Limited Analysis of the Wyoming Department of Transportation Connected Vehicle Pilot Safety Applications

Final Report — June 2022

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William Chupp, Andy Lam, and Wassim G. Najm

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
John A Volpe National Transportation Systems Center
55 Broadway
Cambridge, MA 02142-1093

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This report presents the results of a limited analysis of the safety applications deployed in the Wyoming Department of Transportation Connected Vehicle Pilot site. This deployment included the vehicle-to-vehicle forward collision warning (FCW) application and three vehicle-to-infrastructure (V2I) applications that provided advisories, roadside warnings, and travel guidance to drivers traveling along Interstate 80. Situational awareness, work zone warning, and spot weather impact warning comprised the V2I applications. This analysis was based on the naturalistic driving experience of 327 equipped vehicles, spanning from January through April 2022. The deployed vehicles experienced 490 distinct FCW events and received 83,408 weather condition alerts, 34,962 speed limit alerts, 7,077 work zone alerts, and 3,069 traffic condition alerts. The analysis of FCW events characterized the host vehicle (HV) speed at alert onset and vehicle response to alerts in terms of driving conflict mitigation, response time, and deceleration level. The analysis of V2I advisory alerts focused on the HV speed at alert onset and did not address vehicle response to these alerts. Finally, this analysis compared the speed of all vehicles passing by 64 roadside radars along I-80, between a baseline period from January through April 2017 and the treatment period from January through April 2022.

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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		
in²	square inches	645.2	square millimeters	mm²
ft²	square feet	0.093	square meters	m²
yd²	square yard	0.836	square meters	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km²
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.028	cubic meters	m³
yd³	cubic yards	0.765	cubic meters	m³
		NOTE: volumes greater than 1000 L shall be shown in m³		
		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/m²	cd/m²
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in²	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm²	square millimeters	0.0016	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.195	square yards	yd²
ha	hectares	2.47	acres	ac
km²	square kilometers	0.386	square miles	mi²
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m³	cubic meters	35.314	cubic feet	ft³
m³	cubic meters	1.307	cubic yards	yd³
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/m²	candela/m²	0.2919	foot-Lamberts	fl

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List of Acronyms

BSM	Basic Safety Message
CV	Connected Vehicle
CVP	Connected Vehicle Pilot
DN	Distress Notification
ΔV_{HV}	HV speed reduction
FCW	Forward Collision Warning
ft	Feet
HV	Host Vehicle
ITS JPO	Intelligent Transportation Systems Joint Program Office
m	Meter
mph	Miles per hour
NYC	New York City
R(0)	Range or distance between RV and HV at alert onset
Rdot(0)	Relative speed between RV and HV at alert onset
RSU	Roadside Unit
RV	Remote Vehicle
s	Second
SA	Situational Awareness
SDC	Secure Data Commons
SWIW	Spot Weather Impact Warning
TH(0)	Time headway between RV and HV at alert onset
TIM	Traveler Information Message
TMC	Transportation Management Center
tRC	Time to resolve conflict
TTC(0)	Time to collision between RV and HV at alert onset
U.S. DOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
$V_{HV}(0)$	HV speed at alert onset
$V_{HV}min$	Minimum HV speed
$V_{RV}(0)$	RV speed at alert onset
WYDOT	Wyoming Department of Transportation
WZW	Work Zone Warning

Executive Summary

This report presents the results of a limited analysis that assessed the performance of safety applications deployed in the Wyoming Department of Transportation (WYDOT) Connected Vehicle Pilot (CVP) site. Due to time and schedule constraints, the Volpe team conducted a limited, higher-level analysis for the WYDOT CVP as compared to more detailed analyses for the Tampa and NYC CVP sites.

The WYDOT CVP deployment included vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) safety applications that provided in-vehicle crash-imminent alerts, hazard advisories, and travel guidance to drivers traveling along Interstate 80 (I-80). The WYDOT CVP site has deployed 76 roadside units along I-80 and has equipped a total of 327 motor vehicles with connected vehicle (CV) applications, including V2V forward collision warning (FCW) and V2I situational awareness, work zone warning, and spot weather impact warning. All V2I applications provided advisories based on traveler information messages (TIMs), dealing with speed limits, traffic conditions, weather conditions, and work zones.

The Volpe team analyzed FCW alerts and TIM advisories that were issued to CV drivers during the WYDOT CVP deployment or after period from January through April 2022. The experimental design for this deployment site did not incorporate a baseline or before period for CVs. The Volpe team also analyzed the speed of all motor vehicles traveling on I-80 during January through April in 2017 and 2022.

Key results of this limited analysis are as follows:

<u>FCW</u>: the Volpe team identified 327 of 490 distinct FCW events (67 percent) as valid based on speed data, where the host vehicle (HV) was approaching the remote vehicle (RV) at alert onset. This alert validity analysis did not account for any kinematic information, such as time to collision. The analysis of vehicle/driver response to FCW alerts revealed that 30 percent of valid events were resolved within 10 seconds (s) after alert onset (i.e., the HV was no longer approaching the RV). Due to the lack of brake activation data in the database, the Volpe team was not able to calculate the HV brake response time and average deceleration during braking events.

<u>Traffic Speed</u>: the Volpe team analyzed traffic speed data that were collected by 64 roadside radars at different locations along I-80, comparing speed and time headway measures between a baseline period from January through April 2017 and the treatment period from January through April 2022. Unpaired t-tests revealed statistically-significant differences in performance between the baseline and treatment periods. The average traffic speed was higher by about 1 m/s (2.2 mph) and the average time headway between vehicles was lower by about 36 s in 2022 than in 2017 during the January-April timeframe. Paired t-tests between radar locations revealed statistically-significant differences in performance during peak traffic periods from 6 am to 9 am and 3 pm to 6 pm between the baseline and treatment periods. The average traffic speed was higher by about 1 m/s and the average time headway was lower by about 4 s in 2022 than in 2017 during the January-April timeframe.

<u>TIMs</u>: the Volpe team analyzed a total of 128,591 TIM alerts that were broken down by the following categories: speed limit, traffic conditions, weather conditions, and work zone. About 65 percent of all TIM alerts were related to weather conditions. The Volpe team only analyzed the HV travel speed at the onset of TIM advisory alerts (i.e., initial condition) by each of the four categories. Almost a quarter of TIM advisory alerts about traffic and weather conditions were issued to CVs traveling below 4 m/s (9 mph) and below 8 m/s (18 mph), respectively. This limited analysis of TIM alerts did not address vehicle/driver response to TIM alerts, such as speed reduction.

1 Introduction

This report presents the results of a limited analysis that assessed the safety impact of the safety applications deployed in the Wyoming Department of Transportation (WYDOT) Connected Vehicle Pilot (CVP) site. In September of 2015, the United States Department of Transportation's (U.S. DOT) Intelligent Transportation Systems Joint Program Office (ITS JPO) selected the following three sites to participate in their national CVP deployment Program: New York City (NYC), Tampa, and Wyoming.[1] The goal of this program was to spur innovation among early adopters of connected vehicle (CV) technologies and to gain a better understanding of the impact that these technologies might have on traffic safety, mobility, and the environment.

The CVP program consisted of the three following phases:

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

To satisfy the goal of understanding the impacts of the CVP deployments, the U.S. DOT's Volpe National Transportation Systems Center (Volpe) and Texas Transportation Institute performed independent evaluations at each pilot site. The Volpe team performed the independent safety evaluation of the safety applications deployed at all three CVP sites. The safety evaluation results produced by the Volpe team for Tampa and NYC sites are described in separate reports [1] [2]. On the other hand, the Texas Transportation Institute conducted evaluations on mobility and environmental impacts at the three CVP sites, as well as the national-level evaluations of CV deployments, and evaluated the performance of the overall CVP program.

Due to time and schedule constraints, the Volpe team conducted a limited, higher-level analysis for the WYDOT CVP site as compared to the more detailed analyses for the Tampa and NYC CVP sites.

2 WYDOT CVP Site Description

The WYDOT CVP team deployed CV equipment and devices along Interstate 80 (I-80), which is a major east/west corridor for motor freight traffic in the northwestern part of the country [3]. I-80 reaches its highest elevation of 8,640 feet (ft), 2,633 meters (m), nationwide in Wyoming and stays above 6,000 ft (1,829 m) elevation throughout most of the state. The high elevation and cold climate put vehicles that travel the corridor at risk of experiencing a variety of extreme weather-related events during the summer and winter months, including high winds, heavy snow, blowing snow, and low visibility. When these events occur, they result not only in crashes, injuries, and fatalities, but also in extended road closures that can directly impact the nation's economy. Thus, the primary goal of the WYDOT CVP deployment was to reduce weather-related crashes on the I-80 corridor by providing more accurate, timely, and relevant in-vehicle messages to heavy vehicles traveling the corridor.

The WYDOT CVP deployment included vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) safety applications that provided advisories, roadside warnings, and travel guidance to drivers traveling along the I-80 corridor. This deployment integrated CV technology with an existing transportation

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

management center (TMC) that currently provides road-condition reporting and maintenance. Data collected from CVs not only supported in-vehicle applications, but also provided high-resolution data to the TMC and enabled better traffic and incident management along the I-80 corridor.

2.1 Safety Applications

Table 1 lists the CV safety applications deployed in the WYDOT CVP site, the communication type, alert urgency level of the application, and a description of the application [4]. There are two types of safety applications that are based primarily on either V2V or V2I dedicated short-range communications. V2V applications rely on the communications from other CV-equipped vehicles, while V2I applications are triggered by data from roadside units (RSUs) installed in selected infrastructure locations.

