Multiple Sources of Safety Information from V2V and V2I: Redundancy, Decision Making, and Trust—Safety Message Design Report

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FOREWORD

Vehicles and roadways of the future will employ advanced communications technologies to facilititate applications to make driving safer, more efficient, and more environmentally friendly. The safety benefits will largely be achieved by communicating relevant safety information to the driver. The Human Factors for Connected Vehicles research program is focused on understanding, assessing, planning for, and counteracting the effects of signals or system-generated messages that take a driver's eyes off the road (visual distraction), the driver's mind off the driving task (cognitive distraction), and the driver's hands off the steering wheel (manual distraction). The overall goal of this research is to support the introduction of this technology as a benefit to all transportation users.

The research described in this report provides some intial design guidance for vehicle-to-infrastructure (V2I) safety messages as well as some limited guidance for vehicle-to-vehicle systems. This report primarily uses existing transportation safety research, as well as research from related domains. This information can be used by connected-vehicle system designers and other State transportation department personnel to develop and implement V2I applications, to make sure these systems work effectively and safely within a larger vehicle-to-infrastructure, vehicle-to-vehicle, and vehicle-to-device environment. In this way, these findings will help make the interaction of roadway and vehicle systems safer, reduce the likelihood of crashes and injuries, and increase safety for all roadway users.

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Research and Development

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16. Abstract

This report is part of the Human Factors for Connected Vehicles (HFCV) research 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 guidance for vehicle-to-infrastructure (V2I) safety messages provided using driver-infrastructure interfaces and driver-vehicle interfaces. Existing HFCV research, in addition to research from related domains, was used to develop this preliminary design guidance. The target audiences for this information are CV system designers and other State transportation department personnel involved in the development and implementation of V2I applications that provide safety information. The design topics are divided into two sets. The first set is composed of general topics providing background information and covers issues that apply across multiple V2I applications. The second set includes topics focusing on specific V2I applications. The general objective of the guidance information is to assist in the coordination of V2I and vehicle-to-vehicle displays and messages to safely support driver information needs and decision making. This information may serve as a resource for the development of guidelines that address V2I system-related human factors design issues in future versions of NCHRP 600: *Human Factors Guidelines for Road Systems.*

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
CICAS-SLTA	Cooperative Intersection Collision Avoidance System-Signalized Left Turn Assist
CICAS-SSA	Cooperative Intersection Collision Avoidance System-Stop Sign Assist
CICAS-V	Cooperative Intersection Collision Avoidance System to Prevent Violations
CMS	Changeable message sign
ConOps	Concept of operations
CSW	Curve speed warning
CV	Connected vehicle
DCWS	Dynamic curve warning system
DII	Driver-infrastructure interface
DSRC	Dedicated short-range communication
DVI	Driver-vehicle interface
HFCV	Human Factors for Connected Vehicles
HFG	*Human Factors Guidelines for Road Systems*
ISD	Intersection sight distance
ITE	Institute of Transportation Engineers
ITS	Intelligent transportation systems
LCV	Large combination vehicle
LED	Light-emitting diode
LTAP	Left turn across path
LTAP-OD	Left turn across path—opposite direction
MUTCD	*Manual on Uniform Traffic Devices*
NASS-GES	National Automotive Sampling System-General Estimates System
OVW	Overweight vehicle warning
PCI	Pedestrian crossing intersection
POV	Principal other vehicle
PRT	Perception reaction time
RLVI	Red light violator indication
RLVW	Red light violation warning
RSE	Roadside equipment
SLTA	Signalized left turn assist
SPaT	Signal phase and timing
SSA	Stop sign assist
SWIW	Spot weather information warning
SWIW-RS	Spot weather information warning-reduced speed
TCD	Traffic control device
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-infrastructure, vehicle-to-vehicle, and vehicle-to-device

CHAPTER 1. INTRODUCTION

BACKGROUND

Vehicle-to-vehicle (V2V) communications and vehicle-to-infrastructure (V2I) communications involve the wireless exchange of data among and between infrastructure and vehicles traveling in the same vicinity with the goal of realizing significant safety, mobility, and environmental benefits. This communications capability will enable a host of vehicle- and infrastructure-based safety systems and applications. The vision is that all vehicles on the roadway, (e.g., automobiles, trucks, transit vehicles, and motorcycles), will be able to communicate with other vehicles and the infrastructure to enable active safety applications, as well as improvements in mobility and environmental benefits.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 drivers' eyes off the road (visual distraction), drivers' minds off the driving task (cognitive distraction), and drivers' hands off the steering wheel (manual distraction).

This Federal research investment is a critical factor in developing the knowledge to enable connected vehicle (CV) technologies to save lives and reduce injuries without unintended consequences. The ability to establish the basic principles of attention and distraction within the context of specific advanced communication and messaging technologies (used in vehicles and in roadway infrastructure components) is a challenging effort whose outcomes will form the parameters for and guide consistent development of safer systems and interfaces for countless new applications. When developing new applications, consistency and adherence to basic countermeasures for distraction are paramount to ensuring the ultimate safety of the driver. Human factors research allows the development of more robust algorithms for prioritizing safety and messages that assist the driver, as opposed to providing greater distraction or workload.

From a higher level transportation planning perspective, the National ITS (Intelligent Transportation Systems) Architecture was created to provide a common framework for planning, defining, and integrating ITS. The idea of V2V and V2I communications that enable active safety applications fits into this National ITS Architecture. For example, there are a number of relevant National ITS Architecture Service Packages, including AVSS10-Intersection Collision Avoidance and AVSS05-Intersection Safety Warning[1]. The Intersection Collision Avoidance Service Package describes a system that determines the probability of an intersection collision and provides timely warnings to approaching vehicles so that avoidance actions can be taken. The Intersection Safety Warning Service Package describes a related system that monitors vehicles approaching an intersection and warns drivers when hazardous conditions are detected. 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, a warning is communicated to the involved vehicles using short range communications and/or signs/signals in the intersection[1].

[1]Intelligent Transportation Systems Joint Program Office (2015). Web site: http://www.iteris.com/itsarch/html/mp/mpindex.htm, accessed on 7/13/15.

The scenario described above fits in very closely with the research covered in the current report. In particular, the primary objective of this report is to investigate how drivers handle critical safety information from multiple sources, including V2V and V2I sources. This safety-critical information could include potential conflicts between vehicles occupying or approaching the intersection (e.g., situations where a left turn would be unsafe because of approaching traffic). To meet the objectives of this project, the following specific tasks were completed:

- Task 1: Literature Review and Gap Analysis.
- Task 2: Develop Research Plan.
- Task 3: Execute Research Plan.
- Task 4: Document Design Guidance.

This report documents the design guidance that comprises task 4. The objective of task 4 is to integrate the findings from previous project tasks into a safety message design guidance document that can be readily converted into more formal design guidelines by developers of future versions of NCHRP 600: *Human Factors Guidelines for Road Systems*.

Because this design reference focuses on human factors design issues related to infrastructure and other roadway elements, the current project activities have a similar focus. The target audiences for this information are CV system designers and other State transportation department personnel involved in the development and implementation of V2I applications that provide safety information. Accordingly, the safety messages and design information provided in this report primarily address the V2I component of CV technologies. Also, while V2I communication with drivers can involve both a driver-infrastructure interface (DII) and a driver-vehicle interface (DVI) to provide CV information, this report focuses on providing design guidance related to DIIs, which is the aspect of V2I systems that would be the responsibility of roadway engineers and designers. Table 1 lists the safety message topics and their page locations in this document.

Table 1. DII safety message guideline information.

Topic	Page Number
Topic 1. Considerations for Adding a DII to RSE	12
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RLVW = Red light violation warning.
RSE = Roadside equipment.

OVERVIEW OF THE REPORT

The remainder of this report is composed of the following three chapters:

- **Chapter 2. Overview of CV Applications**: This section provides the definitions for the key terms used to describe the CV communication architecture, in addition to summary descriptions of the safety applications addressed in this report.

