Multiple Sources of Safety Information from V2V and V2I: Phase II Final Safety Message Report

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FOREWORD

Future vehicles and roadways will employ advanced communication technologies to make driving safer, more efficient, and more environmentally friendly. The safety benefits will be largely achieved by communicating relevant safety information to the driver through applications. The Human Factors for Connected Vehicles research program focuses on understanding, assessing, planning for, and counteracting the effects of signals or system-generated messages that take the driver's eyes off the road (i.e., visual distraction), mind off the driving task (i.e., cognitive distraction), and hands off the steering wheel (i.e., manual distraction). The overall goal of this research is to support introducing this technology as a benefit to all transportation users. The research described in this report provides some initial design considerations for vehicle-to-infrastructure (V2I) safety messages as well as some limited considerations for vehicle-to-vehicle (V2V) systems. This report primarily uses existing transportation safety research but also includes research from related domains. Connected vehicle (CV) system designers and other State transportation department personnel can use this information to develop and implement V2I applications to ensure these systems work effectively and safely within a larger vehicle-to-everything (i.e., V2I, V2V, and vehicle-to-device) environment. As such, these findings are expected to help make interactions between roadway and vehicle systems safer, reduce the likelihood of crashes and injuries, and increase safety for all roadway users. The target audiences for this information are developers of vehicle-to-pedestrian technologies, CV system designers, and other State transportation department personnel involved in developing and implementing V2I applications that provide pedestrian safety information.

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16. Abstract
This report is part of the Human Factors for Connected Vehicles (HFCV) program, whose goal is to minimize driver workload by eliminating connected vehicle (CV) device-related distractions. The research described in this document is part of an effort to develop initial design considerations for vehicle-to-pedestrian (V2P) safety messages provided to drivers via driver–infrastructure interfaces (DIIs) and driver–vehicle interfaces (DVIs). Existing HFCV research, in addition to research from related domains, was used to identify driver information needs that can be used by engineers when developing V2P messaging concepts. The target audiences for this information are CV system designers and other State transportation department personnel involved in developing and implementing V2I and V2P concepts and applications that provide safety information regarding pedestrians. The design topics are divided into three sets. The first set is composed of general topics providing background information and general implementation considerations. The second and third sets include topics focusing on human factors issues and driver information needs related to DII implementation and DVI implementation, respectively. Specific topics addressed include message characteristics, timing, warning stages, and display placement for DII and DVI systems.

17. Key Words Connected vehicles, CV, driver–infrastructure interface, DII, driver-vehicle interface, DVI, vehicle-to-infrastructure, V2I, vehicle-to-pedestrian, V2P, design considerations, safety messages, driver behavior, driver assistance system, pedestrians, safety, human factors	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ABBREVIATIONS

CV	connected vehicle
DII	driver–infrastructure interface
DVI	driver–vehicle interface
FCW	forward-collision warning
HFCV	Human Factors for Connected Vehicles
HFG	*Human Factors Guidelines for Road Systems*
ITS	intelligent transportation system
LTAP	left turn across path
MUTCD	*Manual on Uniform Traffic Devices*
PHB	pedestrian hybrid beacon
PISCA	Pedestrian in Signalized Crosswalk Warning application
PMA	Pedestrian Mobility application
RRFB	rectangular rapid-flash beacon
RSE	roadside equipment
V2I	vehicle-to-infrastructure
V2P	vehicle-to-pedestrian
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything

CHAPTER 1. BACKGROUND

Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications involve the wireless exchange of data among and between infrastructure and vehicles traveling in the same vicinity to provide significant safety, mobility, and environmental benefits. Vehicle-to-pedestrian (V2P) communication refers to additional related capabilities involving pedestrians. Together, these communication capabilities will enable the creation of a host of vehicle- and infrastructure-based safety systems and applications. These systems allow all vehicles on the roadway (e.g., automobiles, trucks, transit vehicles, and motorcycles) to communicate with infrastructure, pedestrians, and other vehicles to enable active safety applications. The network of communication that these technologies offer can also be leveraged to improve mobility and environmental impacts. The Human Factors for Connected Vehicles (HFCV) research program seeks to understand, assess, plan for, and counteract the effects of signals or system-generated messages that take the driver's eyes off the road (visual distraction), mind off the driving task (cognitive distraction), and hands off the steering wheel (manual distraction).

The Federal research investment plays a critical role in developing the knowledge needed to fully enable connected vehicle (CV) technologies with the capability to save lives and reduce injuries while still avoiding unintended consequences. Establishing basic attention and distraction principles for specific advanced communication and messaging technologies used in vehicles and infrastructure is a challenge. However, the outcomes will form the parameters for, and guide, consistent development of safer systems and interfaces across countless new applications for a diverse set of manufacturers. When developing new applications, consistency and adherence to basic distraction countermeasures are paramount to ensuring ultimate driver safety. Human factors research allows engineers and developers to design more robust algorithms that prioritize safety and develop messages that assist the driver while minimizing risk of increased distraction and workload.

From a high-level transportation planning perspective, the National Intelligent Transportation Systems (ITSs) Architecture was created to provide a common framework for planning, defining, and integrating ITSs. The idea of V2P, V2I, and V2V communications that enable active safety applications fits into this architecture. For example, there are a number of relevant National ITS Architecture Service Packages, including AVSS10-Intersection Collision Avoidance and AVSS05-Intersection Safety Warning (ITS Joint Program Office 2015). The Intersection Collision Avoidance Service Package describes a system that determines the probability of an intersection collision and provides approaching vehicles with timely warnings so drivers can take the appropriate measures to avoid a collision. The package also describes a related system that monitors vehicles approaching an intersection and warns drivers about detected hazardous conditions. Such a system could detect impending violations (e.g., red-light violations) and potential conflicts between vehicles occupying or approaching the intersection (e.g., situations where a left turn would be unsafe because of approaching traffic). When a potentially hazardous condition is detected, the system transmits a warning to the involved vehicles using short-range communications and/or signs or signals in the intersection.

The scenario described in the previous paragraph relates to the research covered in the two phases of the Multiple Sources of Safety Information from V2V and V2I: Redundancy, Decision

Making, and Trust project (herein referred to as the Multiple Sources project). The objective of this research is to investigate how drivers handle receiving critical safety information about pedestrians from multiple sources, including V2V and V2I sources. A previous phase of this project broadly examined critical safety information across multiple CV applications. A key outcome of that research was the *Multiple Sources of Safety Information from V2V and V2I: Redundancy, Decision Making, and Trust—Safety Message Design Report* that provided initial design considerations for V2I safety messages communicated to drivers using a driver–infrastructure interface (DII) and driver–vehicle interface (DVI) (Richard et al. 2015).

The current study focused on V2P scenarios, specifically on communicating information to drivers. The research included conducting a driving simulator study that examined multiple V2P scenarios. To meet the objectives of this project, the project team completed following tasks:

- Task 1—review literature and conduct gap analysis.
- Task 2—develop research plan.
- Task 3—execute research plan.
- Task 4—document design considerations.

This report documents the design considerations of task 4. The objective of task 4 was to develop additional safety message–design considerations that focused on V2P scenarios to complement the original *Multiple Sources of Safety Information from V2V and V2I: Redundancy, Decision Making, and Trust—Safety Message Design Report* (Richard et al. 2015). Unlike the previous phase of the Multiple Sources project, there was insufficient information to develop formal design considerations for driver-focused V2P safety messages. The following are primary reasons for this lack of information:

- The technical specification of the design considerations is mostly undeveloped, which requires making key assumptions about its operation and function. If the specification diverges from the assumptions, then the applicability of the design considerations could be undermined.

- There is almost no existing research related to communicating safety messages to drivers in V2P scenarios. The applications covered by design considerations in phase I all had at least one large-scale field operational test and multiple supporting development efforts that identified the key human factors issues. The current phase of the Multiple Sources project collected human factors data; however, the scope was substantially smaller than the previous field operational tests, and the data were insufficient to support developing comprehensive human factors guidelines, especially without the benefit of information from other research.

Instead of focusing on human factors considerations for V2P systems targeted at drivers, this report describes basic information needs to consider when developing a system and specific safety messages that communicate pedestrian information to drivers using V2I. This information can facilitate system development by providing key human factors information as an input early in the development process. Also, by guiding the objective toward providing basic information needs and heuristics, the need for a larger body of relevant research to support the development of formal guidelines is reduced.

This document focuses on driver information needs and human factors design issues related to infrastructure and other roadway elements. The target audiences for this information are developers of V2P technologies, CV system designers, and other State transportation department personnel involved in developing and implementing V2I applications that provide pedestrian safety information. Accordingly, the safety messages and design information provided in this report primarily address the V2I component of CV technologies. V2I communication with drivers can provide CV information using both DIIs and DVIs—each of which is covered in this report.

OVERVIEW OF THE REPORT

This report is composed of the following five chapters:

- Summary of CV V2P Technology—provides definitions for the key terms used to describe the CV communication architecture in addition to summaries of the safety applications addressed in this report.
- V2P Safety Message Driver Information Needs—provides a set of safety message consideration topics (including specific design parameters, identified design problems, and/or driver information needs) for designers to use as a reference in developing safety applications.
- Support for V2P Safety Messages Using DVIs—provides a set of safety message considerations topics covering driver information needs from a DVI in V2P scenarios.
- Summary and Conclusions—provides a summary of the key information in this report.
- References—compiles all topic-specific references provided within the individual safety message topics.

CHAPTER 2. SUMMARY OF CV V2P TECHNOLOGY

FHWA developed relevant V2P systems specifications for two Iteris® applications (FHWA 2017b):

1. The Pedestrian in Signalized Crosswalk Warning application (PISCA). This application is designed for transit vehicles but can be applied to any type of vehicle.

2. The Pedestrian Mobility application (PMA). This a smartphone application designed for pedestrians.

Either or both systems may be used to implement a V2P system at signalized intersections; however, the PISCA is most relevant to this document's scope—communicating pedestrian-related safety messages to drivers using infrastructure-based roadside equipment (RSE). The PISCA and PMA are summarized in the following two sections.