The alert urgency level refers to the type of information communicated by the safety applications. The WYDOT CVP side deployed one crash-imminent alert and four advisory alerts:

- Imminent alerts: inform CV drivers that they must respond immediately to avoid a potential crash. For example, forward collision warning (FCW) alerts the driver to take an immediate action (e.g., brake) to avoid a rear-end collision.
- Advisory alerts: provide information to CV drivers that generally helps them drive more safely (e.g., a work zone alert notifies drivers that there is a work zone ahead). A scenario that can trigger an advisory alert may or may not result in a crash-imminent scenario, depending on the actions of the CV and the actions of surrounding vehicles.

Table 1. CV Safety Applications Deployed in the WYDOT CVP Site

CV Safety Application	V2V/V2I	Alert Urgency Level	Description
Forward Collision Warning (FCW)	V2V	Imminent	Improves safety through real-time alert of an impending rear-end collision with a CV ahead.
Situational Awareness (SA)	V2I	Advisory	Improves safety through (near) real-time wide area alerts of conditions in the downstream roadway or planned route, providing advisory information to CV drivers about road closures and speed limit changes.
Work Zone Warning (WZW)	V2I	Advisory	Improves safety through (near) real-time notification of unsafe work zones at specific points on the downstream roadway.
Spot Weather Impact Warning (SWIW)	V2I	Advisory	Improves safety through (near) real-time notification of localized hazardous weather events at specific points on the downstream roadway.
Distress Notification (DN)	Both	Advisory	Notifies emergency authorities and vehicles traveling upstream that an event/crash has occurred.

The limited analysis in this report addresses the FCW, SA, WZW, and SWIW safety applications, excluding the DN application.

2.2 CV Equipment

As of February 2, 2022, the WYDOT CVP site has deployed 76 RSUs along I-80 and has equipped a total of 327 motor vehicles with CV equipment with the ability to:

- Share and receive information via dedicated short-range communication from other connected devices (vehicles and roadside units).
- Broadcast Basic Safety Message (BSM) Parts I and II
- Receive Traveler Information Messages (TIM)
- Communicate imminent and advisory alerts to drivers via human-machine interface.

The breakdown of the 327 CVs, in descending order by their installation rate, is as follows:

- 169 (51.7%) heavy-duty/commercial fleet vehicles
- 66 (20.2%) Wyoming highway patrol vehicles
- 53 (16.2%) WYDOT maintenance fleet vehicles (i.e., snowplows)
- 21 (6.4%) medium-duty fleet vehicles
- 18 (5.5%) Wyoming state pool fleet vehicles

2.3 Experimental Design

The WYDOT CVP deployment had two phases:

- Before (pre-deployment) period: spanned from December 2016 through November 2017. Vehicles were not equipped with CV devices during this period. The WYDOT CVP team collected non-CV system data, such traffic speed data from roadside traffic detectors, weather data, and crash records.
- After (post-deployment) period: spanned from Fall 2021 through Spring 2022. During this period, the WYDOT CVP team deployed CV devices and applications and collected both non-CV and CV system data.

2.4 Evaluation Data

The WYDOT CVP team collected an extensive set of data both from CV systems and the existing traffic management systems (non-CV systems). Table 2 provides a summary of the data types, including a description of the data, sample data elements, and which test period the data source was available for.

Table 2. WYDOT CVP Safety Evaluation Data Sources

Data Type	Description	Data Elements	Before Data
BSM	BSM Parts 1 and 2, collected at 10 Hz around an interaction, otherwise 1/30 Hz.	BSM message set, including controller area network elements.	No
Vehicle speed data	Collected from radar-based speed sensors, providing records for individual vehicles.	Date, time, vehicle length, speed, lane (right or left), etc.	Yes
CV event logs	Logs of all CV alerts issued to drivers.	Event type, timestamp.	No
WYDOT construction events	Records of construction activity.	Location, start time, end time.	Yes
TIM	Provides a variety of roadway information about road closures and construction zones.	Work zones, road closures, emergency events, etc.	No
Road Weather Information System	Wyoming state road weather information logs, collected from roadside weather sensors.	Temperature, pavement temperature, wind speed, wind gust, precipitation, visibility, road surface conditions.	Yes
Variable Speed Limits	Data that indicates the posted speed for a specific road segment at a specific time (due to changes in speed due to weather, etc.).	Location, date, time, suggested speed.	Yes

3 Analysis of FCW Events

This section discusses the results of analyzing FCW events in the WYDOT CVP deployment, including:

- Analysis sample of distinct FCW events
- Filtering of data issues and invalid FCW events
- Analysis of initial conditions at FCW alert onset
- Analysis of vehicle/driver response to FCW alerts

3.1 Distinct FCW Events

The Volpe team analyzed FCW events using the "Alert" and "BSM" data tables in WYDOT CVP's database in the Secure Data Commons (SDC).[2] This analysis identified 197,812 records of FCW alerts in the "Alert" table, which were issued to drivers during the WYDOT CVP deployment period from January through April 2022. Many of these FCW alerts occurred within very short time intervals and involved the same vehicles. Based on the timing of these alerts, the Volpe team determined that FCW alerts should be treated as distinct events when there were no other records of FCW events for the same temporary vehicle ID at least 30 seconds (s) before the alert onset time. Thus, consecutive FCW alerts

[2] The SDC is a cloud-based data analytics platform, built by the ITS JPO to support the CVP program. The platform is designed to maintain the security of the CVP data, while still allowing access to those who need it (i.e., CVP teams and evaluators), and is equipped with analytical tools that evaluators need to conduct the evaluation.

that were within 30 s of the previous alert were treated as the same overall event. This logic yielded a total of 490 distinct FCW events, or 0.25% of the total number of FCW records.

In order to analyze the 490 distinct FCW events, the Volpe team queried the BSM data in the "BSM" table that contained the same temporary vehicle ID and with date-times 20 s before and 20 s after the alert onset time. The resulting BSM dataset allowed for the calculation of initial conditions at FCW alert onset and vehicle/driver response after FCW alert onset.

3.2 FCW Event Filtering

The Volpe team removed FCW events due to the following data issues:

1. Unavailable BSM data for either the host vehicle (HV), receiving the FCW alert, or the remote vehicle (RV), triggering the FCW alert.
2. Unavailable RV data within 0.5 s before and 0.5 s after alert onset.
3. HV speed greater than 85 miles per hour (mph) (38 m/s) at alert onset.

After removing FCW events with data issues, the Volpe team assessed the validity of FCW events based on the premise that valid events involve an HV following or approaching an RV in the same lane ahead at speeds greater than or equal to 5 mph (2.2 m/s). Thus, FCW events would be invalid if:

1. HV and RV were separating at alert onset with relative speed or range rate, Rdot(0), greater than or equal to 2.5 mph (1.1 m/s)
    - $Rdot(0) = V_{RV}(0) - V_{HV}(0)$
    - $V_{RV}(0)$ = RV speed at alert onset
    - $V_{HV}(0)$ = HV speed at alert onset
2. $V_{HV}(0)$ is less than 5 mph

Event filtering resulted in the following two distinct valid FCW events:

- HV following RV, -2.5 mph < Rdot(0) < 2.5 mph
- HV approaching or closing in on RV, Rdot(0) ≤ -2.5 mph

Table 3 presents the results of FCW event filtering and validity. Event filtering removed a total of 156 or about 32 percent of all 490 distinct FCW events, based on the three filters listed above. Unavailable BSM data accounted for 89 percent of all FCW events with data issues. Using the two criteria listed above, the assessment of valid FCW events resulted in only six invalid events. FCW events with valid alerts comprised of only one following event and 327 approaching events, totaling 328 or 98% of all FCW events without any data issues. It should be noted that these events require further validation by:

- Assessment of kinematic information at FCW alert onset, including R(0) = range or distance, TTC(0) = time to collision,[3] and TH(0) = time headway between the RV and HV at alert onset.[4] Such kinematic information has not yet been processed from GPS coordinates at the time of writing this report.
- Visual examination of the time series of HV and RV in each event using Volpe's event visualization tool [1].

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[3] TTC(0) = R(0) / Rdot(0)

[4] $TH(0) = R(0) / V_{HV}(0)$

Table 3. Data Issues and Validity Filters for FCW Events

Filter Type	Filter	Count of Events	Percent of Events
Data Issues	$V_{HV}(0)$ > 85 mph	7	1%
	No RV data within 0.5 s before or after alert onset	10	2%
	No HV or RV BSM data	139	28%
Invalid Alerts	$V_{HV}(0)$ < 5 mph	3	1%
	Vehicles separating at alert onset	3	1%
Valid Alerts	HV following RV at alert onset	1	0.2%
	HV approaching or closing in on RV	327	67%
	Total	490	100%

The Volpe team analyzed the initial conditions and vehicle/driver response to the 327 approaching or closing FCW events and excluded the one following event from the analysis.