- **Chapter 3. DII Safety Message Guideline Information**: This section provides a set of safety message guidance topics for designers to use as a reference—including specific design parameters, identified design problem(s), and/or information—in developing safety applications.

- **Chapter 4. Summary and Conclusions**: This section provides a summary of the guideline effort as a whole, and discusses the key project conclusions .

CHAPTER 2. OVERVIEW OF CV APPLICATIONS

CV COMMUNICATION ARCHITECTURE

This chapter provides definitions of key terms used in the current report to describe the CV communication architecture. This chapter also provides an overview of the operation, collision types addressed, and target-site characteristics for the CV safety applications discussed in this report. The following applications are described in this chapter:

- Stop sign assist (SSA).
- Signalized left turn assist (SLTA).
- Red-light violation warning (RLVW).
- Curve speed warning (CSW).
- Spot weather information warning—reduced speed (SWIW-RS).

Additional CV safety applications have been developed under the CV program. These include applications such as overweight vehicle warning (OVW) and railroad crossing warning. These applications, however, are not discussed in this report.

V2V

V2V communication is the dynamic wireless exchange of anonymous, vehicle-based data using dedicated short-range communication (DSRC) protocols. The minimum transmitted data package from a vehicle is referred to as the "basic safety message" and contains information regarding the vehicle's current position, speed, heading, acceleration, braking status, and vehicle size.(1) This information is broadcast to and received from surrounding vehicles. This communication enables a vehicle to sense the position of other vehicles and the threat or hazard they present with a 360-degree awareness, calculate risk, issue driver advisories or warnings, or take preemptive actions to avoid and mitigate crashes.

V2I

V2I communication is the wireless exchange of safety and operational data between vehicles and the highway infrastructure (via roadside equipment (RSE)) using DSRC protocols. V2I communication is intended to prevent or reduce the severity of vehicle crashes; however, it can also provide system mobility and environmental benefits by supporting applications such as speed harmonization and traffic optimization.(2)

Vehicle-to-Infrastructure, Vehicle-to-Vehicle, and Vehicle-to-Device (V2X)

V2X communication is a term collectively referring to any type of CV communication, including V2V, V2I, or vehicle-to-device communication.

DII

DII is a changeable information display located externally to the vehicle that provides information to drivers and other road users. CV safety application DIIs use V2X information to identify roadway conditions and provide appropriate safety messages, which are typically visible to multiple roadway users, as long as the DII display is pointing towards them. DIIs include a range of equipment, such as changeable message signs (CMSs), blank-out signs, triggered beacons accompanying static signs, dynamic signals, traffic control devices (TCDs), and in-road/in-path lighting.

DVI

DVI is an in-vehicle display (or set of displays) and controls that a driver uses to obtain information from a vehicle.[3] Messages provided via DVI can be targeted to the individual vehicle. A variety of DVIs can support CV safety applications, including dash- or instrument panel-mounted screens, head-up displays, auditory displays, and vibrotactile or haptic displays (i.e., seat pan vibrations or steering wheel torques). Throughout this report, the display element is typically the focus of discussions regarding DVIs for CV safety applications. CV safety application DVIs provide warning information to the driver using information acquired through V2X communication. Not all vehicles will support all CV safety applications; some vehicles may only support specific CV safety applications.

RSE

RSE is roadside-installed hardware used to relay messages using DSRC protocols. RSE may receive messages from vehicles, other RSEs, or from back offices that monitor traffic system performance (i.e., a traffic management center). RSEs may be permanently or temporarily installed, allowing their use for either long-term or short-term (e.g., work zones) applications.

SUMMARIES OF SAFETY APPLICATIONS DISCUSSED IN THIS REPORT

The following section presents a brief summary of each of the five CV safety applications listed in the previous section, along with an overview of the application's operation, collision types it may address, and its target-site characteristics.

SSA

SSA is a system that supports drivers on minor roads who are attempting to either cross or enter the intersecting major road. SSA provides drivers with information about oncoming vehicles traveling on the major road. The objective of this system is to help drivers safely travel through or turn onto a highway from a stop-controlled intersection. This system is related to the Cooperative Intersection Collision Avoidance System-Stop Sign Assist (CICAS-SSA).

SSA has the following attributes:

- **Operation**: Identifies the location and speed of vehicles traveling on the major road and provides the driver on the minor road with information via DII to assist in selecting an adequate gap when turning or going through the intersection.
- **Collision Types**: Includes left/right turn into path (rear-end), sideswipe (same direction), and right-angle crashes with vehicles travelling on the major road.

- **Target-Site Characteristics**: Includes rural stop-controlled/through-stop intersections where lower speed/volume minor roads intersect higher speed/volume median divided highways. The DII is positioned where it can be easily seen by stopped drivers on the minor road.

Figure 1 provides an example of a CICAS-SSA (DII) protype.

Source: National RITS Conference.

Figure 1. Photo. CICAS-SSA (DII) prototype implemented by Minnesota.[(4)]

SLTA

The SLTA system supports drivers who are making permissive left turns at signalized intersections. The system provides information to left-turning drivers about the presence of oncoming vehicles based on proximity or available gap size. The objective of this system is to help reduce driver errors related to detecting traffic and judging gaps. This system is related to Cooperative Intersection Collision Avoidance System-Signalized Left Turn Assist (CICAS-SLTA).

SLTA has the following attributes:

- **Operation**: Identifies the location and speed of approaching vehicles and informs the turning vehicle about their presence by displaying a message on a DII and/or DVI to discourage drivers from making left turns when a gap is inadequate. The SLTA system can also be combined with other systems to provide information about the presence of pedestrians and bicyclists in the left turning driver's path. However, the design information in the current document provides information about SLTA systems for oncoming vehicles only—pedestrian detection/warning is not addressed.

- **Collision Types**: Includes vehicle head-on and sideswipe with on-coming traffic from opposite direction (left turn across path—opposite direction (LTAP-OD)).

- **Target-Site Characteristics**: Includes intersections with a high volume of oncoming traffic and limited sight-distance/visibility for oncoming traffic. The DII may be collocated with existing TCDs to support drivers seeing the display.

Figure 2 provides an example of a CICAS-SLTA at a signalized intersection.

Source: University of California, Berkeley.

Figure 2. Photo. CICAS-SLTA implemented at a signalized intersection.(5)

RLVW

The RLVW system supports drivers in safely traveling through signalized intersections. The system provides a warning to drivers who may potentially enter the intersection in violation of the TCD. The objective of this system is to reduce the frequency of red light violations. This system is related to Cooperative Intersection Collision Avoidance System to Prevent Violations (CICAS-V).

RLVW has the following attributes:

- **Operation**: Identifies vehicles that will enter an intersection in violation of the TCD based on vehicle speed and heading (contained in the vehicle's basic safety message) and the TCD signal phase and timing (SPaT) information. Warnings are provided using DVI and/or DII.

- **Collision Types**: Inclues single and multivehicle collisions occurring within the intersection, including sideswipe (angle), broadside, and rear-end crashes.

- **Target-Site Characteristics**: Includes signalized intersections, especially when sight distances are limited or red light violation crashes are problematic. The DII may include displays collocated with the TCD, signs at the intersection, or in-pavement lighting.

Figure 3 provides an example of a CICAS-V DII.

Figure 3. Photo. Example of a CICAS-V DII. Adapted from previous research implementation.[(6)]

CSW

The CSW application supports drivers in traversing a roadway curve at a safe speed. The system provides an alert/warning to drivers if their current travel speeds exceeds a safe/advisory speed for the curve. The objective of this system is to reduce the occurrence of rollover or run-off-road crashes owing to unsafe speed in curves.