PISCA

The purposes of the PISCA include the following:

- Alert drivers to the possible presence of pedestrians in a crosswalk at a signalized intersection.

- Warn pedestrians (via personal information device) of possible crossing infringement by approaching vehicles.

The following sources provide pedestrian data to the PISCA:

- Infrastructure that indicates the possible presence of pedestrians in a crosswalk at a signalized intersection.

- Pedestrian sensor outputs obtained from image processors or sensors within ITS, most likely from relevant ITS roadway equipment.

- Pedestrian crossing signal activation.

PMA

The purposes of the PMA include the following:

- Adjust traffic controller crossing time and crossing priority based on pedestrian information (e.g., disabled pedestrian) and roadway environment information (e.g., congestion and weather).

- Warn pedestrians (via personal information devices) of possible crossing infringement by approaching vehicles.

The following sources provide pedestrian data:

- Roadside or intersection detectors.
- Wirelessly connected pedestrian- or bicyclist-carried mobile devices (i.e., nomadic devices).

Additional operation details of each system are provided in the appendix.

COMPARISON OF V2P SYSTEM TO EXISTING INFRASTRUCTURE-BASED PEDESTRIAN SIGNALS

There is a high degree of overlap between the PISCA and existing crosswalk signals. The objective of both systems is to communicate to drivers that they must yield to pedestrians. The primary differences between the two are how they activate and communicate with the target vehicle. While both existing and PISCA-enabled systems can be activated by pedestrian action (i.e., push to activate), a PISCA-enabled system is also expected to have the capability to activate if a pedestrian is detected in the crosswalk.[1]

How each type of system is activated has important implications for signaling the driver. Existing crosswalk signals hold back the pedestrian and give the driver time to stop before the pedestrian is signaled that it is safe to proceed through the crosswalk. While PISCA systems would have the same functionality, the specification also indicates that these systems cover situations in which the pedestrian does not activate the crossing signal using the push button, which impacts the timing of safety messages sent to the driver. However, since PISCA DIIs activate when the pedestrian is already in the crosswalk, a lack of crossing signal would result in minimal lead time for the safety messages sent to the driver. There are different possibilities for how to address this issue. At best, the PISCA system could predict an impending pedestrian crossing using a software algorithm that could provide the driver some advanced warning before the pedestrian enters the crosswalk. At worst, the DII would activate just after a pedestrian enters the crosswalk, which would provide minimal advanced warning. Depending on the pedestrian's position relative to an approaching vehicle, DII activation after a pedestrian enters the crosswalk could provide the driver with insufficient time to respond. However, without a PISCA DII, the driver would have no advanced warning of the pedestrian, so providing a warning at least offers a potential alerting benefit.

In addition to warning the driver about a pedestrian who crosses without activating the signal, the V2I communication in a general V2P system provides added capabilities for CVs. These additional capabilities include the ability to present redundant safety messages on in-vehicle displays as well as imminent-collision warnings that include concurrent auditory or haptic alerts.

Implementation Scenarios

The existing PISCA technical specifications do not provide information about how the system can be implemented. However, given the substantial overlap between the PISCA and existing crosswalk signals, a practical implementation would likely be to augment existing or planned

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[1]Some existing crosswalk signals can be activated when a pedestrian is detected in the crosswalk, but this is not currently a common implementation.

pedestrian crosswalk equipment with PISCA and V2I capabilities. In this use case, the equipment would still operate normally at intersections and unsignalized crosswalks (including those without pedestrian activation), but added CV functionality would provide the ability to send safety messages directly to drivers through V2I communications. The additional capabilities include the following:

- DII element activation when a pedestrian enters the crosswalk, even if he/she did not activate the crossing signal.
- DII element activation in certain situations (e.g., vehicle turns at intersections) based on projected vehicle–pedestrian conflicts.
- V2I communication of pedestrian crossing actions to the driver's vehicle, which enables safety message presentation on the vehicle's DVI.

The enhanced capabilities provided by adding V2P RSE would permit these systems to potentially address the following two key driver information needs regarding pedestrians at crosswalks:

- Aiding drivers in seeing the following types of pedestrian who are difficult to detect:
    - Low-visibility pedestrian (i.e., one crossing at night or during inclement weather such as fog or heavy rain).
    - Pedestrian crossing during high driver workload scenarios with susceptibility to detection errors, such as making left or right turns into oncoming traffic.
- Alerting distracted drivers about a crossing pedestrian if drivers are looking away from the roadway and do not see a visible pedestrian.

The intersection of V2P-specific RSE capabilities and the basic driver information needs they support may address unmet safety problems in specific scenarios by implementing V2P communication.

Intersections

Primary use cases for intersections include the following:

- Pedestrian conflicts with vehicles making left or right turns—a V2P system may reduce driver workload and errors by indicating when pedestrians are in the crosswalk.
- Pedestrian jaywalking across the road when vehicles have the right of way—since V2P systems cannot change the traffic signal, a secondary DII would be impractical and could also cause secondary traffic conflicts if drivers brake suddenly. However, a DVI could be suitable in this situation for providing driver safety messages.

Midblock Crosswalk

Primary use cases as a supplement to existing installation at midblock crosswalks include the following:

- Pedestrian signal would activate whenever a pedestrian is in the crosswalk, even if he/she did not press the signal.
- Pedestrian detection could lead to more efficient signal timing since the signal could be extinguished once the pedestrian is no longer detected in the intersection.

The four scenarios listed in the Intersections and Midblock Crosswalk sections inform the relevant information drivers would need from V2P system implementation and operation, which is described in the rest of this document.

CHAPTER 3. V2P SAFETY MESSAGE DRIVER INFORMATION NEEDS

This chapter describes the initial driver information needs that support V2P safety message development. The information needs were developed with the objective of potentially including them in future versions of the *Human Factors Guidelines for Road Systems* (HFG) in conjunction with the design considerations developed in phase I of this project (Campbell et al. 2012). The format of the safety messages provided in this report is similar to annotated outlines developed as part of earlier HFG projects; however, they are more narrative in structure (Campbell et al. 2008, 2012; Campbell, Richard, and Graham 2008).[1] The current topics also do not conform to the two-page format of the HFG.

Though every attempt was made to be thorough and comprehensive while developing the current safety message topics, the scope of the current project prevented applying the same rigor and repeated review cycles that are typically required to develop formal design guidelines (Campbell et al. 2007, 2012). Moreover, the information provided in each topic is intended to serve as a starting point for more formal guidance development efforts in the future rather than as an authoritative source of design guidance that can be used now. Nevertheless, the topics presented in this report identify key sources of existing information and discuss human factors design considerations applicable to the design and implementation of V2I safety systems and corresponding safety messages.

Additionally, the information in this report is framed in terms of driver information needs rather than formal design guidance due to uncertainties about the formal technical and operational specifications of V2P and supporting V2I systems.

The information needs related to specific safety message design topics are presented in this chapter and grouped in the following ways:

- General considerations for safety message design.
- Support for V2P safety messages using DIIs.
- Support for V2P safety messages using DVIs.

TOPIC 1: CONSIDERATIONS FOR INCLUDING A DEDICATED DII WITH AN RSE INSTALLATION

Topic 1 covers considerations for determining whether a DII should be added to a CV RSE to communicate information directly to drivers. The decision to add a DII is not a simple one, because the long-term vision of the CV program is that most vehicles will have a DVI to communicate RSE information to drivers through in-vehicle applications. In general, adding a DII will increase the overall cost of an infrastructure-based safety system, yet under certain circumstances, it might not provide a greater benefit than in-vehicle systems.

[1]Please see chapters 6, 22, and 23 in Campbell et al. 2008, and chapters 4, 5, 10, 11, 13, 22, 23, and 26 in Campbell, Richard, and Graham 2008.

Driver Information Needs

An existing pedestrian safety problem that can be addressed by the V2P capabilities described earlier in this report is a key prerequisite for DII installation. The following are definitions for operational and situational considerations for including a DII at a location with RSE (Richard et al. 2015), with further details provided in the sections that follow:

- Visual interaction at location—a DII allows drivers to keep looking at the roadway environment and is usually easily noticed.
- Driver workload—a DII's location can provide context and permit a simplified message with less workload impact.
- Targeted messaging—a DII's information is available to all drivers who can see the display, offering widespread benefit.
- Driver decisionmaking—a DII supports safe and efficient decisions. Drivers may prefer receiving messages via DII rather than DVI.
- Interaction with other systems—the RSE that supports a DII also facilitates synchronization with V2I- and DVI-based systems.
- Vehicle-to-everything (V2X) market saturation—a DII can be effective at all levels of market saturation because the information is available to all vehicles, regardless of whether they have a V2I- or a DVI-based system.

The remaining sections in this topic provide high-level discussion of these considerations. Most of this information is based on general information adapted from other V2X DII design information (Richard et al. 2015); however, this information also applies to V2P scenarios at a general level.

Visual Demand

A DII's location should be salient and positioned where drivers will be paying attention (e.g., locations where drivers expect to see traffic control devices such as intersections and near the crossing signal). A DII that is not implemented in a salient manner may not be as effective at conveying the intended message since it might not be as easy for drivers to see.

Driver Workload

A given location and situation's inherent workload, as well as the workload imposed by the DII, should be considered. Driver workload is higher during certain maneuvers, such as when turning into oncoming traffic. The DII may reduce higher workload demands in some of these cases in which crashes may occur because the task at hand requires a difficult maneuver (Doctor, Merritt, and Moler 2009). However, a poorly implemented DII could also increase driver workload.

In general, a well-implemented DII will likely have a minimal effect on driver workload, especially if the DII integrates driver information provision with normal driving activities. For example, a DII placed alongside other traffic control devices, such as a pedestrian indicator display located alongside a traffic signal or crossing signal, allows drivers to receive information from the DII while performing normal visual scanning. Regardless of whether it provides useful information, a DII can be an information source that drivers feel compelled to pay attention to, especially if it resembles a regulatory sign or device (Misener et al. 2010). A DII that does not directly address a safety concern can be a source of visual clutter, which may reduce the effectiveness of the DII and may needlessly increase driver workload (Lerner et al. 2003).