3.3 Initial Conditions of FCW Alerts

The Volpe team analyzed the following measures for the initial conditions of FCW alerts:

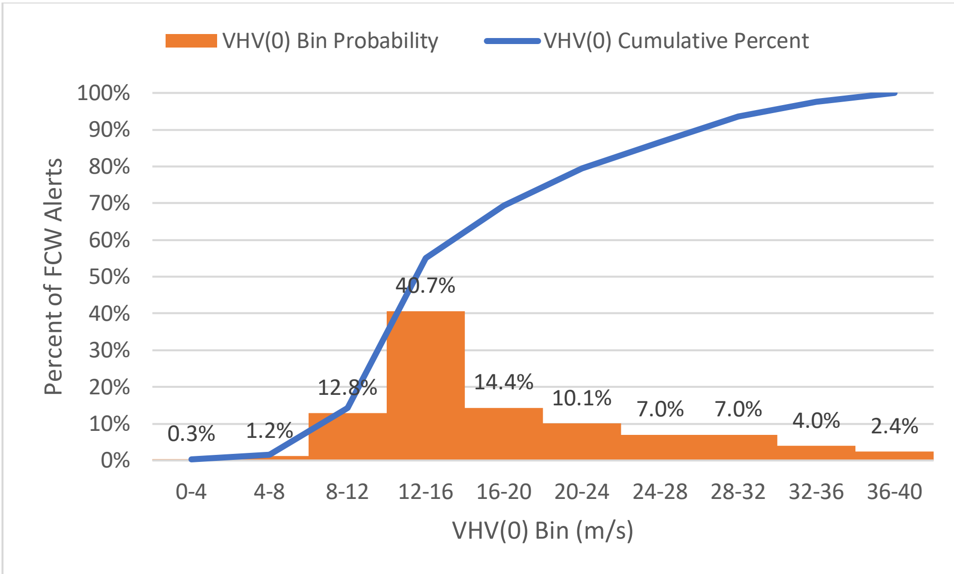
1. $V_{HV}(0)$
2. $V_{RV}(0)$
3. Rdot(0)

Table 4 provides descriptive statistics of valid FCW events at alert onset. The mean HV speed at alert onset was 40.3 mph (18 m/s), at least 15 mph (6.7 m/s) below posted speed limits on freeways. The mean closing speed at alert onset (|Rdot(0)|) was 26.8 mph (12.0 m/s), indicating traffic conditions with very high speed differentials between vehicles.

Table 4. Descriptive Statistics for Initial Conditions of FCW Events

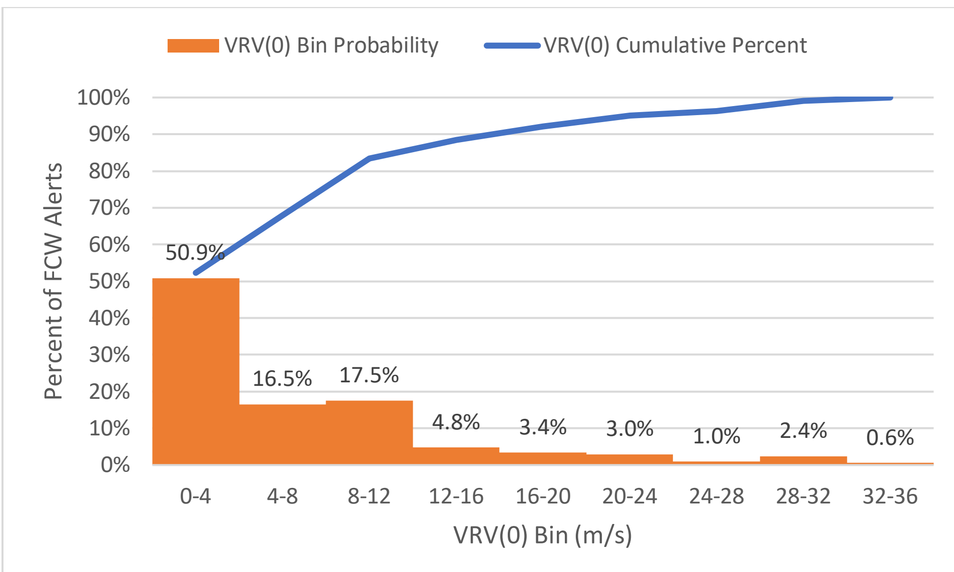
Statistic	$V_{HV}(0)$ (m/s)	$V_{RV}(0)$ (m/s)	Rdot(0) (m/s)
Count	327	327	327
Mean	18.0	6.0	-12.0
StdDev	7.2	7.9	7.3
Minimum	2.8	0.0	-37.8
Median	15.3	2.7	-11.8
Maximum	37.8	32.5	-1.4

Figure 1, Figure 2, and Figure 3 display the probability density functions and the cumulative distribution functions respectively for $V_{HV}(0)$, $V_{RV}(0)$, and Rdot(0). It should be noted that about 51 percent of valid FCW events involved a lead vehicle or RV speed below 9 mph (4 m/s), while the HV was traveling at speeds between 27 mph (12 m/s) and 36 mph (16 m/s) in about 41 percent of these events. Moreover, about 87 percent of valid FCW events happened at absolute relative speed below 45 mph (20 m/s).



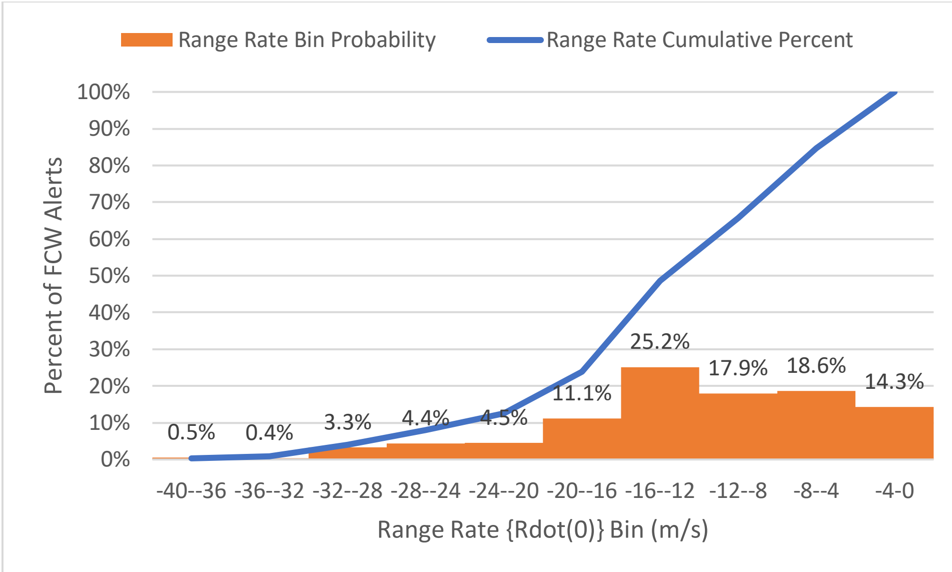
Source: U.S DOT Volpe Center

Figure 1. Probability Density and Cumulative Distribution Functions of HV Speed at Alert Onset



Source: U.S DOT Volpe Center

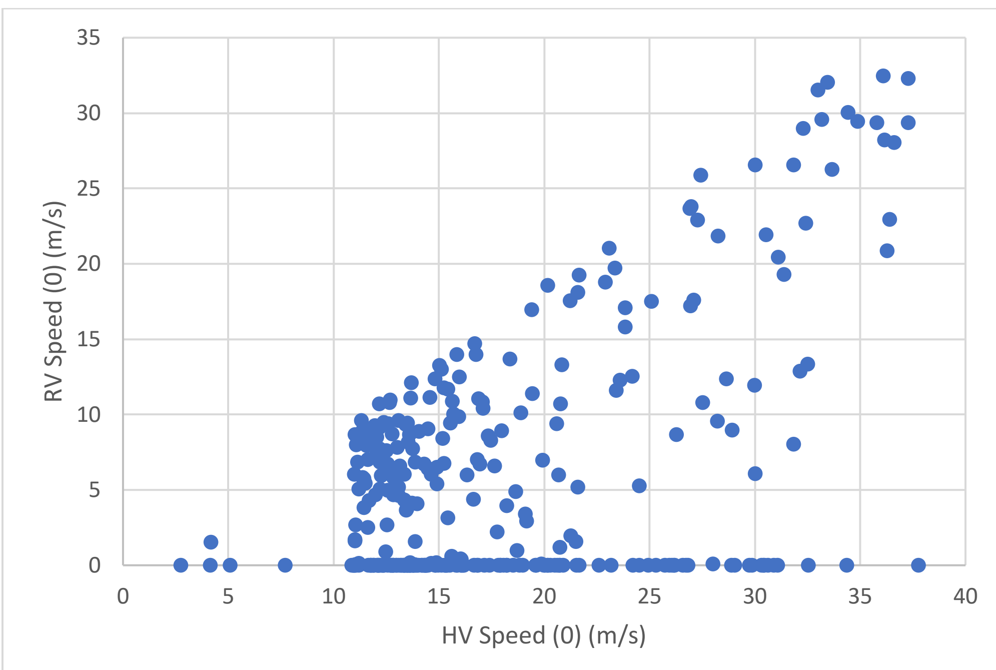
Figure 2. Probability Density and Cumulative Distribution Functions of RV Speed at Alert Onset