CSW has the following attributes:

- **Operation**: Identifies vehicles approaching a curve traveling at a speed above the safe or advisory speed and provides a warning to the driver via DVI and/or DII and advisory speed information.
- **Collision Types**: Includes single-vehicle rollover and run-off-road at road curvatures.
- **Target-Site Characteristics**: Includes horizontal and complex curves. The DII placement should be in accordance with the *Manual on Uniform Traffic Control Devices* (MUTCD) standards and far enough in advance of the curve to allow drivers to make appropriate speed corrections prior to encountering the curve.[(7)]

Figure 4 provides an example of a dynamic curve warning system (DCWS) on a freeway.

Source: Oregon Department of Transportation.

Figure 4. Photo. DCWS.[8]

SWIW-RS

The SWIW-RS system supports drivers who may encounter adverse weather conditions on their travel route. The SWIS-RS system provides drivers with information about potential weather-related hazards and appropriate precautions, such as reduced travel speed. The objective of the system is to reduce the risk of crash under adverse weather conditions.

SWIW-RS has the following attributes:

- **Operation**: Identifies vehicles traveling on roadways that will be or are affected by near-term, adverse weather conditions and provides an alert message via DVI and/or DII with information on the weather event and necessary actions (i.e., reducing speed).
- **Collision Types**: Includes single and multivehicle crashes owing to weather, including pre-crash control loss caused by high winds, flooding, adverse road surface conditions, and reduced visibility.
- **Target-Site Characteristics**: Includes roadways that encounter frequent adverse weather conditions and localized road-weather hazards (e.g., icy bridge).

Figure 5 provides an example of a two-phase CMS message.

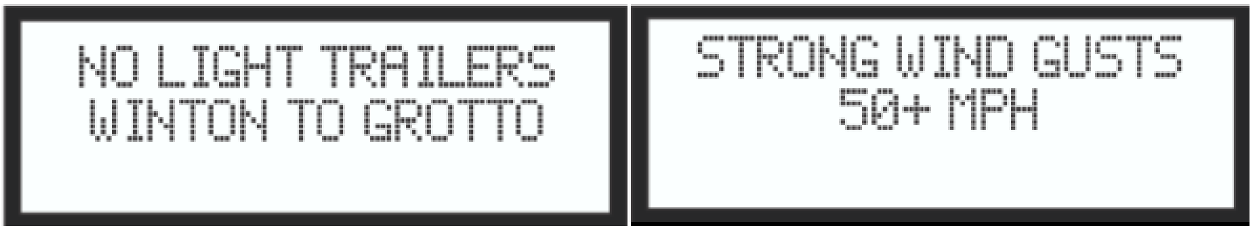


Figure 5. Illustration. Two-phase CMS display showing weather advisory.[9]

CHAPTER 3. DII SAFETY MESSAGE GUIDELINE INFORMATION

This report is part of a broader effort to develop initial design guidance for V2I safety messages provided to drivers using DIIs. This work primarily involved empirical data collection, which used a part-task driving simulator to examine the simultaneous presentation of V2I and V2V messages in left turn across path (LTAP) scenarios.(10) As part of this work, a variety of analytical activities was conducted to develop basic requirements for presenting messages from V2I and V2V sources simultaneously. In particular, many existing research sources that provided information about human factors considerations related to V2I and V2V communication were indentified, in addition to other useful information pertaining to the design and implementation of DIIs. There was sufficient information to support the development of initial annotated outlines that cover basic human factors design topics related to DII implementation.

The remainder of this report provides the initial annotated outlines for DII safety message guidelines. The annotated outlines were developed with the objective of including them in future versions of the *Human Factors Guidelines for Road Systems* (HFG) as part of a single chapter that covers the use of DIIs to communicate V2I information to drivers.(11) The format of the safety messages provided in this report is similar to annotated outlines developed as part of earlier HFG projects; however, they contain a more developed narrative.(11,12,13) Another notable difference is that the topics also do not conform to the two-page format of the HFG, although most of the key sub-sections (e.g., Discussion and/or Design Issues) for individual guidelines are included. Also, the narrative in the Discussion section for each safety message is more detailed and lengthy. This approach was a deliberate attempt to provide a broader starting point for the development of more focused HFG topics in the future. At that time, decisions can be made to eliminate less important information, divide some topics into multiple related topics, or move some information into tutorials.

Note that while every attempt was made to be thorough and comprehensive in the development of the current safety message topics, the scope of the current project prevented application of the same rigor and repeated review cycles that are typically required to develop formal design guidelines.(11,14) Moreover, the information provided in each topic is intended to serve as a starting point for more formal guideline 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 they provide discussion of human factors design considerations that can be applied to the design and implementation of V2I safety systems and corresponding safety messages.

The remainder of the report provides the annotated outlines for the safety message topics. Twelve topics are organized into two sets. The first set is composed of general topics that provide background information and cover issues that apply across multiple V2I applications. The second section includes topics that are focused on specific V2I applications.

TOPIC 1. CONSIDERATIONS FOR ADDING A DII TO A CV RSE

Introduction

This topic 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. Moreover, adding a DII will increase the overall cost of an infrastructure-based safety system, yet under certain circumstances, it may provide no benefit above the in-vehicle systems. The decision to add a DII may arise when an RSE is being installed at a new location, an RSE is being updated, or an engineering study has suggested the addition of an RSE system. Several factors should be considered before adding a DII to an existing or newly installed RSE.

Guideline

A key prerequisite for implementing a DII is the existence of a traffic safety problem at that location that can be addressed by providing drivers with additional information that is not easily obtained from the environment. Table 2 identifies operational and situational factors, along with corresponding advantages and disadvantages, that should be considered in the decision to add a DII at a location with RSE.

Table 2. Operational and situational factors related to DII installation.

Factor	Advantages	Disadvantages	Considerations
Visual Interaction at Location	Allows drivers to keep looking at the roadway environment and is usually easily noticed.	No in-vehicle alerting component (i.e., auditory message). Consequently, DII may be less effective for drawing a distracted driver's attention back to roadway.	The conspicuity of the DII is important. Drivers may look for but not notice a DII.
Driver Workload	Location of the DII can provide context and permit a simplified message with little workload impact.	The DII may add visual clutter that interferes with the driving task and increases workload.	Location complexity and task difficulty may contribute to driver workload.
Targeted Messaging	DII information is available to all drivers that can see the display, so all drivers can benefit from the information.	Non-targeted drivers may receive incorrect or unnecessary information that causes confusion and inappropriate responses.	Research postulates safety concerns about providing non-target drivers with irrelevant information.
Driver Decision-making	A DII can support safe and efficient decisions. Drivers may prefer messages via a DII rather than a DVI.	Generalizability of DII information may make its information unsuitable for some drivers.	Information should be relevant and actionable.
Interaction With Other Systems	Interaction with other connected DII- and DVI-based systems can be managed.	Limited ability to manage interactions with nonconnected systems.	This interaction is primarily a concern with conflicting messages across different systems.
V2X Market Saturation	A DII can be effective at all levels of market saturation.	Until market saturation of CVs is high, the DII will require separate infrastructure-based sensors to provide data on vehicle movements, etc.	This issue relates to targeted messaging and system interactions; it will be less of a concern over time.

Discussion

The decision to include a DII for new or existing RSE depends on factors besides cost (table 2). This guideline presents some high-level information about these factors that should be considered prior to implementation. The information in this guideline is not specific to a particular V2X application.

Before discussing these factors, however, location-specific prerequisites should be defined. As previously stated, a key location-specific prerequisite is the existence of a traffic safety problem that can be addressed by providing drivers with unambiguous and actionable information that is otherwise not easily obtained from the environment. For example, a study may recommend the addition of a CSW for a horizontal or compound curve that has sight distance limitations. A likely operational factor that should be considered is the DII potentially being implemented in a way that provides information in an ambiguous and convoluted manner. For example, if a CSW system can only be implemented at a location ahead of a gore point when it only applies to a single branch, then the message may be ambiguous, and other measures should be examined instead.

The following subsections describe the other factors that should be considered when determining whether it is appropriate to include a DII with RSE.