Targeted Messaging

An important factor to consider when deciding on DII implementation is whether the information will target all road users or only specific road users. There is a risk that nontargeted road users may unintentionally respond to information presented via DII that is only intended for specific road users (Gugerty et al. 2014). A single driver is most likely the message target in most V2P scenarios, which impacts when and how the safety message should be displayed because it may not be desirable for nontargeted drivers to receive the safety messages.

Decisionmaking

A DII can assist driver decisionmaking if driver information needs are not being addressed via DVI or through the existing infrastructure, the DII can provide information in a timely manner, and drivers are able to act on the information provided by the DII. Ideally, a DII would provide clear information to drivers that could eliminate uncertainty about the presence and/or location of a crossing pedestrian, thus easing their decisionmaking process.

Interactions with Other Systems

The decision to install a DII should include assessing the potential for interactions with other DII safety systems as well as non-V2X vehicle-based safety systems. Initial requirements for V2X-based applications (for both DVI and DII) rely on infrastructure RSE for timing (Stephens et al. 2013). Though timing is not expected to be a problem in these systems, there may be exceptions when taking driver and vehicle performance into account. System-level conflicts between DII elements are unlikely, but some combinations of systems are more likely to produce conflicts at either the system or message level (see topic 2).

V2X Considerations

Few data exist depicting the costs or benefits of DII addition when all vehicles are equipped with V2X DVIs. However, until CV technology market penetration reaches a level at which most drivers are receiving V2X information, using DII is a reasonable approach since it is available to all drivers.

Even at the point that most drivers have a DVI, an additional DII may still be useful. Research, including the driving simulator study conducted as part of this phase, suggests that drivers are more inclined to use information provided by a DII (Richard et al. 2015; Gugerty et al. 2014). Additionally, many drivers prefer DIIs as an information source. In a poststudy survey during this research, participants strongly preferred the DII situated in the roadway environment when compared to the DVI. The primary reason that drivers cited for reporting this preference was their reluctance to look away from the road in the different scenarios. This finding is similar to the driver preferences expressed in the *Multiple Sources of Safety Information from V2V and V2I: Redundancy, Decision Making, and Trust—Safety Message Design Report* (Richard et al. 2015).

TOPIC 2: SYSTEM-LEVEL CONFLICTS

Topic 2 covers scenarios in which information presented via both DII and DVI could conflict with information being presented to the driver from other V2X systems. Specifically, these situations involve system-level conflicts in which functionally different V2X applications attempt to communicate to the driver at the same time. Given the diversity of hazards that can occur at locations such as intersections, it is possible that multiple V2X systems could be activated at the same time. Presenting uncoordinated safety messages can burden the driver with unneeded or conflicting information in driving situations that already have elevated driver workload.

Table 1 indicates V2X systems that could result in a system conflict. Most of the conflicts involve scenarios in which the subject vehicle is making a turn at an intersection. In all cases, the subject vehicle's required response would be to break quickly, so there is no conflict in the action the driver would need to take.

Driver Information Needs

The following considerations create a unified strategy for prioritizing and integrating concurrent safety messages from multiple V2X applications to help the driver by preventing message overload and response uncertainty:

- DVIs and DIIs that assess the same hazard should provide consistent instruction or information and should be coordinated if possible.

- System timing and activation algorithms that are compatible and congruent across systems should be used if both systems assess the same hazards.

If V2X systems become common in the vehicle fleet and at key locations, it is possible that V2P DII implementation may co-occur with other V2X system implementation. This co-occurrence raises the potential for information conflicts, incongruencies, and similar concerns regarding situations in which multiple systems that are functionally similar are present at a location and communicating to the same driver. If left uncoordinated, different systems that activate for the same hazard can present incongruent information, potentially leading to driver confusion that may result in delayed reaction times and/or in fostering mistrust of the system. As table 1 indicates, multiple V2X systems have the potential to activate at the same time, especially at intersections. In all cases, the activation will be for different hazards since the V2P system addresses pedestrian hazards while the other concurrent systems address vehicle hazards. The specific V2X system conflicts involving V2P communication are described in the following points:

Table 1. Potential system conflicts between V2X systems.

Location	SSA	SLTA	RLVI	CSW	RLVW	SWIW	IMA	LTAP	FCW	DNPW	BSW + LCW	OVW
V2P intersection	—	*	—	—	—	—	*	*	—	—	—	—
V2P midblock	—	—	—	—	—	—	—	—	*	—	—	—

—Simultaneous system activation is unlikely.

*Systems may be active simultaneously.

BSW + LCW = blind-spot warning + lane-change warning; CSW = curve-speed warning; DNPW = do-not-pass warning; FCW = forward collision warning; IMA = intersection-movement assist; LTAP = left turn across path; OVW = oversize-vehicle warning; RLVI = red light–violator indication; RLVW = red light-violation warning; SLTA = signalized–left turn assist; SSA = stop-sign assist; SWIW = spot weather–information warning.

- Intersection-movement assist—these systems can co-occur, but they communicate the same message to the driver that it is unsafe to proceed. It is unlikely that there would be a response conflict between these systems. There is no research regarding which display should have priority.

- FCW—these systems can co-occur if a lead vehicle is braking in response to a pedestrian's presence in the crosswalk. In this case, the lead vehicle is the primary hazard for the subject vehicle driver, and the display priority should go to the FCW system.

- Signalized–left turn assist and LTAP—these systems communicate qualitatively different information to a driver (i.e., that no oncoming vehicle is within a certain distance) than a V2P display (i.e., a pedestrian is crossing in the parallel direction across path). If the two systems are uncoordinated, it is possible that one system could indicate the driver can turn, while the other indicates the driver should not turn because of a pedestrian. Conflicting messages could increase driver workload as they reconcile the information and increase the chances of a decision error.

When multiple V2X systems will operate at the same location, it is important to consider system-level safety message integration to ensure the driver receives a consistent message. For example, if RSE is responsible for providing both oncoming-vehicle and crossing-pedestrian warnings in a permitted LTAP scenario at a signalized intersection, these two messages could be combined. In this case, the LTAP and the V2P system each have separate message-triggering conditions (i.e., insufficient gap in LTAP and pedestrian presence in V2P). The two separate safety messages and displays could be integrated into a single display that activates based on the combined triggering conditions (i.e., sufficient gap and no pedestrian). This approach would simplify the driver's information acquisition and decisionmaking.

TOPIC 3: SUPPORTING DRIVER TRUST OF SAFETY SYSTEMS

Topic 3 covers general factors related to providing drivers with information from safety systems via DII and DVI in a way that promotes driver trust of the system. Trust is an individual's subjective belief pertaining to his or her willingness to rely on or comply with information provided by a safety system, including those that provide DII-, DVI-, or combined DII/DVI-based messages. Trust in a system affects an individual's likelihood of using the system, which is important because drivers who do not trust a safety system will not benefit from the safety messages provided by a DII or DVI (Hancock et al. 2011). Though little research specifically examines trust of roadway safety system information, the information needs presented here are based on general best practices related to promoting trust in systems and research on users' trust of automated systems.

Driver Information Needs

Trust can be affected directly and indirectly by multiple factors. Design considerations for key factors that affect driver trust are listed in table 2.

Table 2. Design considerations that affect driver trust.

Factor	Design Considerations for Driver Trust Factor
Accuracy	Minimize occurrence of false alarms. False alarms are detrimental to driver trust. Warnings provided when no visible hazards are present may be perceived as inaccurate.
Reliability	Ensure that system performance remains stable over time. Systems perceived as unreliable may not be accepted by drivers.
Understandability	Provide clear and useful information. Information that is easy to understand encourages driver trust. Active elements on DIIs may also help promote driver trust (e.g., a flashing beacon to indicate an ongoing hazard).
Message framing	Use a prohibitive message frame for DII messages. Permissive, advisory/inform, and warn messages may not be perceived as accurate when presented via DII, unless a hazard is visible, or the message is direct and understandable.
Message coordination	Coordinate presentation between the DII and the DVI. Driver trust may be lowered by incongruently presented warnings from the DII and DVI.
Familiarity	Ensure the system functions in a consistent manner when compared with other systems with which drivers would be familiar in a specific region. Familiar systems that are consistent are likely to produce faster driver responses.

More detailed discussion of factors that affect driver trust is available in the *Multiple Sources of Safety Information from V2V and V2I: Redundancy, Decision Making, and Trust—Safety Message Design Report* (Richard et al. 2015).

Support for V2P Safety Messages Using DIIs

A pedestrian notification system is classified as a DII if a trigger state is dynamically activated and a message is communicated based on that state within the driving environment. DII displays should satisfy driver information needs while conforming to current *Manual on Uniform Traffic Devices* (MUTCD) standards (FHWA 2009).

DIIs broadly inform drivers about pedestrians, whereas DVIs have the capability to inform drivers more specifically about hazards in their path. Generally, drivers may prefer to use DIIs over DVIs in a system with multiple sources of information. In a V2P driving simulator study (Hoekstra-Atwood, Richard, and Venkatraman, n.d.), drivers who used both the DII and DVI systems self-reported a preference for the DII and a perception that it was more useful than the DVI. In a previous study using both a DII and DVI to communicate messages to drivers, drivers indicated a general preference for the DII because it was located on the roadway and was perceived as more authoritative than the DVI (Richard et al. 2015). These preferences are also consistent with a study in which participants consistently self-reported a preference for information presented on the DII when asked about stop sign–assist system reliability (Rephlo 2013).

Existing DII infrastructure is typically pedestrian activated (by using a pushbutton to activate the crossing signal). Although the existing technical specification provides only high-level operational requirements, it states that a V2P system should supplement existing installations by taking the following measures (FHWA 2017b):

- Activating the pedestrian signal whenever a pedestrian is in the crosswalk, even if he/she did not press the pushbutton to activate the crossing signal (passive pedestrian detection).

- Increasing the efficiency of signal timing since a signal may extinguish once the pedestrian exits the intersection.