Source: U.S DOT Volpe Center

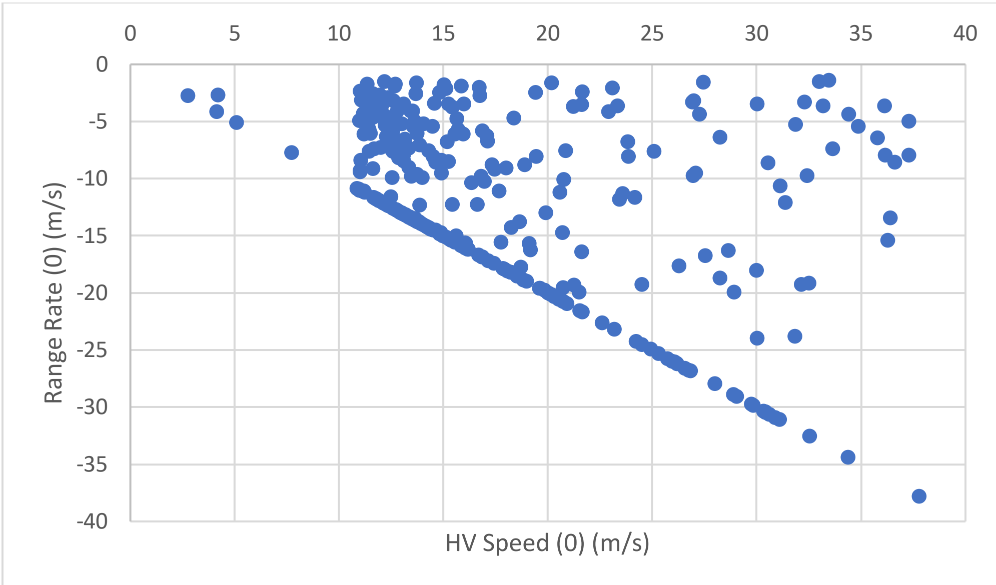
Figure 3. Probability Density and Cumulative Distribution Functions of Range Rate at Alert Onset

Figure 4 and Figure 5 present the scatter plots of $V_{HV}(0)$ versus $V_{RV}(0)$ and $V_{HV}(0)$ versus Rdot(0), respectively. The diagonal line in Figure 5 refers to FCW events where the RV speed was zero at alert onset.



Source: U.S DOT Volpe Center

Figure 4. Scatter Plot of HV Speed versus RV Speed at Alert Onset



Source: U.S DOT Volpe Center

Figure 5. Scatter Plot of HV Speed versus Range Rate at Alert Onset

3.4 Vehicle/Driver Response to FCW Alerts

The Volpe team analyzed vehicle/driver response to FCW alerts during a 10-s window after alert onset, using the following measures of performance:

1. Driving conflict resolution, whether the closing speed fell below 2.5 mph (1.1 m/s) over 10 s after alert onset.
2. Time to resolve the driving conflict (tRC), measured from alert onset time until the time Rdot > -2.5 mph.
3. HV speed reduction by over 5 mph (2.2 m/s).
4. Vehicle/driver response time from FCW alert onset until HV speed was reduced by 5 mph.
5. Minimum HV speed (V_{HV}min).
6. HV speed reduction or delta V (ΔV_{HV}), where $\Delta V_{HV} = V_{HV}(0) - V_{HV}$min.
7. HV mean and peak deceleration values from $V_{HV}(0)$ to V_{HV}min.

Table 5 shows the results of FCW driving conflict resolution, including the count and percentage of resolved and unresolved FCW events. The majority of FCW events (70%) was not resolved within 10 s after alert onset. This implies that FCW alerts were issued at long TTC(0), the HV changed lanes in response to the alert, the HV needed longer than 10 s to resolve the driving conflict, or the HV and RV might not have been in the same lane at alert onset (i.e., invalid alert).

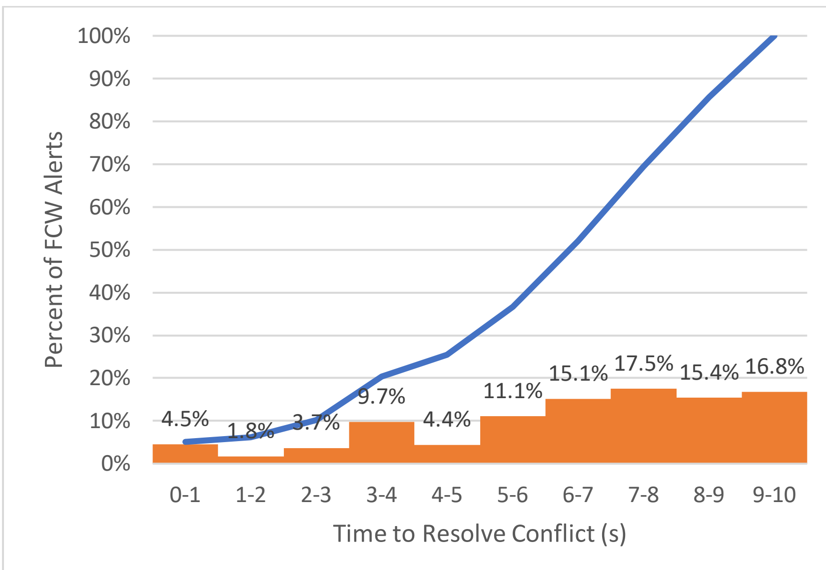
Table 5. Analysis Results of FCW Driving Conflict Resolution

Conflict Resolved?	Count of Events	Percent of Events
No	229	70%
Yes	98	30%
Total	327	100%

Table 6 provides descriptive statistics of tRC in the 98 FCW events that were resolved by the vehicle/driver in response to the alert. Figure 6 displays the probability density function and the cumulative distribution function of tRC. It took at least 5 s from alert onset to resolve about 75 percent of FCW events and under 1 s to resolve 5 percent of the events.

Table 6. Descriptive Statistics of Time to Resolve FCW Conflicts within 10 Seconds after Alert Onset

Statistic	Time to Resolve Conflict (s)
Count	98
Mean	6.33
StdDev	2.44
Minimum	0
Median	6.55
Maximum	9.8



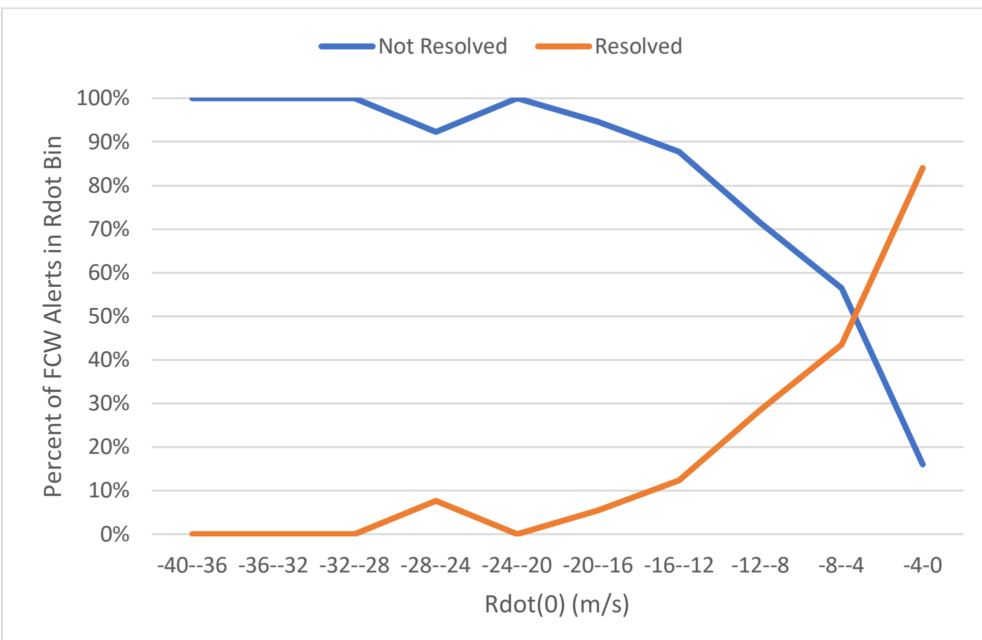
Source: U.S DOT Volpe Center

Figure 6. Probability Density and Cumulative Distribution Functions of Time to Resolve FCW Conflict

Table 7 provides counts of resolved and unresolved FCW events (i.e., driving conflicts) as a function of Rdot(0), as well as the percentages of these two types of events in each Rdot(0) bin as illustrated in Figure 7. There is a clear trend where more FCW events were resolved at lower absolute Rdot(0) bin values within 10 s after alert onset, as opposed to more unresolved FCW events at higher absolute bin values of Rdot(0). It is possible that some of the unresolved events in the latter case were due to invalid alerts (i.e., HV and RV were potentially not in the same lane) or involved an HV simply changing lanes to pass the RV safely without slowing down. For closing speeds over 35 mph, Rdot(0) < - 16 m/s, 75 out of 78 (96%) FCW events were unresolved within 10 s after alert onset. On the other hand, 69 out of 112 (62%) FCW events were resolved for closing speeds under 18 mph, Rdot(0) > -8 m/s.