Visual Demand: The location of a DII must be salient and positioned where drivers will be paying close visual attention (e.g., locations where drivers expect TCDs, such as intersections and roadway edges). A DII that is not implemented in a salient manner may not be as effective in conveying the intended message. This same benefit of providing easily noticed information, however, means that distracted drivers may not see the DII message unless an attention-getting device (e.g., flashing beacons) is employed. V2X communication supports providing these messages inside the vehicle through the DVI, although a majority of vehicles will not have this technology for some years.

Driver Workload: The inherent workload of a given location and situation, as well as the workload imposed by the DII, should be considered. In areas where workload is already increased, such as traveling through a complex interchange with high traffic volumes, the additional workload imposed by the DII may not justify the benefits of providing additional information. In cases when crashes are occurring because the task at hand requires a specifically difficult maneuver, the DII may reduce those demands.[(15)] In contrast, for low workload areas, such as rural intersections with low traffic, the additional workload imposed by a DII is not likely to have a deleterious effect.

In general, a well-implemented DII will likely have a minimal effect on driver workload, especially if the DII supplies the driver with information that is integrated with normal driving activities. For example, a DII placed alongside other TCDs, such as an SLTA located alongside a signal, allows drivers to gain information from the DII while performing normal visual scanning. However, whether it provides useful information or not, a DII can be a source of information drivers feel compelled to pay attention to, especially if it resembles a regulatory sign or device.[(5)] 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 a driver's workload.[(16)]

Targeted Messaging: An important factor when deciding to implement a DII is whether the information will target all road users or only specific road users. Information presented via DII that is intended for specific road users may be unintentionally responded to by nontargeted road users.[(17)] For instance, a driver in a multilane approach to a signalized intersection could receive a DII-based RLVW message intended for a slower driver in the adjacent lane, which could result in the nontargeted driver unnecessarily braking or stopping in the intersection and creating a safety concern. In similar situations, the DVI approach may be the optimal method for providing targeted information.

Decision Making: A DII may support driver decision making if: (1) driver information needs are not being addressed via DVI or through the existing infrastructure, (2) the DII can provide information in a timely manner, and (3) the information provided about the required maneuver is actionable by the driver. Ideally, a DII would provide information to drivers that could eliminate uncertainty about immediate driving conditions, thus facilitating their decision making. However, this process requires drivers to trust the system enough to rely on the information provided. (See topic 6 for more information.)

Interactions With Other Systems: The decision to install a DII should include the potential for interactions with other DII safety systems, as well as non-V2X vehicle-based safety systems. Initial requirements for V2X-based applications rely on the infrastructure RSE for timing (both of the DII and the DVI).(18) While timing is not expected to be a problem in these systems, there may be exceptions regarding vehicles that take into account driver and vehicle performance. While system-level conflicts between DII elements are unlikely, some combinations of systems are more likely to produce conflicts at either the system or message level. (See topics 2 and 3.)

V2X Considerations: Little cost or benefits data exist regarding adding a DII when all vehicles are equipped with V2X DVIs. This issue is a key consideration until CV technology market penetration is at a level in which a majority of drivers may be expected to receive V2X information. Therefore, if some communication with the driver is required, then a DII may be a reasonable approach. If drivers are unlikely to be provided with safety-related information via a DVI, then DII warnings about imminent hazards (e.g., CSW, spot weather information warning (SWIW), or RLVW) are potentially beneficial.

Even if drivers can be reasonably expected to have a DVI available, an additional DII may still be useful. Research suggests that drivers are more inclined to use information provided by a DII.(10,17) If the driver's task is complicated or time constrained, such as making vehicle gap judgments, then a well-placed DII may be easier to integrate into the driving task than a DVI message because it can be located near visual targets that drivers look at while performing the gap judgment task. Also, the placement of the sign can permit messages to be simplified because relevant information is provided by the driving context. For example, an LTAP DII positioned to a left-turn signal may not need to indicate the nature of the hazard (oncoming vehicle) because it is implied by the DII's association with the left turn.

Design Issues

Before implementing a DII, ensure that the available data suggest the intended benefit is likely. Some novel DIIs, especially V2X DIIs, have limited evidence for their safety benefits and cost effectiveness. For example, a field test of a CICAS-SSA demonstrated an increase in likelihood of making a complete stop; however, it demonstrated no improvements in accepted gaps or time-to-collision.(19) It may be beneficial to carefully examine the empirical support for a system before implementing a novel DII.

TOPIC 2. SYSTEM-LEVEL CONFLICTS

Introduction

This guideline covers scenarios in which information presented via both DII and DVI could result in conflicting information being presented to the driver. There are two general forms of conflicts: (1) system-level conflicts involving functionally different applications that attempt to communicate to the driver at the same time, and (2) message-level conflicts involving incongruent information presented by two different sources to the driver. This guideline provides information on system-level conflicts. Message-level conflicts are covered by topic 3. If multiple infrastructure and/or vehicle-based safety systems are active at locations such as intersections, then system conflicts may occur if they are triggered simultaneously. (See table 3.) As the number of available infrastructure-based safety systems increases, especially when multiple systems are attempting to address the same basic hazard, the engineer must be aware of the potential for conflicting messages coming from uncoordinated systems. Presenting uncoordinated messages can burden drivers with unneeded or conflicting information when driver workload is already elevated because of the driving situation.

Guideline

The following design guidance is applicable for the use of DII and DVI:

- In general, DII displays should conform to driver expectations and observations.
- 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 they assess the same hazard.
- DIIs should incorporate available V2X information to reduce false and nuisance alerts.

Table 3. System activation overlap matrix.

DII \ DVI	SSA	SLTA	RLVI	PCI	CSW	RLVW	SWIW	IMA	LTAP	FCW	DNPW	BSW + LCW	OVW
CICAS-SSA	1							1*					
CICAS-SLTA		1	2*	1					1*				
RLVI		2*	1										
PCI	2	2		1		2			2				
CSW					1		2			2**			2***
RLVW						1		1		2**			

Blank cell = Simultaneous system activation is unlikely.
1 = Systems are active for the same hazard.
2 = Systems active for different hazards.
*Possible conflict resulting from warning activation parameters.
**Forward traffic must be present.
***It is remotely possible to have an OVW and a CSW if there is an entrance to a tunnel or overpass just before a curve, as the OVW alert or warning should be given well in advance of the actual hazard to the driver can exit and take an alternate route.
BSW + LCW = Blind spot warning and lane change warning.
DNPW = Do not pass warning.
FCW = Forward collision warning.
IMA = Intersection movement assist.
PCI = Pedestrian crossing intersection.
RLVI = Red light violator indication.

Discussion

While vehicle-based communication applications (i.e., V2X systems such as V2V and V2I) have the potential to greatly reduce the likelihood and severity of certain crashes, the market penetration necessary for reliable V2X communication is still many years away. Even after this level of V2X market penetration is reached, many vehicles on the road will still not have this capability. Infrastructure-based solutions (i.e., a DII) can offer safety benefits in the absence of V2X communication. However, a DII in the presence of other V2X communication raises the potential for information conflicts, incongruences, and similar concerns when multiple systems that are functionally similar are present and attempting to provide information to the 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 mistrust of the system. The information in this guideline is meant to provide engineers with guidance regarding the types of incongruencies that may occur across systems and some general approaches for reducing the potential negative impacts of such incongruencies.

Congruence With Driver Expectations: At the highest level, system implementation should be congruent with driver expectations and observations. An important prerequisite for managing information from multiple sources is for each system to be itself compatible with drivers' expectations of the situation-based cues provided by the situation and the maneuver. Drivers rely on information from the infrastructure to provide guidance and decision-making support.[20] The DIIs and DVIs should cue the driver to a sequence of behaviors that support safe driving. Information that conflicts with what drivers expect or observe may lead to confusion and mistrust of the warnings.[21] (See topic 6.) The following subsections discuss the types of system-level conflicts that can occur and how their occurrence may be mitigated.