These added functionalities may reduce false alarms, assist a pedestrian who did not—or could not—press the pushbutton to activate the crossing signal (e.g., a jaywalker or visually impaired pedestrian who may have trouble finding a pedestrian actuation pushbutton), and assist a pedestrian who may require more time to complete a crossing (e.g., a disabled pedestrian or pedestrian in inclement weather) (Barlow, Bentzen, and Bond 2005; Bentzen et al. 2004).

The information needs to consider when designing compliant DII display systems (i.e., display characteristics, location, message warning stages, and message timing) for midblock and signalized intersection crossings are discussed in topics 4–11.

The DII in Midblock Crossings

This section includes topics that cover multiple characteristics of DIIs at midblock crosswalks, including the following:

- DII display characteristics.
- DII placement.
- DII message stages.
- DII message timing.

Specific information needs and supporting information for each characteristic will be separately discussed.

Since midblock crosswalks only allow drivers to move straight through a single crosswalk, and pedestrians at the crosswalk are the only road users with conflicting paths, the driver's information needs are minimal (table 3). The MUTCD provides display options that can fully communicate this information to drivers (FHWA 2009).

Table 3. Driver information needs in midblock crossings.

Driving Maneuver	Information Requirements
Driver proceeding straight through crosswalk	Does the driver need to yield at the crosswalk for a pedestrian?

In most cases, the driver is expected to be able to visually acquire this information without the help of the midblock DII. In the research conducted for this phase of the Multiple Sources project, 32 percent of participants who had experience with the V2P system's DII identified already having the information they needed as a factor that reduced their willingness to use the system at midblock crosswalks (Hoekstra-Atwood, Richard, and Venkatraman, n.d.). However, there may be situations in which the driver's attention is averted, or part of their view of the crosswalk is occluded (e.g., by a large vehicle), when the DII may be the only source available to satisfy the driver's information needs.

TOPIC 4: DII MIDBLOCK CROSSING DISPLAY CHARACTERISTICS

Topic 4 covers the physical characteristics of the DII display and some common display implementation options for midblock crosswalks.

Driver Information Needs

The display should communicate when the driver is expected to yield to avoid a potential vehicle–pedestrian conflict in the crosswalk area.

The MUTCD offers several options for displays that can alert the driver to a pedestrian approaching or traveling through a midblock crosswalk (table 4) (FHWA 2009). These displays are pedestrian hybrid beacons (PHBs), pedestrian-warning signs with added dynamic attributes, and rectangular rapid-flash beacons (RRFBs). Another option is to place the displays in roadway lights. The physical characteristic requirements (e.g., size, content, color, flash rates) for each of these options are described in detail in the MUTCD references provided.

Table 4. MUTCD-based display options at midblock and roundabout crosswalks.

MUTCD DII Display Option	Description	Where to Find Helpful Information
Pedestrian hybrid beacon	A traffic signal that has a beacon head consisting of two red beacons above a yellow beacon. The signal is used to both warn and control roadway and pedestrian traffic at marked crosswalks.	MUTCD 2009 Edition, chapter 4F, "Pedestrian Hybrid Beacons" (FHWA 2009).
In roadway lights	Flashing lights installed on the road surface at marked crosswalks with applicable warning signs to increase conspicuity.	MUTCD 2009 Edition, chapter 4N, "In-Roadway Lights" (FHWA 2009).
Pedestrian-warning signs with dynamic attributes	Pedestrian-warning signs with dynamic components (e.g., warning beacon, LED unit on sign border, LED unit within sign symbol).	*Informational Brief: Treatments for Uncontrolled Marked Crosswalks* (FHWA 2017a). MUTCD 2009 Edition, chapter 2B, "Regulatory Signs, Barricades, and Gates" (FHWA 2009). MUTCD 2009 Edition, chapter 2A, "General" (FHWA 2009). MUTCD 2009 Edition, chapter 4L, "Flashing Beacons" (FHWA 2009).
Rectangular rapid-flash beacon	Pedestrian-actuated amber LEDs that supplement warning signs at unsignalized intersections or midblock crosswalks.	*Interim Approval 21 – Rectangular Rapid-Flashing Beacons at Crosswalks* (Knopp 2018).

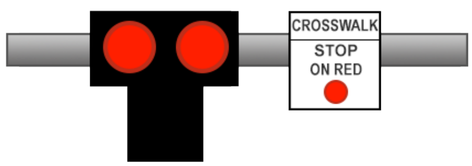
LED = light-emitting diode.

The MUTCD states that these facilities may also be used at roundabout crosswalks, but information on this type of implementation was not analyzed.

The selected display should effectively communicate when the driver should yield or stop for a pedestrian. In addition to already being compliant, the use of existing displays allows designers to take advantage of the yielding-behavior benefits these displays can provide and supports the driver's expectations for recognizing and interpreting display messages. Yield rates for PHBs and RRFBs have been analyzed and compared in on-road observational studies. On average, PHBs tend to have higher yield rates than RRFBs and are associated with greater reductions in crash risk. A Texas study also compared these fixtures to traffic control signals, which had much higher yielding rates (98 percent) than both RRFBs (86 percent) and PHBs (89 percent) (Fitzpatrick et al. 2014). In addition, for PHBs, higher driver yielding compliance was associated with wider crossing distances, whereas lower compliance was observed at wider crossing distances where RRFBs were installed (Fitzpatrick et al. 2014).

Other factors that may impact whether drivers yield to specific displays are the number of devices used within a city and the number of days since installation, where greater compliance may occur due to driver familiarity (Fitzpatrick et al. 2014).

The most recent project phase collected drivers' ratings of the message content and design of existing and theoretical DII displays based on how well they thought the sign communicated whether they should yield at an upcoming crosswalk (Hoekstra-Atwood, Richard, and Venkatraman, n.d.). Drivers were provided with a view of the sign's position from the driver's perspective as well as a close-up depiction of each sign. Drivers preferred the sign for the PHB in the pedestrian walk interval mode (mean = 3.86/5; figure 1) over the actuated RRFB display (mean = 3.5/5; not shown). A display similar to the PHB that also provided direct meaning information was rated higher on message comprehension than both the PHB and the RRFB, with a mean response rating of 4.32/5 (figure 2). Other general trends were that drivers preferred DII displays positioned overhead versus those located next to the roadside and direct messages over symbolic messages. Although drivers preferred messages with more text, symbols are generally preferred for road sign implementation because they are mostly language neutral, and under normal driving conditions, drivers can identify signs using symbols from greater distances compared with text signs (Dewar and Ells 1974). Common symbols have also been shown to have shorter comprehension times compared with text (Ells and Dewar 1979). However, the use of symbols on signs may be advantageous only when the symbol is familiar to drivers (Shinar and Vogelzang 2013).



Source: FHWA.

Figure 1. Graphic. Example of a pedestrian hybrid beacon, which is a direct meaning display.

Source: FHWA.

Figure 2. Graphic. Example of a direct meaning display that had the highest ratings for comprehension of the requirement to yield to pedestrians.

As dictated by Interim Approval 21, any RRFB installation must comply with implementation and documentation requirements laid out in the MUTCD Interim Approval document (Knopp 2018).

TOPIC 5: DII PLACEMENT AT MIDBLOCK CROSSWALKS

Topic 5 covers how the DII should be positioned to best support driver information acquisition from the display or the driving environment that helps inform whether drivers need to yield at the crosswalk for a pedestrian.

Driver Information Needs

The display should be collocated to the pedestrian detection task.

Safety message location and content should take into consideration the constraints imposed by the driving task they are intended to support. Collocating the DII to the driving task should support information acquisition by minimizing the time drivers need to spend oriented away from time-critical, safety-relevant information about pedestrians and oncoming vehicles. In a simulator study, 16 percent of participants who had experience with the V2P system's DII identified the inconvenient display location as a factor that reduced their willingness to use the system at midblock crosswalks (Hoekstra-Atwood, Richard, and Venkatraman, n.d.).

Section 2A of the MUTCD provides a range of acceptable placement values for dynamic-midblock crossing signs along the *x*, *y*, and *z* planes (FHWA 2009). However, FHWA guidance is that the signs should be located at, or immediately adjacent to, an uncontrolled marked crosswalk. Some additional specifications are that PHB signal face locations should follow the same requirements laid out in section 4D of the MUTCD, and that crosswalk signs in urban areas should not be placed more than 4 ft in advance of the crosswalk (FHWA 2009).

In the simulator study, drivers' most preferred locations for DII displays in a midblock crosswalk setting were above the lanes in which the drivers were traveling (locations E and F, figure 3) (Hoekstra-Atwood, Richard, and Venkatraman, n.d.). The typical placement for RRFB rectangles (below the pedestrian sign; locations A and I, figure 3) had among the lowest preference ratings.

Source: FHWA.

Figure 3. Graphic. Potential DII display locations in a midblock crossing.

TOPIC 6: DII MIDBLOCK CROSSING MESSAGE STAGES

Topic 6 covers how to use the DII to relay single driver-required information without causing confusion for other drivers who will receive the same message.

Driver Information Needs

This section covers the implementation of DIIs that change their message to reflect the severity of the hazardous situation. Three different hazard stages are defined for CV systems, including advisory, inform, and warn messages. In the context of V2P driver messages, these stages would apply to the following driving conditions:

- Advisory—a persistent alert that a crosswalk is located ahead. This is analogous to advance roadway signage.

- Inform—an alert indicating that a pedestrian is in or near the crosswalk. For the DII, the message is visible whenever the pedestrian is in the crosswalk. However, a distance criterion may also be applied for a DVI (i.e., at stopping distance based on average braking) (Stephens, Schroeder, and Klein 2015).

- Warn—an alert indicating that a pedestrian is in or near the crosswalk and the vehicle is on a trajectory that will lead to a direct conflict with the pedestrian unless the driver takes immediate action. A distance criterion is applied (i.e., at stopping distance based on aggressive braking) (Stephens, Schroeder, and Klein 2015).