Table 7. Counts of Resolved and Unresolved FCW Events as a Function of Rdot(0)

Rdot(0) m/s	Count of Conflicts Not Resolved	Count of Conflicts Resolved	Total Count	Percent of Conflicts Not Resolved	Percent of Conflicts Resolved	Total Percent
-40--36	1	0	1	100%	0%	100%
-36--32	2	0	2	100%	0%	100%
-32--28	10	0	10	100%	0%	100%
-28--24	12	1	13	92%	8%	100%
-24--20	15	0	15	100%	0%	100%
-20--16	35	2	37	95%	5%	100%
-16--12	71	10	81	88%	12%	100%
-12--8	40	16	56	71%	29%	100%
-8--4	35	27	62	56%	44%	100%
-4-0	8	42	50	16%	84%	100%
Total	**229**	**98**	**327**	**70%**	**30%**	**100%**



Source: U.S DOT Volpe Center

Figure 7. Percentages of Resolved and Unresolved FCW Events by Rdot(0) Bin

In order to characterize vehicle/driver brake response to FCW alerts, the Volpe team analyzed the following measures: HV speed reduction by over 5 mph (2.2 m/s), V_{HV}min, and ΔV_{HV}. It should be noted that brake activation data were not available in WYDOT CVP's BSM data. All entries for brake activation columns were empty or 0 for all BSM data surrounding FCW alerts. Therefore, the Volpe team defined a brake response as a reduction in speed after alert onset by 5 mph or greater. Table 8 provides the counts and percentages of FCW events that experienced such a speed reduction or not. The majority of FCW events (85%) exhibited a speed reduction of at least 5 mph within 10 s after alert onset.

Table 8. Counts and Percentages of FCW Events by HV Speed Reduction of at Least 5 mph

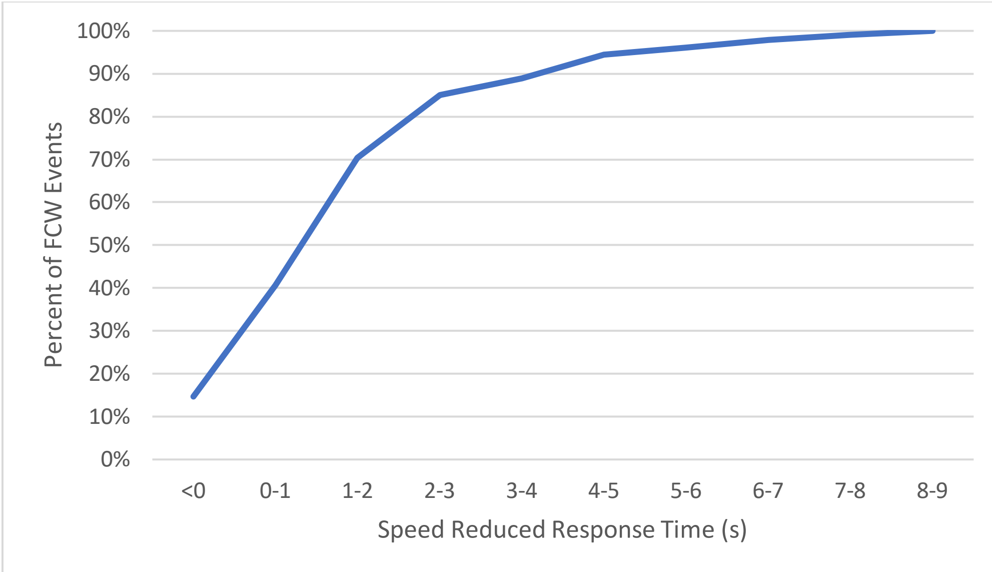
HV Speed Reduced?	Count of Events	Percent of Events
No	48	14.7%
Yes	279	85.3%
Total	327	100.0%

Table 9 provides descriptive statistics of various measures of performance for vehicle/driver brake response to FCW alerts. The average HV response time to reduce initial speed at FCW alert onset by 5 mph was about 2 s, with mean and peak deceleration levels to V_{HV}min respectively at 0.11 and 0.23 g (9.81 m/s^2).

Table 9. Descriptive Statistics of Various Vehicle/Driver Brake Measures in Response to FCW Alerts

Statistic	Speed Reduced Response Time (s)	Mean Deceleration (m/s^2)	Peak Deceleration (m/s^2)	V_{HV}min (m/s)	ΔV_{HV} (m/s)
Count	279	279	279	279	279
Mean	1.98	-1.12	-2.24	7.40	9.80
StdDev	1.66	0.50	0.92	6.95	4.59
Minimum	0.20	-3.16	-5.97	0.00	1.34
Median	1.50	-1.11	-2.13	5.70	9.22
Maximum	8.80	-0.15	-0.36	35.96	25.34

Figure 8 shows the cumulative distribution of vehicle/driver response time from FCW alert onset until HV speed was reduced by 5 mph for all valid FCW events. The Volpe team observed that drivers reduced their speed by 5 mph in less than 3 s after alert onset in over 85 percent of FCW events.



Source: U.S DOT Volpe Center

Figure 8. Cumulative Distribution of Time to Reduce HV Speed by 5 mph in Response to FCW Alerts

Due to the lack of baseline data (i.e., vehicle/driver performance in FCW events with 'silent' alerts) in the WYDOT CVP deployment, the Volpe team was not able to compare the various vehicle/driver response measures between the baseline condition and the treatment condition (i.e., vehicle/driver performance in FCW events with 'active' alerts).

4 Analysis of Traffic Speed

This section presents the results of analyzing traffic speed data that were collected by 64 roadside radar sensors along I-80. This analysis compares the speed of all motor vehicles passing by these radar locations between a baseline period from January through April 2017 and the treatment period from January through April 2022. The baseline period did not include any CVs while the treatment period had at least 327 CVs (Section 2.2). It should be noted that this analysis included all speed data and did not remove speed values over 85 mph (38 m/s), as done in the FCW analysis.

The Volpe team examined the following measures of performance:

- Mean traffic speed
- Minimum traffic speed
- Maximum traffic speed
- Mean speed of vehicles traveling under the posted speed limit
- Mean speed of vehicles traveling over the posted speed limit
- Mean time headway between vehicles (time between measurements of vehicles traveling in the same lane)

All speed measures were computed using as units the average values of recorded speed for each lane at each radar location. Similarly, the time headway was averaged from the time intervals between speed measurements of vehicles traveling in the same lane at each radar location.

Table 10 provides the descriptive statistics of above measures for the baseline and treatment periods, along with the unpaired t-test results for any statistically-significant difference between the two periods. The counts in Table 10 are per radar location, per lane, per month, and per time period (5 blocks per 24-hour day and not all radar locations have all hours). The statistical analysis revealed statistically-significant differences between the baseline and treatment periods in all six measures of performance (i.e., P value is under 0.05). Generally, the average traffic speed was higher in 2022 than in 2017 during the January-April timeframe by about 1 m/s (2.2 mph). In contrast, the average time headway between vehicles was lower in 2022 than in 2017 during the same timeframe by about 36 s. These statistics are independent of weather and day/time conditions.

Table 10. Descriptive Statistics and Unpaired t-Test Results for Various Measures between 2017 and 2022

Measure	Period	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
Mean Speed (m/s)	2017	654	29.9	2.7	18.8	30.4	36.5	<< 0.05
	2022	1,268	30.9	2.2	21.5	31.3	36.2	
Minimum Speed (m/s)	2017	654	7.1	4.5	0.0	6.7	21.8	<< 0.05
	2022	1,268	5.1	3.6	0.0	4.9	22.4	
Maximum Speed (m/s)	2017	654	54.1	8.0	28.2	54.1	64.8	<< 0.05
	2022	1,268	58.2	5.3	42.0	59.1	64.8	
Mean Speed Limit Differential under Speed Limit (m/s)	2017	654	-4.9	1.9	-13.3	-4.5	-2.3	<< 0.05
	2022	1,268	-4.2	1.6	-12.0	-3.9	-1.7	
Mean Speed Limit Differential over Speed Limit (m/s)	2017	654	3.0	0.9	0.0	2.8	7.3	<< 0.05
	2022	1,268	3.3	0.9	1.3	3.3	7.3	
Mean Headway (s)	2017	654	74.7	218.6	6.0	34.0	3042.0	<< 0.05
	2022	1,268	38.4	29.0	6.0	28.0	209.0	