Hazard Conflicts: Conflicts can arise when a DII and a DVI detect the same hazard using different information or activate simultaneously for different hazards based on the same scenario. These conflicts are not concerns for most combinations of DII and DVI elements. Table 3 shows conflicts that may arise from the use of uncoordinated systems (e.g., the hazard identification and timing algorithms between systems are not coordinated). Even with this uncoordinated environment, however, the majority of system overlaps do not present a potential conflict. Further, many CV safety applications are DVI only or are highly unlikely to be active in the roadway environments where the DII elements explored in this report are located (e.g., do not pass warning or blind spot warning and lane change warning). The potential for system-level conflicts may be determined through comparison of current or planned CV safety applications. This process may be done by comparing which DII elements are present (shown in the rows of table 3) against which DVI components (shown in the columns of table 3) may be active at the same time.

When conflicts occur, drivers may receive multiple messages or may not understand the intent of the warning. An example of this issue (see table 3) is red light violator indication (RLVI) and CICAS-SLTA. The CICAS-SLTA can inform a driver waiting to turn left that no oncoming vehicle is present, implying that the driver can enter the intersection to turn; however, a red light runner approaching from the right would trigger an RLVI intended to warn the driver to not enter the intersection. In this scenario, the CICAS-SLTA system indicates that the roadway is clear, while the RLVI system warns of unsafe conditions. This type of incongruence could potentially cause driver confusion and have a negative effect on the driver’s use of the system. Another concern is that with multiple hazards, it may be necessary to arbitrate message presentation so drivers only receive the most safety-critical message. This discussion is beyond the scope of this report but is covered in detail in Campbell et al.[22] These scenario types require special consideration because any number of different DVIs may be present or become available during the lifespan of a particular DII element. However, understanding which CV safety applications may present conflicts or coordinating between CV safety applications that are present can largely eliminate this potential problem.

Another consideration is to avoid system-level conflicts by coordinating hazard-detection algorithms and message timing across systems that assess the same hazard. Incongruent information presented across two different systems represents a conflict at the algorithm or implementation level. The presentation of information should always be consistent between DVI and DII to avoid driver confusion. Recent requirement specifications provide for the DII to act as the coordinating timing source, as well as the source of safety messages to DVIs.[18] One way to reduce system-level conflicts is to use only one application that calculates hazards across systems.

When feedback from a V2X-based system is available, information provided to the driver via DII should reflect that information. The use of V2X information should reduce the potential for providing incongruent information and can serve as a way to increase the accuracy of a DII message. Accordingly, information provided to the driver via the DII should reflect available vehicle safety data recorded by the in-vehicle system. In scenarios involving a conflicting principal other vehicle (POV), DII information should also incorporate relevant data available from the POV, especially when there is a high probability that the driver may execute a maneuver that the DII is warning against because it is safe for that individual driver to do so based on the driver's capabilities. In this case, if the V2X application determines that the conflict will be completely avoided through the current behavior of the vehicle and driver, then the DII and DVI warning presentation can be suppressed. However, if the alert is presented when the driver sees no threat or hazard, then it can be viewed as a false or nuisance alert, which can have a negative impact on the driver's trust in DIIs.

Design Issues

There is a tradeoff between using a DVI or a DII for alerting a driver to a hazard. The DVI has an advantage for salience in that it is able to present a message in a multimodal manner using visual and auditory elements, which can make it generally easier for the driver to detect. In contrast, the DII may be viewed as more reliable by drivers and is able to benefit all drivers regardless of the presence of CV technology within the vehicle.(23) These issues, and those discussed in topic 3, should be considered when implementing a new safety application.

It is unknown to what extent drivers will rely on the DII compared with the DVI when either analogous or incongruent messages are provided. Competing messages from a DVI can be more salient and attention-getting if they are accompanied by auditory signals. In addition, driver preference for DIIs and DVIs can vary on a number of factors, such as driver characteristics (e.g., age and experience with the location), their perception of the scenario, and the presence of a DVI.(23) Therefore, the DII should provide direct and authoritative messages in support of drivers' visual sampling of the environment for relevant information.

TOPIC 3. MESSAGE-LEVEL INCONGRUENCE BETWEEN DII AND DVI SYSTEMS

Introduction

This guideline addresses conflicts between safety applications that occur at the level of individual messages, primarily because of incompatible or incongruent message characteristics. When messages are incongruent, drivers may have to visually attend to multiple locations in the environment to help resolve the conflict. This process can lead to a delayed response to the warning and may reduce the warning's overall effectiveness. The engineer implementing a DII-based system should be aware of the different types of incongruence that can occur and should work to minimize their impact on drivers while remembering that clear, actionable messages lead to the most rapid and accurate driver responses.

Guidelines

The following design information describes strategies for avoiding incongruent messages:

- **Message Timing**: Warning messages pertaining to the same hazard should be presented at the same time. Timing support the coordinated presentation of DVI and DII messages when V2X information is available.

- **Message Content**: The information and wording in separate messages should be consistent across systems with respect to the basic hazard being communicated.

- **Message Format**: Standard message formats should be used, such as those specified in the MUTCD or generally recognizable icons and wording.

- **Message Frame**: Multiple DIIs related to a single hazard should provide the same level of warning or advice. Ensure that messages broadcast via V2X communications use the same message framing as the DII.

- **Message Stages**: Multiple DIIs related to a single hazard should be coordinated regarding the number of message stages implemented and how and when messages move through different stages. Messages broadcast via V2X communications should include message staging information.

Table 4 provides definitions of message characteristics related to congruence.

Table 4. Definitions of message characteristics related to congruence.

Message Characteristic	Definition
Message Timing	The time frame in which the message is provided to the driver relative to the identified hazard.
Message Content	The information within the message identifying the referent hazard and/or any driver actions that should be considered.
Message Format	The manner in which information is presented to the driver. For DIIs, this manner is typically visual and can include text, icons, lights, and other typical DII presentation means.
Message Frame	The instruction level of the message provided to the driver. Possible instruction levels include "permissive," "advise/inform," "alert/warn," and "prohibit."
Message Stages	Stages represent different hazard severity levels, such as "inform/advisory" and "warn" messages.

Discussion

An increasing number of safety applications that use the DII are available or under development, and it is likely that future systems will be able to communicate via V2X to take advantage of the DVI within the vehicle. However, multiple DII- or DVI-based safety systems simultaneously presenting different messages can result in incongruent information reaching the driver. This conflict can produce a range of undesirable outcomes, such as increased reaction times to alerts, lower trust in the system, and drivers ignoring alerts.[21,24] (See topic 6.) When an infrastructure-based system is implemented, it is important to consider how the DII message will be presented, what other messages might be presented in the roadway environment, and what other messages may be presented within the vehicle. Being cognizant of these potential information sources can help engineers minimize incongruent messages. This guideline covers different ways that messages presented via DII may be incongruent.

Message incongruence can result when multiple conflicts are derived from any of the following five message characteristics: timing, content, format, framing, and staging. It is also possible that multiple hazards may be portrayed within a single DII message (e.g., integrated PCI and SLTA). While engineers have the greatest influence on reducing incongruence when multiple DIIs are present, the design of connected DIIs can help reduce the incongruence between a DII and a DVI as well.