An advisory message that a crosswalk is located ahead may be achieved using traditional, static signs. Inform messages communicate essentially the same information as a traditional crosswalk signal—that a driver must yield to a pedestrian. Thus, an inform message is compatible with a DII. However, warn messages are not compatible because it is potentially hazardous to display a high-severity warning that can be readily seen by road users that are not the intended recipient of the message. The ubiquitous visibility of infrastructure-based messages could have the unintended consequence of warning the wrong drivers and eliciting unnecessary evasive responses (Richard et al. 2015).

TOPIC 7: DII MIDBLOCK CROSSING MESSAGE TIMING

Topic 7 covers some timing attributes for the DII display that should be considered for providing drivers with enough time to receive the information they need and respond appropriately (e.g., stopping before the crosswalk).

Driver Information Needs

Drivers require a minimum hazard preview time (ideally at least 3 s) to respond to a hazard. This need may require supporting geometric sign features or predictive pedestrian movement algorithms.

Pedestrians may not always engage a traditional DII system for which the beacons are solely activated by pedestrian action. An observational study showed crossing signal activation rates for pedestrians who crossed at a nonactivated crosswalk were 91 percent (Fitzpatrick and Pratt 2016). This lack of action can significantly reduce a DII system's impact on drivers' yielding compliance. In another observational study, drivers were observed to be around three to four times more likely to yield when the beacons were activated than when they were not (Potts et al. 2015). Thus, it is important the V2P system supports providing a signal lead time for pedestrians entering the crosswalk as well as an appropriate clearance time for pedestrians to exit the crosswalk safely.

Leading pedestrian intervals have proven safety benefits for vulnerable road users. FHWA reports that the safety benefit of providing leading pedestrian intervals is a 60 percent reduction in pedestrian–vehicle crashes at intersections (FHWA 2017b). In contrast, the simulator study synchronized DII activation with the pedestrians' crosswalk entrance in the roadway (Hoekstra-Atwood, Richard, and Venkatraman, n.d.). Of the participants who experienced driving with the DII, 8 percent identified the message onset time being too short as a factor that reduced their willingness to use the system at midblock crosswalks.

Section 4E of the MUTCD recommends at least a 3-s lead time, but if signal activation is matched with pedestrians entering the travel lane, the actual lead time may be significantly less (FHWA 2009). There are also common kinematic cases where lead times need to be greater than 2 s for a driver to stop safely (see Swanson et al. [2016] for a detailed table on the relationships between minimum stopping distance, initial velocity, and braking level). For example, if a driver was traveling 35 mph and was able to decelerate comfortably at 11.2 ft/s^2 (between 0.3 and 0.4 *g*), the driver would need at least 2 or 3 s of lead time from brake onset to stop the vehicle (AASHTO 2018; Swanson et al. 2016). This calculation suggests that simple activation (by pedestrians stepping into the crosswalk within the vehicle lanes) will not give the driver sufficient time to execute an avoidance maneuver.

One option that allows for pedestrian lead time to pedestrians stepping into vehicle traffic is having the system support pedestrian crossing signal actuation using a pushbutton or mobile phone application and then using MUTCD timing algorithms to determine the lead time. Another option is creating a pseudo-lead-time by adjusting the roadway layout that allows passive pedestrian detection to identify pedestrians entering the crossing area prior to entering the vehicle travel lanes (e.g., adding wider staging areas, bicycle lanes, parking lanes) (FHWA 2009). Another approach could be analyzing the trajectory of vehicles and pedestrians to predict high-probability conflicts; however, no formal evaluation of this type of predictive system using a DII display exists.

Chapter 4E of the MUTCD provides detailed information about clearance times based on pedestrian movement speeds and crossing distances for pedestrian-actuated systems. However, since the V2P systems should support passive pedestrian detection, the system could switch off based on pedestrians' actual speed or after the crosswalk is cleared (FHWA 2009). It may be prudent to provide a safety margin between pedestrian exit and DII message offset, but drivers may not consistently comply with this safety margin. A simulator study observed that approximately 40 percent of drivers restarted their travel before pedestrians completely exited the crosswalk (Hoekstra-Atwood, Richard, and Venkatraman, n.d.). Out of the drivers who received a DII message, 20 percent of participants in each of these groups waited for 2 s after pedestrians exited the road (until the safety message was extinguished).

The DII in Signalized Intersections

This section includes topics that cover multiple characteristics of DIIs at signalized intersections, including the following:

- DII display characteristics.
- DII placement.
- DII message stages.
- DII message timing.

Specific information needs and supporting information for each characteristic will be separately discussed.

Although traditional driver signals mitigate potential conflicts between drivers proceeding straight through the intersection and pedestrians crossing perpendicular to those drivers, there are driving scenarios in which the traffic control signals allow drivers to perform maneuvers that can put them in conflict with pedestrians in the intersection crosswalks (e.g., all turning maneuvers).

The pedestrian-related information needs for drivers approaching a signalized intersection are listed by intended vehicle maneuver in table 5. The scope of these information needs does not include jaywalking or drivers disobeying the traffic control signal. Jaywalking is not included in the scenarios, since addressing this hazard would require suddenly changing the traffic signal. The DVI is a more suitable display for communicating jaywalking information to the relevant drivers.

Table 5. Driver information system requirements to be satisfied by the V2P system assuming neither drivers nor pedestrians will violate the existing signals.

Driving Maneuver	Driver Information Requirements Not Satisfied by Existing Traffic Control Signals
Driver proceeding straight through the intersection on a green/yellow light.	None.
Driver turning right on a green/yellow light.	Is there a pedestrian in the right-side crosswalk?
Driver turning right on a protected turn.	None.
Driver turning right on a red light.	Is there a pedestrian in the near-side crosswalk?
Driver turning left on a protected turn.	None.
Driver turning left on a yield turn/steady green/yellow light.	Is there a pedestrian in the left-side crosswalk?
Driver performing a channelized right turn on a red light.	Is there a pedestrian crossing the channel?
Driver performing a legal U-turn.	None.

In most cases, the driver is expected to be able to visually acquire the information provided in table 5 without the help of the midblock DII. In the research conducted for this phase of the Multiple Sources project, 27 percent of participants who had experience with the V2P system's

DII identified already having the information they needed as a factor that reduced their willingness to use the system at signalized intersections (Hoekstra-Atwood, Richard, and Venkatraman, n.d.). However, there are scenarios in which the driver's attention is averted, or part of their view of the crosswalk is occluded (e.g., by a large vehicle), when the DII may be the only source available to satisfy the driver's information needs.

Maneuvers in which the vehicle was turning either left or right with the pedestrian crossing the road accounted for 10 percent of target pedestrian crash costs (e.g., lost productivity, medical costs, legal and court costs, emergency service costs, insurance administration costs, travel delay, property damage, and workplace losses) in 2011 and 2012 (Swanson et al. 2016). The V2P system is potentially more equipped to address these scenarios than systems that rely on forward-looking detection sensors such as radar and cameras (Swanson et al. 2016).

The envisioned V2P DII system is compatible with the next traffic signal system generation, the Multi-Modal Intelligent Traffic Safety System (Office of the Assistant Secretary for Research and Technology and USDOT, n.d.). The system bundle includes the Mobile Accessible Pedestrian Signal system, which aims to manage pedestrian traffic flow while minimizing vehicle delays. This system integrates traffic and pedestrian information from roadside or intersection detectors with pedestrian-carried nomadic devices (e.g., mobile phones) to request dynamic pedestrian signals or to inform pedestrians when to cross and how to remain aligned with the crosswalk based on real-time Signal Phase and Timing and Mobile Accessible Pedestrian Signal information. The system accommodates nonmotorized travelers and bicyclists equipped with compatible nomadic devices and supports manual pedestrian call sensors for unequipped pedestrians. The system specifications also call for adjustable crossing times for nonmotorized travelers in cases of inclement weather (University of Arizona 2012).

TOPIC 8: DII SIGNALIZED INTERSECTIONS DISPLAY CHARACTERISTICS

Topic 8 covers the physical characteristics of the DII display and MUTCD-compliant display implementation for crosswalks at signalized intersections.

Driver Information Needs

The display should communicate when the driver is expected to yield to avoid a potential vehicle–pedestrian conflict in the crosswalk area.

The MUTCD does not permit most dynamic signs or beacon configurations that communicate that drivers should yield to pedestrians while performing a turning maneuver at signalized intersections. An exception described in chapter 2B of the MUTCD is the "Turning Vehicles Yield to Pedestrian" sign, which may be used in conjunction with a beacon (FHWA 2009). This sign could be adequate to support the driver information needs at signalized intersections that are not covered by the traffic control signal (since all the relevant vehicle maneuvers involve turning); however, the intent behind allowing this sign at an intersection seems to be to remind drivers to check for pedestrians, not to communicate a pedestrian-in-crosswalk state.

Although the sign and beacon configuration in figure 4 is compliant with MUTCD intersection design, the similarities between the beacon's shape and color to the traffic signals' shape and color may cause driver confusion about the state of the intersection. A future safety message consideration to support drivers' information needs when performing turning maneuvers at signalized intersections would be developing and evaluating new dedicated dynamic displays (e.g., changeable message signs with symbols) that drivers could use for reference. These displays could be positioned close to the relevant crosswalks (see topic 9) to communicate that drivers should yield to pedestrians but should be visually distinct from, and not distract from, traffic signal information.

Source: FHWA.

Figure 4. Image. Example of turning vehicles yielding to pedestrian sign with beacon at East Lake Sammamish Parkway SE and SE 56th Street, Issaquah, WA.

TOPIC 9: DII PLACEMENT AT SIGNALIZED INTERSECTIONS

Topic 9 covers how the DII should be positioned to best support driver information acquisition from the display or the driving environment that helps inform whether the drivers need to yield for crossing pedestrians.

Driver Information Needs

The display should be collocated to the pedestrian detection task.

Safety message location should take into consideration the constraints imposed by the driving task they are intended to support. Collocating the DII to the driving task should support information acquisition by minimizing the time drivers need to spend oriented away from time-critical, safety-relevant information about pedestrians and oncoming vehicles. In a simulator study, 10 percent of participants who had experience with the V2P system's DII identified inconvenient display location as a factor that reduced their willingness to use the system at signalized intersections (Hoekstra-Atwood, Richard, and Venkatraman, n.d.).