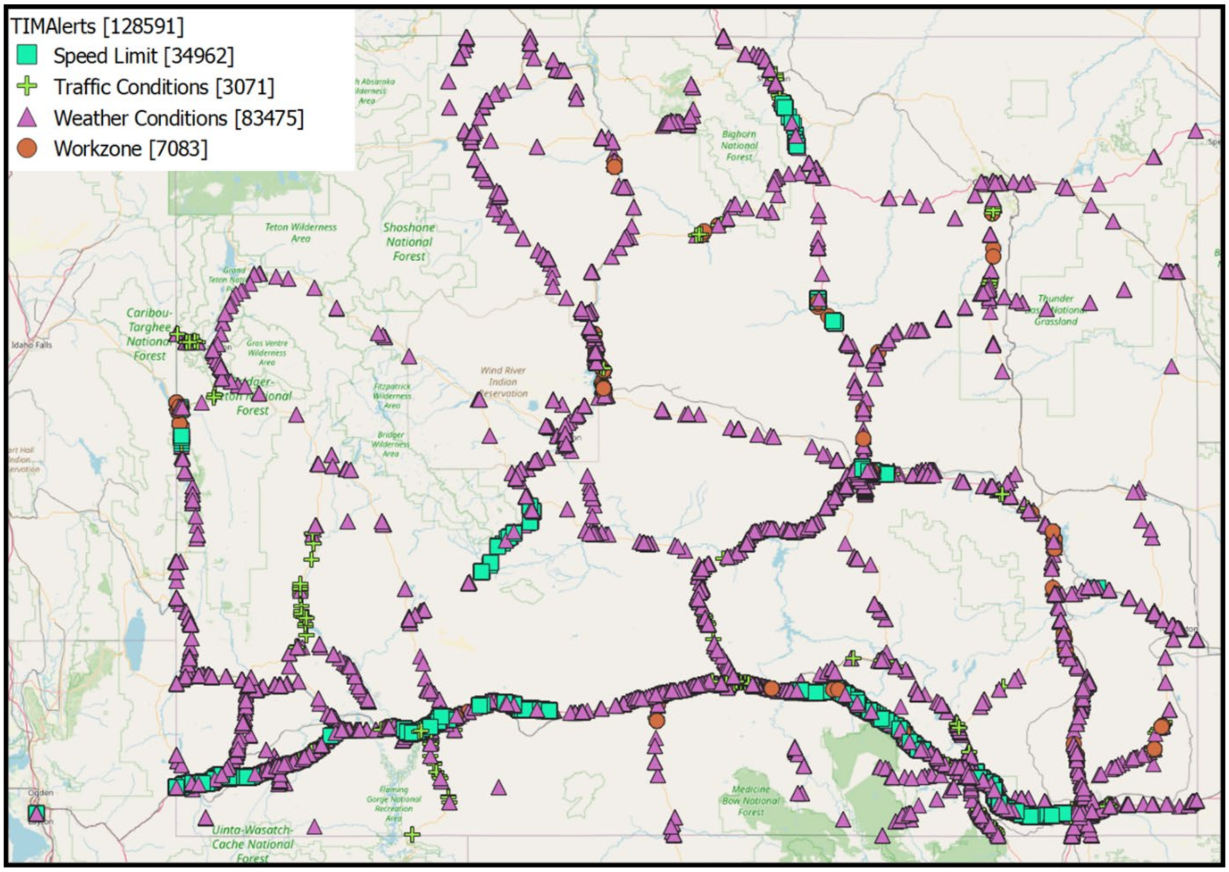
Table 11 provides descriptive statistics of the six measures of performance for the baseline and treatment periods during peak traffic periods from 6 am to 9 am and 3 pm to 6 pm, along with paired t-test results for any statistically-significant difference between the two periods. The counts in Table 11 are only per radar sensor and only for sensors that had data in 2017 and 2019; many radar sensors only had data in one of the two periods. The statistical analysis revealed statistically-significant differences between the baseline and treatment periods in all six measures of performance (i.e., P value is under 0.05). Generally, the average traffic speed was higher in 2022 than in 2017 during the January-April timeframe by about 1 m/s (2.2 mph). In contrast, the average time headway between vehicles was lower in 2022 than in 2017 during the same timeframe by about 4 s. These statistics are independent of weather and the day of the week.

Table 11. Descriptive Statistics and Paired t-Test Results for Various Measures during Peak Travel Hours between 2017 and 2022

Measure	Period	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
Mean Speed (m/s)	2017	28	30.2	1.9	25.0	30.5	34.4	<<0.05
	2022	28	31.0	2.3	25.0	31.5	35.1	
Minimum Speed (m/s)	2017	28	7.0	2.6	2.2	6.6	14.2	<<0.05
	2022	28	5.7	2.5	0.9	5.4	11.3	
Maximum Speed (m/s)	2017	28	54.7	5.0	42.1	54.3	63.4	<<0.05
	2022	28	58.2	4.2	49.5	58.4	64.4	
Mean Speed Limit Differential under Speed Limit (m/s)	2017	28	-4.8	1.6	-9.7	-4.5	-2.6	<<0.05
	2022	28	-4.2	1.8	-9.5	-3.6	-2.5	
Mean Speed Limit Differential over Speed Limit (m/s)	2017	28	3.2	0.6	2.1	3.1	5.5	<<0.05
	2022	28	3.4	0.7	2.0	3.4	5.8	
Mean Time Headway (s)	2017	28	29.1	10.7	11.7	29.1	55.3	<<0.05
	2022	28	25.2	8.2	10.9	24.8	42.3	

5 Analysis of Traveler Information Alert Applications

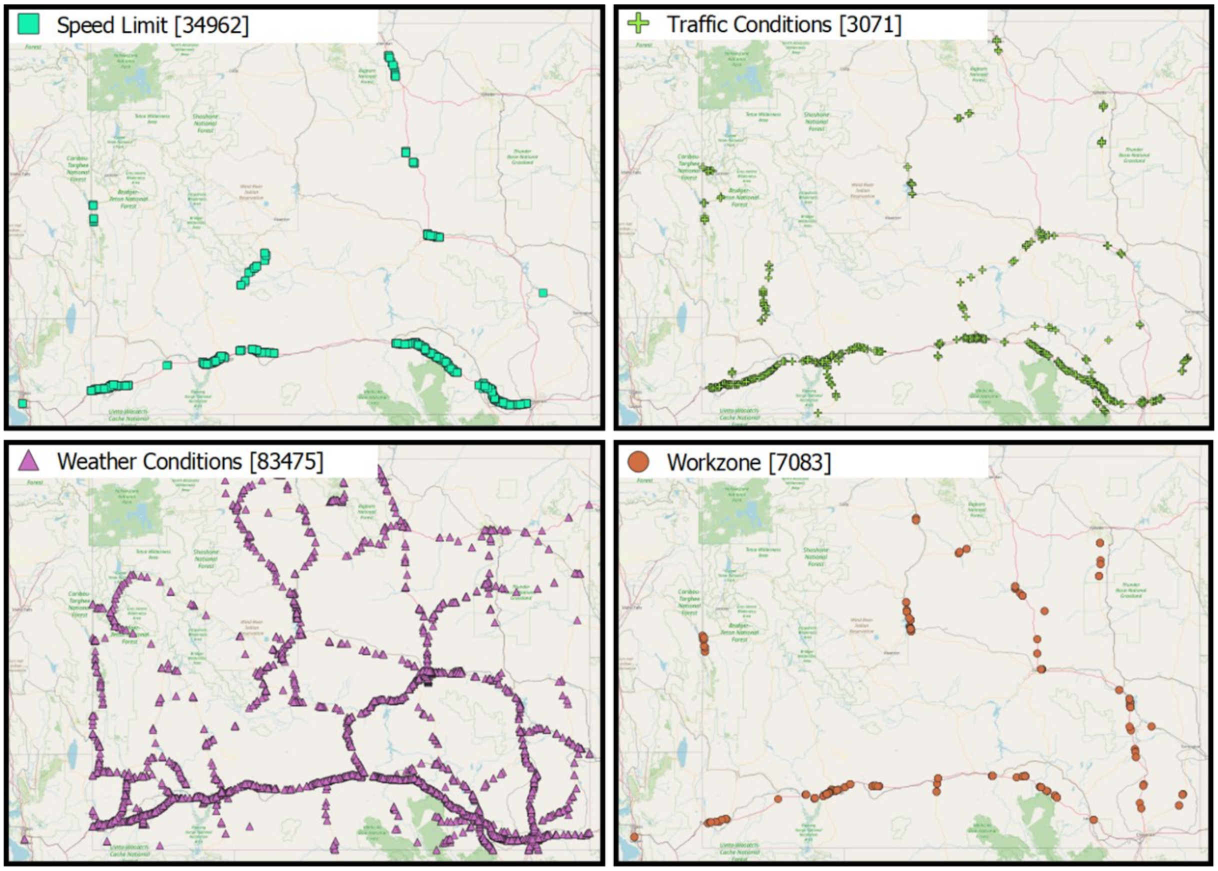
This section presents the results of analyzing TIM alerts that convey important traffic information and provide situational awareness warnings to CV drivers. These alerts fall under four categories: speed limit, traffic conditions, weather conditions, and work zone. The SA application addresses speed limit changes, traffic conditions, and area-wide weather conditions. The WZW application issues notifications about upcoming work zones. The SWIW application alerts drivers to localized adverse weather conditions. Figure 9 provides the geographical locations of all TIM alerts that the CVs received while traveling on Wyoming roadways. These alerts were supposed to be transmitted from RSUs located throughout I-80 in the WYDOT CVP site to CVs; however, the CVs received such alerts anywhere in the state by short-range communications and other means of communications. Figure 10 illustrates the geographical distribution of TIM alerts by each of the four alert categories.



Source: U.S DOT Volpe Center

Figure 9. Geographic Locations of All TIM Alerts Received by CVs from January through April 2022[5]

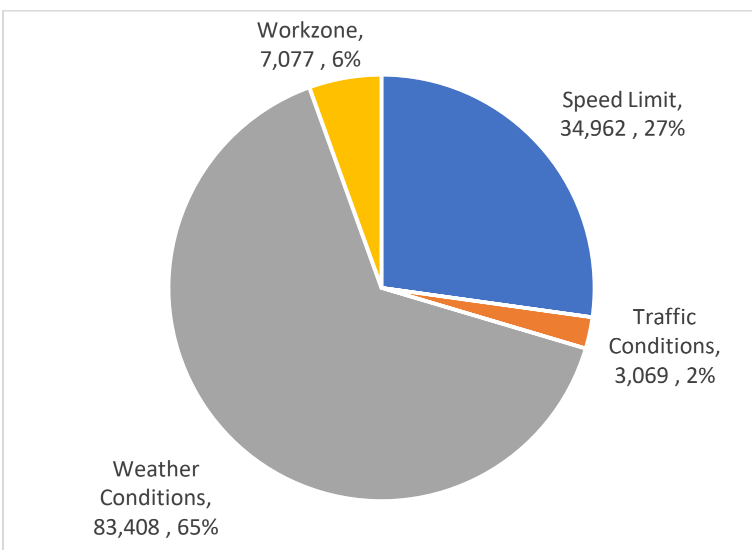
[5] Base maps for the figures above curtesy of the Open Street Maps project (© OpenStreetMap contributors). Copyright information available at https://www.openstreetmap.org/copyright



Source: U.S DOT Volpe Center

Figure 10. Locations of TIM Alerts Received by CVs from January through April 2022 by Alert Category

Figure 11 illustrates the distribution of all TIM alerts by the four different categories.