Message Timing: The timing of multiple related DII messages should be coordinated. If multiple warnings about the same hazard are presented in an uncoordinated manner, then the driver may not understand that all of the messages are referring to a single hazard. For example, if one DII message is delayed relative to other messages for the same hazard, then drivers may believe that the warning encountered later pertains to a different hazard. Similarly, nontargeted drivers who observe a DII message targeting another driver may unnecessarily respond if the message appears to be relevant to their situation.(25) Likewise, with more advanced vehicles or CVs, the driver may receive messages pertaining to the same hazard via the DVI. Thus, the infrastructure should support the coordinated presentation of DVI and DII messages when V2X information is available. Resources are available that explore the prioritization of multiple safety messages and the integration of multiple V2X messages.(26,27)

Message Content: Applicable standards, such as National ITS Architecture market packages, should be used when the system operational characteristics are compatible. For new messages, consistent message content should be used across multiple systems when referring to the same hazard, which can serve as an unambiguous warning. Message consistency can be achieved by ensuring that DII elements agree in their identification of a hazard and that they all signify the same hazard. Coordinated messages between DII and DVI are also important because it has been shown that coordinated DII-DVI messaging is more effective than either DVI or DII alone.(28) If different DII elements are not consistent, then drivers may not clearly understand the intended message or may have delayed reactions as a result of having to interpret the intended meaning of the sign.(29) For example, the integrated PCI/SLTA example alluded to earlier should be designed so the driver perceives the information as flowing from one system and not multiple systems. The perception of multiple systems can result in a scenario in which drivers look to two or more different locations and must make a comparison between the information received from each before finalizing a reaction.

Message Format: Standard message formats as identified in the MUTCD (or generally recognized formats) should be used to avoid message incongruence when multiple interfaces are present. In particular, different DII elements may present information using different formats, such as a CMS using text and a blank-out sign using an icon. It is therefore important that the representation used across different DII elements is consistent with driver expectations because drivers may not understand nonstandard symbols or messages.(10,30) If multiple DIIs of the same type and configuration are referring to the same hazard, then they should use the same message format. When V2X communication is available, this information can be provided to the DVI as well to provide a greater level of standardization.

Message Frame: The following frame incongruencies can result when multiple DIIs related to a single hazard present conflicting types of information:

- Permissive (stating that the action is allowable).
- Advise/inform (providing neutral information about a traffic condition, such as time to arrival of cross traffic, and leaving the hazard judgment up to the driver).
- Alert/warn (providing information about an active hazard).
- Prohibit (stating that an action is not allowed).

These messages used on different displays that pertain to the same hazard should be carefully crafted to ensure that they use the same message frame. Failure to do so can lead the driver to misinterpret the intended message. For instance, the presentation of an advisory message about pedestrians along with an activated "pedestrian present" warning from a PCI system could lead the driver to see the PCI as another advisory sign and to consequently ignore the message. This form of incongruence can also occur between a DII and DVI. When available, broadcast messages via V2X communications at the same level as those provided by the DII.

Message Stages: The number of stages across DII elements that refer to the same hazard should be the same. Multiple-stage messages are those that move through different frame levels (e.g., advise/inform, alert/warn, prohibit). When possible, multiple DIIs related to a single hazard should have the same number of message stages, and changes in stages should be coordinated in time. Otherwise, drivers may not be able to accurately interpret messages received from multiple DIIs that present information using different stages, because the status of the hazard and/or corresponding required driver actions would be unclear.

TOPIC 4. MESSAGE CONTENT: MESSAGE ELEMENTS

Introduction

This guideline discusses the message elements that could be included as part of a message provided by a V2I safety system. Message elements are components of the message that each provide a specific piece of information that describes the situation to drivers. Regardless of the message format (e.g., text and/or symbols), the information elements in the message are important to consider because the driver's interpretation of the message will depend on these elements. The basic message elements discussed in this topic were adapted from existing guidance for messages displayed on CMSs.(31)

Guideline

The following design guideance is applicable to the development of message content.

- The message provided to drivers should include some combination of the message elements described in table 5. The required elements vary across systems and depend on the situation or context.

- Unnecessary elements may be excluded from the message.
- In general, the message elements to include are those required to accurately convey the pertinent aspects of the situation (especially when a hazard is not visible or if it affects only a subset of the drivers) and to motivate the desired driver behavior.

Table 5. Message elements for consideration.

Message Element	Definition	When to Include
Problem	Provides information about what the driver will encounter.	When the hazard is neither visible nor implied by the situational context.
Location	Describes the location of or distance to the situation.	When the hazard is not ahead on the same route on which the driver is traveling, or when the message could be misinterpreted to apply to a relevant hazard from another direction.
Action	Provides a recommendation to the driver in response to the problem and location information.	In all system messages.
Audience for Action	Includes the subset of roadway users who are the intended recipients of the message.	When the hazard is not on the current route or when the hazard only affects a subset of drivers and the audience cannot be implied by DII placement.
Good Reason for Following the Action	Provides additional justification intended to give a driver confidence that following the message will result in safety or time benefits.	When it is necessary to motivate drivers to take an action (e.g., they should follow it for a reason other than fulfilling a normal driving objective such as avoiding a collision).

Using these message elements as a structure, the information elements were enumerated for each of five different V2X safety systems. Table 6 includes a row for each of the warning systems and a column for each message element. In each cell is the specific form that the message element would take for that warning system. Note that the form of the message element is not meant to suggest specific wording but rather to describe the nature of the content that should be conveyed by the message. The font style denotes whether the element needs to be included in the message for that warning system. Italicized font elements are otherwise apparent to the driver and therefore do not need to be included. Font elements in roman may or may not be necessary to the driver. Bold font elements definitely should be conveyed to the driver in some way.

Table 6. Enumerated combinations of message elements by warning system.

Warning System	Problem	Location	Action	Audience	Reason
SSA	*Crossing or merging vehicle(s)*	Left, then right	**Yield**	*Left-turners, right-turners, straight traffic*	*Avoid crash with vehicle*
SLTA	Oncoming vehicle	Forward	**Yield**	**Left-turners**	*Avoid crash with vehicle*
RLVW	**Red light**	Ahead	**Stop**	*Approaching traffic*	*Avoid crash with vehicle*
CSW	Sharp curve, blind curve, compound curve, unexpected curve	*Ahead*	**Slow down**	*Approaching traffic*	Avoid losing vehicle control
Road Weather	**Unexpected road weather**	*Ahead* **(possibly on another route)**	**Varying**	*Approaching traffic* **(or other route traffic)**	Safety/time savings
Rail-Grade Highway Crossing	**Oncoming train***	Left or right	**Yield**	*Straight traffic*	*Avoid crash with train*

Note: Bold indicates esstential, roman indicates possibly necessary, and italic indicates not necessary.
*May be situationally implied.

Discussion

The following discussion provides information about considerations for including each of the message elements. By looking at the columns in table 6, it is possible to determine trends in situational characteristics that make each message element necessary (i.e., by looking across the warning systems and using information about situations when those systems would activate). These characteristics are discussed in the following subsections.

Problem: The problem element is important to state either when the hazard is not visible or when it is not implied by the situational context. For road weather (e.g., icy roads), it is likely necessary to state the exact problem because drivers often cannot see it because it is miles ahead or imperceptible, such as black ice. In addition, in some hazard scenarios, oncoming vehicles or upcoming geometry may not be visible to the driver, so the message may require a direct statement of the hazard to make sense to the driver. It is also possible that the placement and content of the DII might help imply the presence of the hazard (e.g., placing an SLTA DII near the oncoming traffic stream) such that a direct statement of the problem may not be necessary. For a situation in which multiple hazards are present (e.g., oncoming vehicles and crossing pedestrians in SLTA), however, it may not be clear which hazards are accounted for by the system and which are not. This uncertainty may affect driver reaction times once the display returns to the inactive state if drivers are unsure whether they need to consider other hazards in the environment. For example, if an SLTA system is blank because an oncoming vehicle is not approaching, will drivers understand whether they still need to look for pedestrian hazards?

Location: The location element should be included when the hazard is not ahead on the same route that the driver is traveling or when the message could be misinterpreted to apply to a relevant hazard from another direction. Dudek states that generally, if drivers observe a changeable message, then they will assume that the hazard is ahead on the same roadway unless they are told otherwise.[31] Therefore, the location ahead does not need to be stated, but conversely, the location is important to include if the hazard is on a different roadway. The location element should also be included when the warning message could be interpreted to apply to a hazard from another direction (e.g., cross traffic for SSA). The location of the hazard, however, might be implied by the physical location of the DII (e.g., near the oncoming hazard).

