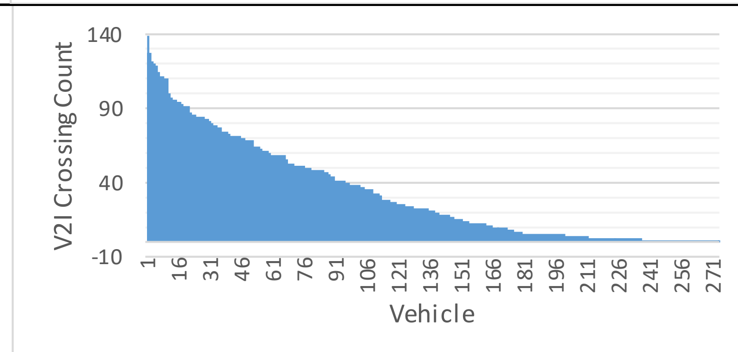
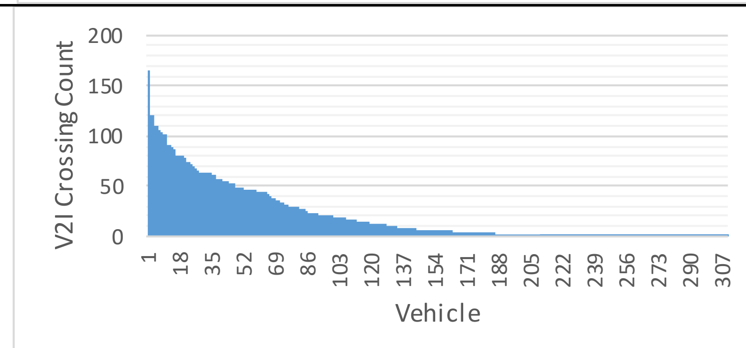
Application	Criteria	V2V Communication Time per Vehicle
IMA	Both vehicle headings are roughly perpendicular to each other within 120 m range. Their perpendicular headings are within |30| degrees (i.e., 90 ± 30 degrees) and their elevations are within |4.3|m.	
VTRFTV	Both Trolley and other equipped vehicles are roughly travelling in parallel within 50 m of longitude range (VTRFTV alert range) and 11.1 m (average of 3 lane widths) of latitude range. Both vehicles have similar headings within |10| degrees and elevations within |4.3| m.	

Table 30. V2I Exposure Criteria and Calculated Crossing Count per Vehicle by Safety Application

Application	Criteria	V2I Crossing Count per Vehicle
PCW	HV approaching and crossing the pedestrian crosswalk at the courthouse, on E Twiggs Street.	
ERDW	HV entering the REL ramp during morning rush hours.	
WWE	HV approaching E Twiggs Street or N Meridian intersection.	

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