Source: U.S DOT Volpe Center

Figure 11. Distribution of TIM Alerts by Category Observed from January through April 2022

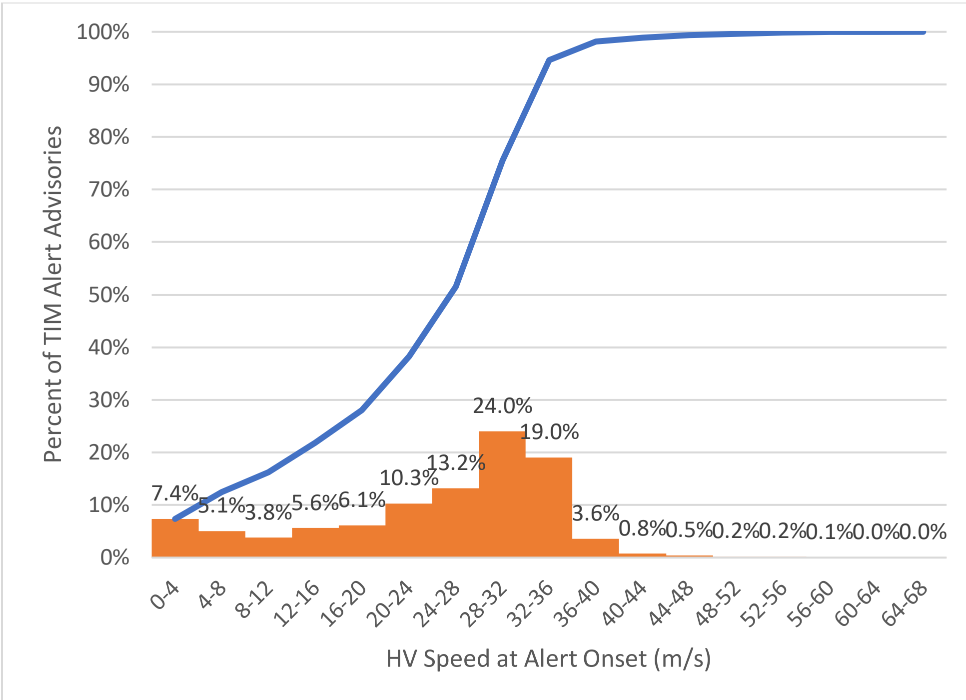
The Volpe team only analyzed the HV travel speed at the onset of TIM advisory alerts (i.e., initial condition) by each of the four categories, independent of vehicle type. This limited analysis did not address vehicle/driver response to TIM alerts. Moreover, this analysis considered all TIM alerts and did not focus on only those alerts that occurred on I-80 (i.e., WYDOT CVP site).

Table 12 provides the descriptive statistics of HV speed at TIM alert onset. The CVs received TIM alerts at all travel speeds, including zero speed (i.e., stopped CVs) and speeds as high as 67 m/s (150 mph). It should be noted that the Volpe team did not filter out any observed travel speed, since very high speeds might be attributed to highway patrol vehicles. TIM alerts about traffic conditions corresponded to the smallest observed mean travel speed of about 18 m/s (40 mph), indicating that the traffic had already been moving below the speed limit at the onset of these alerts. On the other hand, TIM alerts about speed limit changes and work zones were issued to vehicles traveling at a mean speed of about 24 m/s (55 mph).

Table 12. Descriptive Statistics of HV Speed (m/s) at Onset of TIM Advisory Alerts

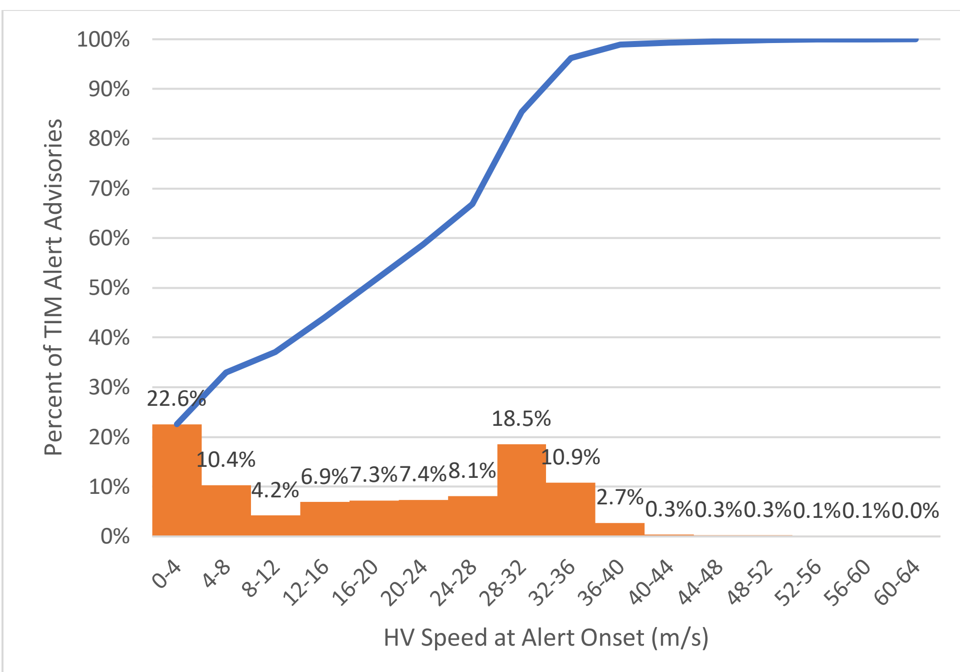
TIM Category	Count	Mean	StdDev	Minimum	Median	Maximum
Speed Limit	34,962	24.3	10.7	0.0	27.5	67.2
Traffic Conditions	3,069	18.2	12.6	0.0	19.4	60.4
Weather Conditions	83,408	20.2	11.4	0.0	22.9	67.0
Work Zone	7,077	24.2	10.6	0.0	28.3	67.1

Figure 12, Figure 13, Figure 14, and Figure 15 display the probability density and cumulative distribution functions of HV travel speed at the onset of TIM advisory alerts respectively for speed limit changes, traffic conditions, weather conditions, and work zones. Almost a quarter or about 23 percent of TIM advisories about traffic conditions were issued to vehicles traveling below 4 m/s (9 mph). Also, about 24 percent of TIM advisories about weather conditions were issued to vehicles traveling below 8 m/s (18 mph). It should be noted that the Volpe team did not distinguish TIM advisories about weather conditions between wide-area or localized weather events.



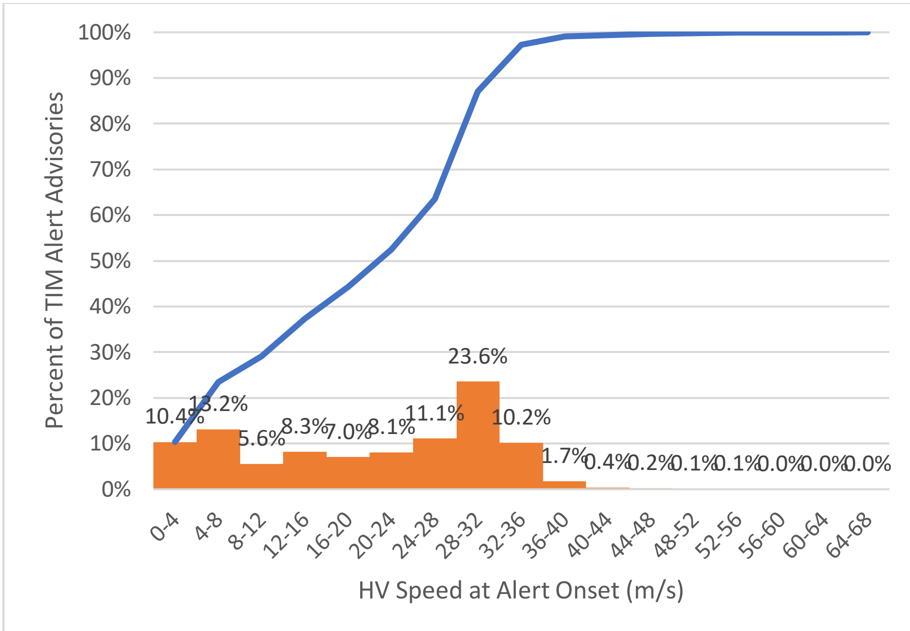
Source: U.S DOT Volpe Center

Figure 12. Probability Density and Cumulative Distribution Functions of HV Speed at Alert Onset for Speed Limit Changes