Action: The action element should always be included. The main objective of messaging is to change or influence driver behavior. Therefore, the desired behavior needs to be conveyed to the driver.

Audience for Action: The audience for action should be included when the hazard does not affect the current route or when the hazard only affects a subset of drivers and the audience cannot be implied by DII placement. For example, in an SLTA scenario, it may be possible to imply that the audience for the message is left-turning drivers, either by the message content or the DII placement. However, if the DII is placed overhead and the message content is more ambiguous (e.g., yield), then there may be confusion regarding which drivers need to follow the message. Similarly, if the message is for drivers who will be transferring to another route (e.g., road weather on a different route), then it is important to specify which drivers are affected.

Good Reason to Follow the Action: This element should be included when it is necessary to motivate drivers to take an action (e.g., they should follow it for a reason other than fulfilling a normal driving objective such as avoiding a collision). This requirement is particularly important when drivers cannot perceive the hazard (e.g., hidden curve) or they underestimate the severity of the hazard and, therefore, need a reason to change their behavior.

Design Issues

This information applies to symbolic messages, text messages, and combination symbol-text messages. Symbolic messages may not directly state the elements but instead convey them visually. In addition, some of the message elements may be implied by other display aspects, such as placement of the display within the context of the roadway geometry.

TOPIC 5. MESSAGE CONTENT: USE OF SYMBOLS AND TEXT

Introduction

This guideline discusses considerations for designing DII and DVI sign messages using symbols, text, or a combination of both. These messages most likely use a combination of existing TCD message elements. Some V2X-based messages will likely differ from existing messages in important ways (i.e., the inclusion of temporal information), which may require the modification of existing messages or the design of new ones. Given the type of safety applications involved, these messages are typically intended to be viewed in time-limited situations, which requires them to be simple and quickly understood. There is substantial existing research and guidance on message elements. The current guideline only provides a summary of key design considerations and identifies key references that should be used to obtain more comprehensive information regarding these considerations.

Guideline

Table 7 provides general considerations for implementing symbols and text elements in signs to produce messages that are clear and easy for drivers to understand. Key information sources are provided next to each consideration.

Table 7. General considerations for implementing symbols and text elements in signs.

General Sign Design Guidance	Key Reference(s)
• Maintain spatial, conceptual, and representational compatibility among the sign text, symbols, and the message they represent. These elements are all related to how the sign is perceived by the driver. See Discussion for a more detailed description.	Shinar et al.[30] Ben-Bassat and Shinar[32] Ng and Chang[29]
• Use familiar sign elements and messages.	MUTCD[7]
• Use standard colors, shapes, symbols, and text.	Campbell et al. [33] Ng and Chan[29] MUTCD[7] HFG[11]
• Ensure that all message elements required to understand a message are included in the sign. Avoid requiring drivers to infer additional meaning to the message.	Shinar et al.[30]
Symbol Design Guidance	
• Use symbols on roadway signs to communicate information to drivers in the following situations: o To provide safety and warning information. o To indicate prohibited actions. o In visually degraded conditions. o In areas with higher posted speeds. • Use a clear and simple font. • For simple messages, limit text to no more than two to three words. • Use precise symbol descriptions. • Use nontechnical, common vocabulary.	HFG[11] Icon Guidelines[33]
• Minimize use of abbreviations.	MUTCD[7] Shinar and Vogelzang[34]

• Use text on roadway signs to communicate information to drivers in the following instances: o For highly complex messages. o When indicating a hazard in or near the roadway to drivers. o For destination information. o In areas requiring unexpected or unique driver actions (e.g., frequent lane changes).	HFG[11]
Symbol and Text Design Guidance	**Key Reference(s)**
• If a symbol could potentially be unfamiliar to a number of drivers, the addition of text on the sign can help them more easily understand the meaning of the sign.	Shinar and Vogelzang[35]
• When the sign communicates a particularly important message or warns of a particularly hazardous situation, text can be used to give drivers another method to receive the information in addition to the use of a symbol.	HFG[11]
• When symbols are abstract and have no conventional or broadly understood meaning, text can be used to supplement the symbol.	Shinar and Vogelzang[35]

Discussion

DII and DVI displays for safety applications are unique in that drivers will likely encounter them infrequently during the early stages of general adoption—particularly DIIs. Because of these low levels of exposure, drivers may require more support to understand the intent of a message. Thus, it is important that messages be clear and easy for drivers to understand, especially when drivers first encounter them.

General Sign Guidance: In general, the design of roadway signs should closely follow the three ergonomic design principles of sign-content compatibility, familiarity, and standardization. Sign-content compatibility is a combination of the following three principles:

- *Spatial compatibility* is the physical arrangement of objects in the environment relative to the position of information and directions (i.e., the direction in which the road is turning is presented by an arrow bending the same direction on the sign).

- *Conceptual compatibility* is the extent to which symbols and/or text match associations that drivers have with a concept. An example of this concept is using an airplane symbol (MUTCD sign I-5) on a sign to indicate that an airport is nearby.

- *Representational compatibility* refers to the similarity between the content (the symbol and/or text on the sign) and the object or situation it is intended to communicate to the driver. An example of good representation on a sign is using a symbol of a person using a shovel (MUTCD sign W21-1) to indicate road construction or road work nearby.

In a study that asked participants to rate road signs on how closely their design followed these ergonomic design principles, the signs that most closely followed ergonomic design principles were better understood by both local and nonlocal drivers.[32] While one cannot design for familiarity as one can for compatibility or standardization, designing new signs according to the compatibility and standardized design principles can influence drivers to better understand these new signs. Using familiar sign elements can also influence drivers' understanding of signs.

Symbol Guidance: Symbols are often used on road signs because they can communicate information to a wider range of drivers because they are mostly language-neutral. Under normal driving conditions, drivers can identify signs using symbols from greater distances compared with text signs.[36] Common symbols have also been shown to have generally shorter comprehension times compared with text comprehension times.[37] In a more recent study by Shinar and Vogelzang, however, the use of symbols on signs was shown to be advantageous only when the symbol was familiar to drivers.[35]

Text Guidance: Text messages do not have to be interpreted to the same extent as symbols, which is an advantage for messages that are challenging to communicate with symbols. The guidance for text information addresses text legibility, which, when implemented, helps drivers read and comprehend sign information. Another potential concern is that text is language-specific, meaning that the use of text on a sign may be less effective than symbols for communicating with drivers who do not speak the local language. Text should be used for highly complex messages, destination names, and other similar types of information. The references in the table provide more detailed information about the use of text on signs.

Symbol and Text Guidance: If there is uncertainty about whether to use symbols or text in a sign, then one option is to use both. In a recent study, Shinar and Vogelzang compared three sign conditions (text only, symbol only, and symbol and text) for level of comprehension and comprehension time.[35] Results indicated that level of comprehension was highest for signs that used both symbol and text, followed by text-only signs and was worst for signs that used symbols only. For symbols that may be unfamiliar to some drivers, the addition of text to the sign gives drivers the opportunity to pair the meaning of the sign with the symbol used to portray it.

One issue that may be problematic for DVI/DII sign messages is the use of symbols that do not physically or conceptually resemble an object or scenario or have a well-learned association with the context. In this case, the association of these symbols with their meaning must be learned over time. However, if drivers are infrequently exposed to these symbols, at least initially, then learning the symbol meaning will be more difficult. Consequently, symbols should only be used if they can provide a clear representation of the situation or required action. If this clarity cannot be achieved, then it may be better to use a text sign[30].