Driver information needs not covered by traffic control signals at signalized intersections are present when drivers intend to perform a turning maneuver.

Drivers acquire most visual task information for left turns from the areas in the visual scene that contain oncoming traffic, the turn path to the left (including the crosswalk), oncoming vehicles (if there are any), and the traffic signal. For a right turn on red, drivers are mostly glancing toward the left and right along the crosswalk for pedestrians, looking for a gap in traffic traveling to the right, visually scanning the turn path, and checking the traffic signal. Whereas for right turn on green, drivers are visually glancing toward oncoming left-turning vehicles, checking the traffic signal, checking the turn path to the right for pedestrians and oncoming bicyclists, and scanning the turn path (Richard, Campbell, and Brown 2006).

Thus, the following should be considered:

- Vehicle placement during a left turn makes an overhead display difficult to view without looking away from time-critical driving task information.
- DII placement on the right side of the channel for channelized right turns collocates the display with time-critical driving task information.
- A separate DII placed toward the left side of the intersection channel may be needed to support a left turn maneuvers at intersections.

Drivers observed in a simulator study performing an LTAP with an active DII did not show performance improvements (choosing safer gaps before making a left turn), possibly due to high visual demand that concentrated the drivers' glances toward the left side of the visual scene (Hoekstra-Atwood, Richard, and Venkatraman, n.d.). After drivers positioned their vehicle for a left turn, the overhead DII was visible but located in the upper part of the visual scene, well separated from key driving information. Even though drivers in this study preferred the overhead position for the DII at intersections (locations C and D, figure 5), the DII would likely require a dedicated display in a more suitable location closer to the crosswalk, such as above a crosswalk signal, to accommodate driver viewing angles.

Source: FHWA.

Figure 5. Graphic. Potential DII display locations at intersection crosswalks.

TOPIC 10: DII SIGNALIZED INTERSECTION MESSAGE STAGES

Topic 10 covers the implementation of DVIs that change their message to reflect the severity of the hazardous situation. The following driver information needs and three hazard stages are the same as those for midblock crosswalks (topic 6): advisory, inform, and warn messages. In the context of V2P driver messages, these stages would apply to the following driving conditions:

- Advisory—a persistent alert that a crosswalk is located ahead. This is analogous to advanced roadway signage.
- Inform—an alert indicating that a pedestrian is in or near the crosswalk. For the DII, the message is visible whenever a pedestrian is in the crosswalk. However, a distance criterion may also be applied for a DVI (i.e., at stopping distance based on average braking) (Stephens, Schroeder, and Klein 2015).
- Warn—an alert indicating that a pedestrian is in or near the crosswalk and the vehicle is on a trajectory that will lead to a direct conflict with the pedestrian unless the driver takes immediate action. A distance criterion is applied (i.e., at stopping distance based on aggressive braking) (Stephens, Schroeder, and Klein 2015).

Driver Information Needs

A DII is suitable for an inform message but is potentially unsuitable for presenting a warn message.

An advisory message that a crosswalk is located ahead may be achieved using traditional, static signs. Inform messages communicate essentially the same information as a traditional crosswalk signal—that a driver must yield to a pedestrian. Thus, an inform message is compatible with a DII. However, warn messages are not compatible because it is potentially hazardous to display a high-severity warning that can be readily seen by road users who are not the intended recipient of the message. The ubiquitous visibility of infrastructure-based messages could have the unintended consequence of warning the wrong drivers and eliciting unnecessary evasive responses (Richard et al. 2015).

TOPIC 11: DII SIGNALIZED INTERSECTION MESSAGE TIMING

Topic 11 covers some timing attributes for the DII display that should be considered for providing drivers with sufficient time to receive the information they need and respond appropriately (e.g., stopping before the crosswalk). Some of these needs repeat those for midblock crossings (see topic 7), but signalized intersection message timing needs diverge on needing to support turning maneuvers and the existing research cited.

Driver Information Needs

Drivers require a minimum hazard preview time (at least 3 s) to respond to a hazard. This need may require supporting geometric sign features or predictive pedestrian movement algorithms.

Pedestrians may not always engage a traditional DII system for which the beacons are solely activated by pedestrian action. Thus, it is important the V2P system supports providing a signal lead time for pedestrians entering the crosswalk as well as an appropriate clearance time for pedestrians to exit the crosswalk safely.

Leading pedestrian intervals have proven safety benefits for vulnerable road users. FHWA reports that the safety benefit of providing leading pedestrian intervals is a 60-percent reduction in pedestrian–vehicle crashes at intersections (FHWA 2017b). In contrast, the simulator study synchronized DII activation with the pedestrians' crosswalk entrance in the roadway (Hoekstra-Atwood, Richard, and Venkatraman, n.d.). Of the participants who experienced driving with the DII, 14 percent identified the message onset time being too short as a factor that reduced their willingness to use the system at signalized intersections.

The MUTCD recommends at least a 3-s lead time, but if activation of the signal is matched with pedestrians entering the travel lane, the lead time may be significantly less (FHWA 2009). This observation suggests that simple activation (by pedestrians stepping into the crosswalk within the vehicle lanes) will not give drivers sufficient time to execute an avoidance maneuver.

Presently, there is insufficient information to provide recommendations on DII timing for a vehicle turning at a signalized intersection. Since turns—especially turns across traffic—are a complex maneuver, a different timing sequence may be required for this DII than for a DII at a midblock crosswalk. Before implementing a proposed time sequence, designers should evaluate how long it takes for drivers to confirm that making a turn is safe for both drivers who have stopped and drivers making a turn at speed. The time may be close to regular pedestrian crosswalk signal lead time for drivers who are in motion, but it is possible the maneuver will require more time since it is more complex.

CHAPTER 4. SUPPORT FOR V2P SAFETY MESSAGES USING DVIs

Drivers are the road users who most often alter their path to resolve conflicts with pedestrians (Ortiz, Ramnarayan, and Mizenko 2017). A DVI can deliver timely V2P scenario information to drivers because it is located close to the driver and it permits the use of display elements (e.g., sound) that can help draw drivers' attention to the immediate hazard. In the context of V2P systems, DVIs are primarily intended to supplement a DII by providing redundant and enhanced information on pedestrian or bicyclist presence in or near crosswalks. In an external environment, DVIs may be the sole information source in the absence of a DII. This chapter discusses driver information needs from a DVI in V2P scenarios.

DVI messages can be a practical approach for warning drivers about pedestrian hazards. Advantages of using DVIs to communicate information in V2P scenarios include the following:

- DVI messages do not require expensive roadside equipment.
- DVI messages can directly target drivers whose path is in conflict with another road user, whereas DII messages inform all drivers who can see the message.
- DVI messages can provide information on recommended driver actions.
- DVI messages (e.g., inform and warn) can have stages reflecting hazard severity.
- DVI messages can be tailored to vehicle movements and can reflect the situation's change in urgency with graded alerts.
- DVI message presentation and mode can be tailored to drivers' attention orientation to minimize the incidence of nuisance alarms as a means to alert drivers.

Disadvantages of using DVIs to communicate information in V2P scenarios include the following:

- CV DVI availability in the future vehicle fleet is still uncertain, and it could take many years before there is sufficient market penetration to achieve safety benefits.
- DVI placement is determined by original equipment manufacturers and may not occur in an in-vehicle location that adequately supports V2P applications (e.g., LTAP scenario).
- V2P messages may have to share the DVI with other in-vehicle infotainment applications, which necessitates a holistic approach to resolving resource conflicts.
- Most drivers prefer receiving their information from a DII.

The design of in-vehicle DVI information for CV applications is a relatively established field of research. Specific details about the design of DVI messages have been discussed in other reports and publications (Campbell et al. 2004, 2016). This chapter discusses high-level driver information needs that can be satisfied using an RSE-based DVI and references key documents.

The design of inputs the system could receive from drivers (e.g., to control the occurrence of perceived-nuisance warnings) is beyond the scope of this report. At this early stage of development, the source of the DVI safety message is currently undefined. One possibility is that automotive manufacturers take responsibility for developing and implementing the safety messages. Another possibility, which is consistent with other Federal Highway Administration CV specifications, is that the RSE is responsible for transmitting the DVI safety message to the in-vehicle safety system (Stephens et al. 2013). In this case, departments of transportation would be responsible for developing and implementing the safety messages. The sections in this chapter provide initial driver information needs related to specific characteristics of a DVI in V2P scenarios.

TOPIC 12: DVI MESSAGE VISUAL CHARACTERISTICS

Topic 12 covers the visual appearance of DVI messages, which refers to the presentation format of message elements such as icons, text, digital and analog displays, and maps. The design of the visual appearance directly corresponds to what information is presented to drivers as well as the desired driver response.

Driver Information Needs

The visual appearance of the DVI messages should be consistent with functional requirements that serve information needs, and different message elements can be used. The following characteristics promote drivers' understanding of messages:

- Symbolic or representational displays that use familiar icons to convey the type of hazard and its spatial location.

- Text displays that are directly interpretable in safety-critical situations that require immediate action.

- Visual displays that provide safety-critical messages that are salient, contain collocated elements, and present actionable information.

Text, symbolic, and representational displays can be used for V2P messages. Figure 6 through figure 9 show examples of each display. Text displays, when used appropriately and not exceeding three words, help drivers extract and interpret messages, resulting in lower driver response times when compared to symbolic or combined displays (Shinar and Vogelzang 2013). Notably, text displays can be detrimental to the performance of drivers unfamiliar with the local language—universally appropriate and familiar symbols may be desirable in these cases (Alliance of Automobile Manufacturers 2006). Representational displays can enhance the contextual relevance of symbol or text messages by locating message characters in a spatial or temporal overlay. Hybrid displays combine aspects of each of these three display types to present some form of icon or layout enhancement that might require further explanation, which may increase driver interpretation demands and so must be used judiciously.