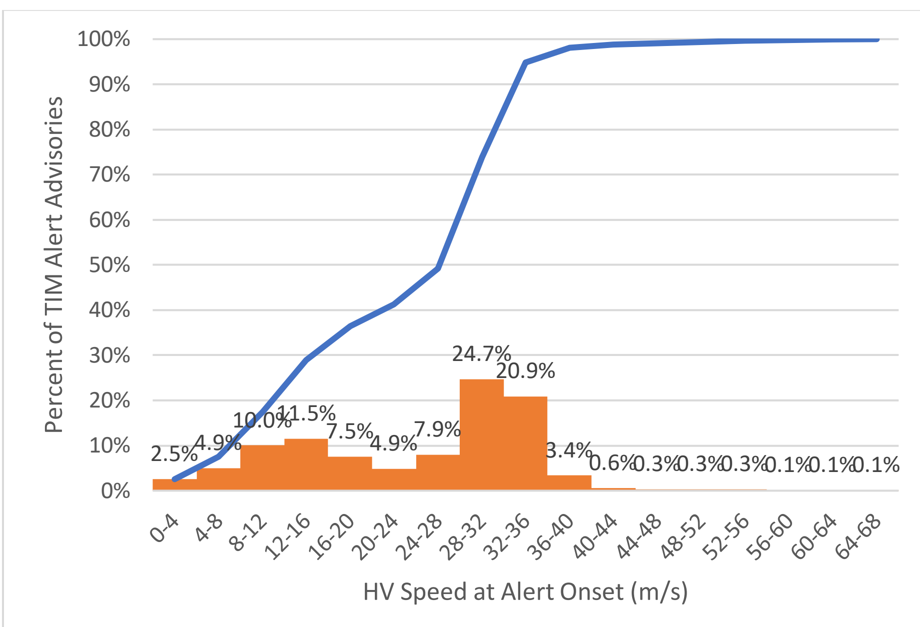
Source: U.S DOT Volpe Center

Figure 13. Probability Density and Cumulative Distribution Functions of HV Speed at Alert Onset for Traffic Conditions



Source: U.S DOT Volpe Center

Figure 14. Probability Density and Cumulative Distribution Functions of HV Speed at Alert Onset for Weather Conditions



Source: U.S DOT Volpe Center

Figure 15. Probability Density and Cumulative Distribution Functions of HV Speed at Alert Onset for Work Zones

Finally, the Volpe team conducted further analysis of TIM advisory alerts about speed limit changes by examining HV speed at alert onset for each specific speed limit. Table 13 provides descriptive statistics of this measure for 13 different speed limits, varying from 15 mph (6.7 m/s) to 80 mph (35.8 m/s).

Table 13. Descriptive Statistics of HV Speed (m/s) at Onset of TIM Alerts about Speed Limits

Speed Limit	Count	Mean	StdDev	Minimum	Median	Maximum
Speed-limit 15 mph (6.7 m/s)	23	6.2	7.1	0.0	3.8	28.8
Speed-limit 25 mph (11.2 m/s)	16	18.6	12.0	1.3	24.3	31.3
Speed-limit 30 mph (13.4 m/s)	11	22.2	4.3	14.7	22.4	28.1
Speed-limit 35 mph (15.6 m/s)	392	19.2	12.1	0.0	20.8	42.4
Speed-limit 40 mph (17.9 m/s)	5	17.1	3.2	12.6	16.4	20.4
Speed-limit 45 mph (20.1 m/s)	5,912	17.3	9.8	0.0	15.6	60.1
Speed-limit 50 mph (22.4 m/s)	154	23.0	7.4	0.0	23.3	36.5
Speed-limit 55 mph (24.6 m/s)	2,334	21.7	12.2	0.0	25.2	62.0
Speed-limit 60 mph (26.8 m/s)	2,948	23.0	5.1	0.0	23.5	66.7
Speed-limit 65 mph (29.1 m/s)	6,306	26.7	10.0	0.0	29.7	66.5
Speed-limit 70 mph (31.3 m/s)	211	28.7	6.8	4.1	30.6	41.2
Speed-limit 75 mph (33.5 m/s)	13,035	26.0	11.0	0.0	29.9	67.0
Speed-limit 80 mph (35.8 m/s)	1,927	27.3	7.8	0.0	29.7	66.6

6 Conclusion

The Volpe team conducted a limited analysis of the V2V FCW application, traffic speed, and TIMs related to the V2I SA, WZW, and SWIW applications deployed in the WYDOT CVP site along I-80. These safety applications issued crash-imminent and advisory alerts to 327 CVs that comprised 190 commercial medium- and heavy-duty vehicles and 137 state vehicles. The analysis of active FCW and TIM alerts was based on data collected during the CV treatment period between January and April 2022. The WYDOT CVP deployment did not incorporate a baseline period for CVs to receive silent alerts, hindering the comparison of vehicle/driver response between silent and active alerts. In contrast, the analysis of traffic speed involved data from roadside detectors that collected speed information of all motor vehicles traveling along I-80 during the CV treatment period and a baseline period from January through April 2017.

The primary goal of the WYDOT CVP deployment was to reduce weather-related crashes of commercial vehicles traveling on the I-80 corridor. Thus, the safety impact assessment should focus on this type of vehicles driving along I-80 under adverse weather conditions. The limited analysis in this report included all 327 CVs independent of weather and traffic conditions. Subsequent analysis should then consider distinguishing between commercial and state vehicles driving under various weather, traffic, day/time, and natural lighting conditions at different locations of I-80.

6.1 FCW

The Volpe team analyzed 490 distinct FCW events based on 197,812 records of FCW alerts in the SDC. Many of these recorded FCW alerts occurred within very short time intervals and involved the same vehicles. The limited analysis of FCW events identified 327 valid events, or 67 percent of all 490 distinct FCW events, where the HV was approaching the RV at alert onset. The alert validity analysis only considered the RV and HV speed data and did not account for any kinematic information, such as TTC(0) and TH(0), because this information has not yet been processed from HV and RV GPS coordinates at the time of this analysis. Subsequent analysis of FCW alert validity should assess kinematic information and visually examine the time series of the HV and RV in each event using Volpe's event visualization tool.

The analysis of vehicle/driver response to FCW alerts revealed that only 30 percent of the 327 valid events were resolved within 10 s after alert onset; i.e., the HV was no longer approaching the RV. Subsequent analysis might need to consider a longer time window (e.g., 15 or 20 s). Due to the lack of brake activation data in WYDOT CVP's BSM records, the Volpe team was not able to calculate the HV brake response time and average deceleration during braking events that are critical to the safety impact assessment of FCW. Instead, the Volpe team used alternate performance measures such as tRC, ΔV_{HV}, and average deceleration from $V_{HV}(0)$ to $V_{HV}min$. Subsequent analysis should also consider using derived kinematic parameters, such as minimum TTC or minimum TH, for response measures of performance.

Since the CVs in the WYDOT CVP did not experience a baseline period with silent FCW alerts, subsequent analysis should consider comparing the performance of CV/driver response to FCW alerts or rear-end driving conflicts in the treatment period to that of commercial vehicles experiencing silent FCW alerts or encounters with rear-end driving conflicts in a baseline period from past field operational tests or naturalistic driving studies [5] [6].

6.2 Traffic Speed

The Volpe team analyzed traffic speed data that were collected by 64 roadside radars at different locations along I-80, comparing five speed measures and time headway between a baseline period from January through April 2017 and the treatment period from January through April 2022. Unpaired t-tests revealed statistically-significant differences between the baseline and treatment periods in all six measures of performance. Generally, the average traffic speed was higher by about 1 m/s (2.2 mph) and the average time headway between vehicles was lower by about 36 s in 2022 than in 2017 during the January-April timeframe. Paired t-tests between radar locations also revealed statistically-significant differences during peak traffic periods from 6 am to 9 am and 3 pm to 6 pm between the baseline and treatment periods in all six measures of performance. The average traffic speed was higher by about 1 m/s (2.2 mph) and the average time headway was lower by about 4 s in 2022 than in 2017 during the January-April timeframe.

The limited statistical analysis was performed independent of weather and day/time conditions. Subsequent analysis should consider additional statistical comparisons between the baseline and treatment periods by specific weather conditions (i.e., adverse versus clear weather), day/time conditions (i.e., weekdays versus weekends and peak versus non-peak traffic periods), and lighting conditions (i.e., daylight versus nighttime) at specific locations along I-80.

6.3 TIM Alerts

The Volpe team analyzed a total of 128,591 TIM alerts that were broken down by the following categories: speed limit, traffic conditions, weather conditions, and work zone. The CVs received these alerts over geographical locations across the state of Wyoming roadways, and not only on I-80 as they were supposed to by the design of the WYDOT CVP deployment. About 65 percent of all TIM alerts were related to weather conditions. The Volpe team only analyzed the HV travel speed at the onset of TIM advisory alerts (i.e., initial condition) by each of the four categories. Almost a quarter of TIM advisory alerts about traffic conditions and about weather conditions were issued to CVs traveling below 4 m/s (9 mph) and below 8 m/s (18 mph), respectively.

This limited analysis of TIM alerts did not address vehicle/driver response to TIM alerts, such as speed reduction. Moreover, this analysis considered all TIM alerts and did not focus on only those alerts that occurred on I-80 (i.e., WYDOT CVP site). It should also be noted that the Volpe team did not filter out any very low or high travel speeds, since very high speeds might be attributed to highway patrol vehicles, and did not distinguish TIM alerts about weather conditions between wide-area or localized weather events. Subsequent analysis should address vehicle/driver response to the different four TIM alert categories, only along I-80, removing TIM alerts with speed anomalies, separating between wide-area and localized weather events, and correlating CV speed data around the onset of TIM alerts to radar-based traffic speed at specific locations along I-80 corridor.

7 References

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U.S. Department of Transportation
John A. Volpe National Transportation Systems Center
55 Broadway
Cambridge, MA 02142-1093

617-494-2000
www.volpe.dot.gov