Source: FHWA.

A. Pedestrians in crosswalk verbal meaning display.

Source: FHWA.

B. Pedestrian crossing verbal meaning display.

Figure 6. Graphic. Examples of text signs that convey verbal meaning.

Source: FHWA.

A. Symbolic display that combines two concepts.

Source: FHWA.

B. Symbolic display that warns of pedestrian and bicyclist hazards.

Figure 7. Graphic. Examples of symbolic signs that convey symbolic meaning (icon or picture).

Source: FHWA.

A. Representational inform display indicating pedestrian in crosswalk.

Source: FHWA.

B. Representational warn display indicating pedestrian in crosswalk.

Figure 8. Graphic. Examples of representational signs that convey spatial information.

Source: FHWA.

A. Hybrid symbolic–verbal sign.

Source: FHWA.

B. Hybrid symbolic–representational sign.

Figure 9. Graphic. Examples of hybrid signs that convey symbolic–verbal and symbolic-representational information.

In a driving simulator study using common V2P driving scenarios, participants preferred familiar signs and direct information for inform and warn messages (Hoekstra-Atwood, Richard, and Venkatraman, n.d.). The two inform messages that participants rated the highest were a symbolic–verbal display (figure 9-A) and a verbal meaning display (figure 6-A). Both message types provided direct information about the hazard ("pedestrian" text or icon), and the higher rated hybrid symbolic-verbal message also provided information about the required driver action ("stop"). Representational, symbolic, and hybrid symbolic–representational displays were not as preferred, possibly due to participant unfamiliarity with such displays or because the messages were less direct. These lower rated displays may also increase interpretation demands on participants.

The ratings for the warn messages were very similar, with the same two types of messages receiving the highest ratings. The primary difference was that the text display (figure 6-B) was rated higher than the hybrid symbolic–verbal display (figure 9-A). The "Stop for Pedestrian" display was the same as the inform message described in the previous paragraph. This display is somewhat ambiguous in terms of the immediacy of the conflict situation; thus, it could be perceived as an acceptable display for both inform and warn messages. The "Pedestrians in Crosswalk" display used in the inform message has an advisory tone, which contrasts with the "Stop Pedestrians Crossing" display in the warn message that has a more urgent tone based on its visual features.

Table 6 lists key factors and parameters that influence the appearance of the DVI display. These features are discussed at a high level in the following sections.

Table 6. DVI appearance and parameters.

Appearance Factors	Key Design Parameters (Campbell et al. 2016)
Salience	Color, contrast, illumination, flash, and location.
Character features	Proximity, pixel size, fonts, shape form (open/closed), color, contrast, and spacing.
Actionable information	Text: Verbs such as "stop" or "look," nouns such as "caution" or "danger" and "pedestrian" or "bicyclist." Symbols and spatial representation: Pedestrian or bicyclist icons, yellow or red colors, "stop" icon, arrows indicating location.

Salience

DVI message salience can be varied using several features, including those listed in table 6 (Lee et al. 2017). Saliency can be graded to reflect the situation's urgency. Flashing visual icons are recommended when indicating safety-critical information (Kiefer et al. 1999). Saliency should be varied by using the appropriately colored wavelength for high- and low-light situations such as nighttime (Mantiuk, Rempel, and Heidrich 2009). In general, care should be taken so that drivers are not overloaded by, nor inappropriately rely on, salient information. Furthermore, key information should be presented so that it is salient, easy to comprehend, highly accurate, and trustworthy.

Character Features

Several features affect how the display is visually perceived. One example is the proximity between characters in the sign. Character proximity influences perception and cognitive processing. Information that should be processed together (conceptual proximity), such as the two icons and text in figure 9-A, should be located close enough so they are processed together as a unit (physical proximity) on the display (Lee et al. 2017). Visual clutter (elements per unit of display area) of nontarget information should be minimal, with sufficient intracharacter spacing, to facilitate easy information extraction.

Actionable Information

To the extent feasible, DVI messages should provide actionable information containing the nature of the desired driver's response when appropriate (Campbell et al. 2016). An example is the "Stop Pedestrians Crossing" sign used in warn messages. One of the benefits of using a visual DVI message is the potential for action recommendations. However, action recommendations can have unsafe consequences if the RSE predictions are inaccurate, as they may result in a cognitive leap from sensation to action rather than deliberative processing of sensory information (information processing model), particularly when the driver trusts the system (Rasmussen 1993). Thus, algorithms that prescribe actions should be reliable and robust.

TOPIC 13: MULTIMODAL DVI MESSAGES

There are many challenges when using visual displays to communicate safety messages. Visual displays may be missed by drivers who are not looking at the general display location, who "look but may not see," or who are visually overloaded by a complex scenario (e.g., LTAP with pedestrian crossings). In addition, ambient interference, such as glare, external noise, or vibration, may degrade the drivers' ability to sense any one mode. To overcome such problems and reorient driver attention to safety-critical situations, auditory or haptic messages can be incorporated into the DVI message. This result cannot be achieved with DII displays alone. Multimodal displays (e.g., visual and auditory warnings) provide message redundancy, which increases the number of perceptual channels that deliver information.

Driver Information Needs

More than one mode of message delivery can generate a warning that drivers can quickly and reliably comprehend. The *Human Factors Design Guidance for Driver-Vehicle Interfaces* provides the following principles for general characteristics of multimodal messages (Campbell et al. 2016):

- Simultaneous multiple mode signal activation enhances temporal redundancy and increases the likelihood that the drivers receive the warning.

- Increasing urgency of a situation can be communicated by increasing the number of modes of reception (inform, only visual; warn, visual and auditory) or by a corresponding change in signal feature (e.g., loudness of an auditory signal).

- Simple audio tones are generally recommended for multimodal V2P messages in combination with a visual DVI.

- Verbal speech messages may be used when complex, detailed, or nonobvious information must be communicated to drivers. Present a simple alerting tone before the speech.

- Selected frequency and amplitude combination for both auditory and tactile alerts should be highly detectable without being annoying.

- Both auditory and haptic interface signals should be discernable and accommodate real-time changes in ambient noise, vibration, and posture shifts of drivers.

Simple, nonspeech tone auditory alerts are primarily preferred for warning drivers about imminent collision situations (Campbell et al. 2016). Simple tones are abstract, can convey varying levels of urgency, and can be obtrusive and salient to capture drivers' attention in critical situations. Visual displays are often suggested as supplementary information to auditory alerts to maximize reception channels, explain the nature of the hazard pictorially, and indicate the hazard is in the forward direction (Kiefer et al. 1999). Speech interfaces can be used to convey information that is not directly apparent to drivers such as a bicyclist in a blind spot when making a turn or a pedestrian obscured by the geometry of the intersection. Generally, speech should be used only in noncritical, inform or advisory messages because drivers do not respond as quickly to speech as simple tones (Campbell et al. 2016).

In the driving simulator study of V2P scenarios, an auditory tone was presented along with a visual message as a warning alert in an imminent collision scenario (Hoekstra-Atwood, Richard, and Venkatraman, n.d.). The auditory tone was designed according to recommendations in the *Human Factors Design Guidance for Driver-Vehicle Interfaces*—the tone was a simple sine wave tone with a pulse width of 6 pulses per second, regular rhythm, and high fundamental frequency of 800 Hz (Campbell et al. 2016). The visual message was located in the center console. The pedestrian was occluded for part of the event by a stopped truck at an intersection and emerged in the vehicle's path just as the vehicle was approaching the crosswalk. The majority of the participants (80 percent) reported hearing the sound, and 70 percent reported that it helped them with pedestrian detection.

As with other design features, multimodal messages have disadvantages. They can be nuisance alerts to drivers who are already attentive and responsive to the upcoming conflict. The parameters of auditory alerts that differentially affect urgency and annoyance perception are pulse duration, interpulse interval, alert duty cycle, and type of sound and should be selected appropriately (Marshall, Lee, and Austria 2007). Some drivers may receive false alarms, especially if the RSE algorithm predictions are inaccurate, which could lead to driver confusion and loss of trust in the DVI.

TOPIC 14: DVI DISPLAY LOCATION

A visual DVI's location within the limited space available in the vehicle cab plays an important role in facilitating rapid information extraction. Operating conditions should be carefully considered. Key factors include hazard type and location and perceptual limits of drivers due to illumination, contrast, and size. In multimodal displays, auditory or haptic signals can be spatially localized to facilitate information access and comprehension.

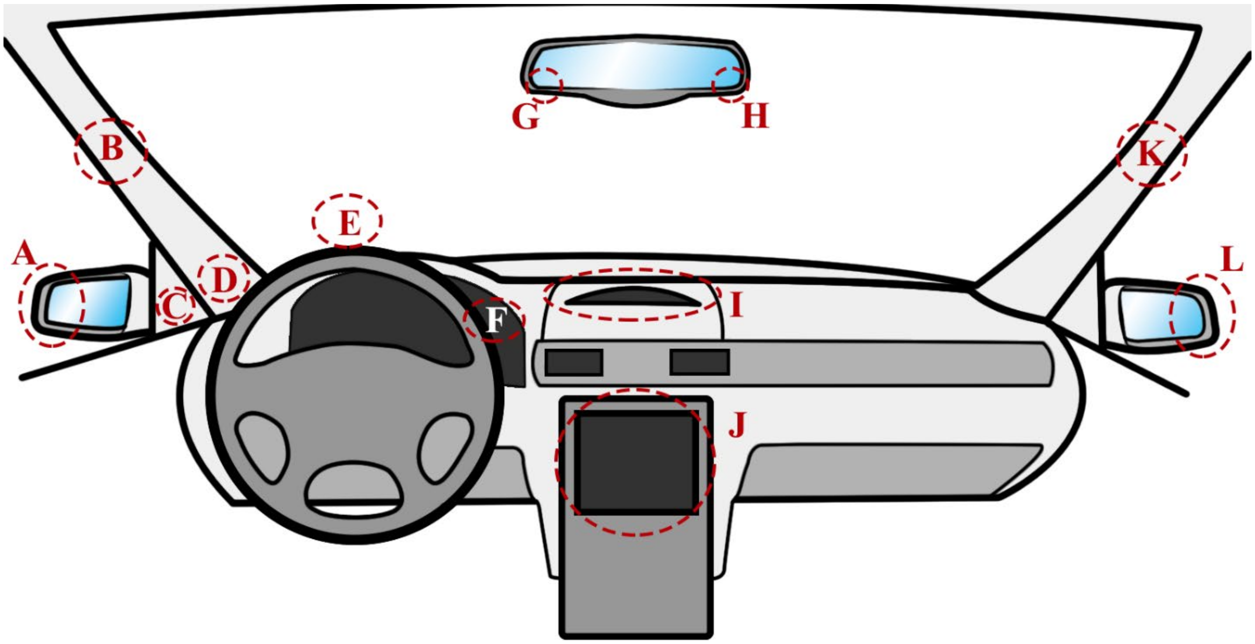
Driver Information Needs

DVI messages positioned in locations that are close to other parts of drivers' natural information acquisition process facilitate rapid access to the information. The *Human Factors Design Guidance for Driver-Vehicle Interfaces* provides the following general considerations for DVI display location (Campbell et al. 2016):

- Integrating visual information related to the situation into one location.
- Placing time-critical information such as warnings within ±5 degrees of the central line of sight.
- Considering the influence of color of icons and text on whether objects are detected in peripheral vision and taking into account choice of location.
- Addressing driver preference of head-down displays over head-up displays for communicating text and symbols.
- Making localized auditory and haptic alerts discernible.
- Using appropriate spacing between the receptors in a vibrotactile seat and accommodating real-time shifts in posture.

Suitable locations for in-vehicle V2P messages share directional correspondence with key external elements to cue rapid information extraction. For example, DVIs that indicate a pedestrian is in the crosswalk when a driver is trying to make a turn could include the A-pillars—left pillar locations B and D for left turns and right pillar location K for right turns in figure 10 (Campbell et al. 2016). Another possible placement, particularly for midblock inform and warn messages, is as close to the central line of sight as possible (location E, figure 10).

Horizontal offsets to such a central location may be considered in intersection and turning situations. In a driving simulator study that had drivers navigate a challenging V2P LTAP scenario, the DVI was located away from key driving task information (Hoekstra-Atwood, Richard, and Venkatraman, n.d.). Specifically, the DVI was located down to the right in the center console (location J, figure 10), while the key visual information was located to the drivers' left. The findings indicated that drivers did not rely on the DVI safety messages to inform their go or no-go decisions. Participants in this study also rated the locations closest to the central line of sight as the most preferred locations to receive DVI messages. Particularly, locations E, I, F, and G were the four most preferred locations (figure 10). These locations have the potential to be less obtrusive to forward scene glances while capturing drivers' focal or near-peripheral visual attention when needed. The center display console J received low preference ratings, which is in line with previous research on the center line of sight being the preferred location (Campbell et al. 2016).



Source: FHWA.

Figure 10. Graphic. In-vehicle DVI locations.

TOPIC 15: MULTISTAGE SAFETY MESSAGE

Topic 15 covers the implementation of DVIs that change their message to reflect the severity of the hazard situation. Three different hazard stages are defined for CV systems, including advisory, inform, and warn messages. In the context of V2P driver messages, these stages would apply to the following driving conditions:

- Advisory—a persistent alert that a crosswalk is located ahead. This message is analogous to advance roadway signage.
- Inform—an alert indicating that a pedestrian is in or near the crosswalk. For the DII, the message is visible whenever a pedestrian is in the crosswalk. However, a distance criterion may also be applied for a DVI (i.e., at stopping distance based on average braking) (Stephens, Schroeder, and Klein 2015).
- Warn—an alert indicating that a pedestrian is in or near the crosswalk and the vehicle is on a trajectory that will lead to a direct conflict with the pedestrian unless the driver takes immediate action. A distance criterion is applied (i.e., at stopping distance based on aggressive braking) (Stephens, Schroeder, and Klein 2015).

Advisory V2P messages are not examined in this section. An advisory V2P DVI would be essentially the same as a static advisory sign placed ahead of a crosswalk. The same practices could be used for determining advisory message timing and content. The remaining discussion focuses on two-stage DVI messages.

Driver Information Needs

In critical vehicle–pedestrian conflicts in which the pedestrian is directly in the vehicle's path and the driver has minimal time to respond, a DVI can do the following:

- Augment driver alerting by providing a salient, time-critical safety message.
- Supplement a DII safety message with a salient auditory signal signifying the increased severity of an impending pedestrian conflict.

The *Human Factors Design Guidance for Driver-Vehicle Interfaces* provides the following basic guidance from other CV documents about applying staged messages as well as their timing and triggering conditions (Campbell et al. 2016):

- Two-stage alerts are recommended when hard braking needs to be avoided (e.g., close-following rear vehicles) or when there is sufficient time and accuracy to estimate the pedestrian and the driver are on a collision path.

- Warn messages, whether in one- or two-stage systems, should only be used in critical situations when a collision is imminent if no action is taken.

- Audio or haptic modes can be used as primary warn messages, but they should be supplemented with visual information.

- The urgency communicated by the message at each stage (e.g., visual flash, audio pulse rate, haptic amplitude) should map to the urgency of the situation (e.g., approach speeds), but no more than the perceived urgency to minimize confusion and annoyance.

The *Human Factors Design Guidance for Driver-Vehicle Interfaces* (Campbell et al. 2016) and *Task Analysis of Intersection Driving Scenarios: Information Processing Bottlenecks* (Richard, Campbell, and Brown 2006) provide the following additional information on message timing and triggering conditions:

- DVI message timing should coincide, when possible, with the DII message timing.

- DVI warn messages, if provided, should be provided early enough that the driver has sufficient time to respond and avoid collision but without causing driver annoyance or the potential for false alarms.

- DVI message timing should consider perception and decision reaction times in addition to motor reaction times.

Some evidence suggests that staged messages provide a safety-relevant benefit to drivers. Information about usefulness of staged messages was obtained in a driving simulator study that examined a V2P scenario in which drivers were "surprised" by an expected pedestrian jaywalking in the vehicle's path (Hoekstra-Atwood, Richard, and Venkatraman, n.d.). In this scenario, an inform message presented 5 s prior to the sudden appearance of the pedestrian was used by most drivers to anticipate the potential hazard and prepare for a response. Presenting these messages did not appear to distract drivers from enacting a time-critical response.

Furthermore, providing multiple sources of information yielded a response benefit when the conflict severity increased. In the V2P simulator study, participants made safer driver actions when they received a DII message in addition to a DVI message that included an auditory warn sound presented 2.5 s before the pedestrian encounter. A smaller proportion of drivers benefited when only the auditory warn sound accompanied the DII (which was only an inform message). Nevertheless, these findings suggest that supplementing an inform DII message with a DVI message that has a warn stage may facilitate driver crash-avoidance responses.

In general, the timing of the alerts should reflect the cognitive, motor, and mechanical components of drivers' braking responses. The cognitive component accounts for the time it takes drivers to sense, perceive, and select a response to the hazard. The motor component incorporates time to move the foot toward the brake pedal and depress the brakes. The mechanical component is vehicle and environment dependent but should be included to account for the time it takes the vehicle to respond to drivers' brake input. Generally, alerts should activate before drivers take their foot off the accelerator pedal. The warning timing should also be based on vehicle deceleration levels that are more comfortable to drivers (e.g., $<0.35\ g$). These parameters have been shown to enhance drivers' trust in FCWs (Abe and Richardson 2005; Campbell et al. 2016).

CHAPTER 5. SUMMARY AND CONCLUSIONS

This project examined safety message presentation to drivers in V2P scenarios. Empirical research was conducted to examine driver information needs in specific scenarios. This research provided the basis for developing design information for certain aspects of V2P safety messages. However, since V2P systems are relatively undeveloped at this stage, providing a formal set of design guidelines for safety messages was impractical because of the lack of V2P human factors research to support guidance development. Instead, this report focused on identifying and describing driver information needs. Basic information was developed for both DII and DVI safety messages, and general considerations were gleaned from other CV safety message–design considerations (Richard et al. 2016).

This document develops basic information needs covering 15 topics grouped into general considerations for safety message design, support for V2P safety messages using DIIs, and support for V2P safety messages using DVIs. The individual topics represent a starting point for organizing and adding new findings-related driver information needs in V2P scenarios. They also define the range of issues that future V2P system specification developers should consider.

APPENDIX. FUNCTIONAL REQUIREMENTS FOR PISCA AND PMA V2P SYSTEMS

This appendix provides information about the functional requirements for PISCA and PMA V2P systems (table 7).

Table 7. Functional requirements for PISCA and PMA V2P systems.

System Type	Scope	Functional Requirements
PISCA	Data acquisition	• Pedestrian position. • Crosswalk locations. • Vehicle data (trajectory). • Roadway geometry.
	Analysis	• Whether a pedestrian is present in the target crosswalk. • Whether the vehicle is turning. • Potential vehicle infringement into the target crosswalk.
	Information to send to the driver	• Warn the driver about a pedestrian in the target crosswalk.
	Information to send to the traffic controller	• No requirements.
	Information to send to the pedestrian	• Crossing status. • Potential vehicle infringement into the crosswalk.
	Other	• Application should determine application errors and avoid failures when performance issues or system failure occur. • System must have a common time source for synchronization. • System component location information needs to be accurate enough to create alerts or warnings when warranted and avoid false positive alerts or warnings.
PMA	Data acquisition	• Pedestrian priority commands. • Traffic data (volume, speed, occupancy, vehicle classification incidents). • Bicyclist data (location, speed, bicycle type). • Pedestrian data (calls, location, pedestrian type).
	Analysis	• Process traffic, pedestrian, and bicyclist data to prioritize pedestrian and bicyclist crossing.
	Information to send to the driver	• No requirements.
	Information to send to the traffic controller	• Pedestrian and bicyclist priority commands.
	Information to send to the pedestrian	• No requirements.

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