A logical solution would be to use symbols with which drivers are already familiar. If the symbols are used in a way that differs from their typical meaning, however, then drivers may have difficulty interpreting the intended meaning. For example, one simulator study examining an SLTA system compared driver understanding during first exposure of signs using two familiar symbols to communicate the presence of an oncoming vehicle (i.e., that it was unsafe to turn).[10] When a left turn prohibited symbol was used, many drivers thought that the sign indicated a permanent left-turn restriction at this intersection, which is consistent with how this symbol is typically used. In contrast, almost all drivers correctly interpreted a different sign based on a yield symbol. This fact suggests that designers should be cautious when using symbols to communicate messages that differ from the symbol's typical meaning.

Design Issues

Given that new DVI/DII systems may require new types or designs of signs, MUTCD signs should always be used when possible. Any new sign designs should not contradict or be inconsistent with the guidance provided in the MUTCD.

TOPIC 6. SUPPORTING DRIVER TRUST OF SAFETY SYSTEMS

Introduction

This guideline covers general factors related to providing drivers with information from safety systems via DII and DVI in a way that supports 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.(38) While little research specifically examines trust in roadway safety system information, the guidance presented here is based on general best practices related to supporting trust in systems and research in trust of automated systems.

Guideline

Trust can be affected directly and indirectly by multiple factors. Design considerations for key factors are listed in table 8.

Table 8. Design considerations that affect driver trust.

Factor	Design Considerations for Driver Trust Factors
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 that are 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.
Message Framing	Use a prohibitive message frame for DII messages. Permissive, advise/inform, and warning 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 incongruent presentation of warnings between the DII and the DVI.
Familiarity	Ensure that the system functions in a consistent manner when compared with other systems with which drivers would be familiar within a region. Familiar systems that are consistent are likely to produce faster driver responses.

Discussion

Trust can be defined as an "attitude that an agent (i.e., a DII or DVI) will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability."(39) In the case of safety messages, DIIs or DVIs provide information to reduce uncertainty or vulnerability regarding driving maneuvers. Driver acceptance of these messages is related to their trust of the system. Trust has a direct relationship with the likelihood of using a system, and research from a variety of fields has demonstrated that operators who distrust a system will underutilize that system.(38,40) Moreover, Lee and Moray suggest that trust is determined by both the performance of the system and the operators' confidence in their own decisions.(41)

Research on driver trust with regard to V2X and DII systems is in a nascent stage. Because of the relative lack of research examining this topic, much of what is known about supporting driver trust in roadway safety systems is drawn from studies examining trust in automation and vehicle-based active safety systems. While these two topics overlap in many areas, further examination of how connected safety systems can best use DII- and DVI-based presentations to support driver trust is clearly needed. This guideline provides information on the determinants of trust and how a system can ensure that driver trust is supported.

Accuracy and Reliability: Information accuracy and reliability are the most influential determining factors in drivers' trust of information coming from a system.(41) Accuracy for a system is its performance at identifying a safety issue at a given point in time. Research examining the presentation of traffic information suggests that 70-percent accuracy is a minimally acceptable value, below which drivers are unlikely to accept or use information.[42] However, it is recommended that engineers target higher levels of system accuracy in their designs.

Drivers may also question the accuracy of a system when it presents a safety message in the absence of a detectable threat. An evaluation of a wildlife crossing warning system found that drivers did not slow for a warning presented without a visible animal, while speeds were reduced when a decoy animal was located along with the warning sign.[43] Similarly, an examination of flooded road warning signs found that the visible threat posed by water on the road surface was a factor in driver compliance with a warning sign.[44]

The timing accuracy of the safety message may affect driver trust. The timing of a safety message represents a tradeoff between presenting a message early enough to allow a comfortable driver response and avoiding false alarms from alerting to a scenario that will not develop into a hazard.[14] Providing false alarms can have an extremely detrimental effect on driver trust in a system.[45] In addition, drivers may ignore messages from a system when a maneuver appears to be safe.[10] Therefore, the timing of the system should incorporate considerations for minimizing false alarms.

Reliability is the ability for a system to maintain a level of accuracy over time. Reliable systems increase trust, whereas unreliable systems decrease trust and can lead to underutilization or ignoring the system.[38,46] Research on automated systems suggests that reliability can have an effect on both driver satisfaction as well as drivers' willingness to use a system.[47] In addition, preconceptions of system reliability can have an effect on how individuals use a system.[48]

Understandability: *Understandability* refers to the ability of the DII or DVI to provide legible and easily understood information to the driver. When a system is easily understood, drivers' trust is supported. This includes aspects such as ensuring that messages provided by DIIs using CMSs are concise, convey the hazard clearly, and provide the driver with enough information to respond.[34] For other types of DIIs, providing active warning elements (e.g., a flashing beacon to indicate an ongoing hazard) can assist drivers in understanding the presence of a threat.[44] An examination of an SSA system for rural highways examined both countdown and icon displays compared with a hazard sign.[49] DIIs with active elements (i.e., the countdown and icon displays) were rated as providing more trustworthy information by participants.

Message Framing: *Message framing* refers to the instruction level of the message. (See topic 3.) A message may have one of multiple types of message frames, including the following:

- **Permissive**: Stating that the action is allowable.
- **Advise/Inform**: Providing neutral information about a traffic condition, such as time to arrival of cross traffic, and leaving the hazard judgment up to the driver.
- **Alert/Warn**: Providing information about an active hazard.
- **Prohibit**: Stating that an action is not allowed.

There is a lack of research examining how message frame relates to trust; however, it is reasonable to assume that driver trust in a DII or DVI safety message may depend on a message's framing. For example, a permissive DII stating a left turn is safe may be viewed as less trustworthy than a prohibitive DII stating a left turn is unsafe because it leaves drivers in a more vulnerable position.

Message Coordination: Coordination between DII and DVI can support driver trust. Research suggests that drivers prefer information presented via DII and view it as more authoritative than DVI messages.(10,23) It is unclear whether this preference for DII information will be a stable effect over time, especially as the prevalence of CV applications in vehicles increases. As safety messages provided via DVI become more common, drivers may begin to view them as equally authoritative as DII messages. Therefore, coordination between DII and DVI is an important factor to consider in establishing drivers' trust in a safety system. (See topic 2.)

Familiarity: Familiarity with a DII may have an effect on the driver's trust of the system; drivers who are familiar with a system message may respond faster.(34) The faster responses result from drivers being able to make assumptions about what message the system is trying to convey, based on their understanding of other familiar systems or messages (rather than interpreting and applying the information). Consequently, a DII or DVI that has familiar elements should function consistently with the key operational aspects of the original systems. Otherwise, those driver assumptions will be incorrect, leading to reduced trust. A drawback of familiarity is that a message that drivers view repeatedly may be attended to less frequently by the driver.(46) Ensuring that safety-critical messages appear in a salient manner can help reduce this potential issue.

TOPIC 7. FACTORS THAT AFFECT GAP CHOICE

Introduction

This topic covers human factors considerations for the use of driver gap choice for a safety system activation algorithm (e.g., intersection decision support systems). Gap choice is a measure that represents gap sizes within a traffic stream that most drivers will reject or accept, depending on the measurement approach. It reflects a strategy for selecting a warning system activation parameter that is based on driver behavior at specific locations. The use of gap choice as an activation parameter may serve to enhance driver acceptance of a system if the message activation is tuned appropriately using pertinent factors that affect gap choice. There are many options for assessing driver gap acceptance. The purpose of this guideline is to illustrate the importance of considering the factors that affect gap acceptance. The content applies to conflicts at both two-way stop controlled intersections and left turn situations at four-way intersection (e.g., LTAP, straight crossing path, and left/right turn in path crash types).

Guidelines

The following design guideance is applicable to when considering factors that affect gap choice:

- Consider situational factors that may apply at a location when developing timing algorithms. (See table 9.)

- Assess lag and gap independently because lag is qualitatively different from gap. There is considerably higher variation in lag compared with gap sizes.

Table 9 provides a list of situational/site factors that can affect gap choice.

Table 9. Situational/site factors that can affect gap choice.

Situational/ Site Factors	Finding	Data Quality	Design Relevance
Distribution of Gap Sizes	Gaps in traffic that are large enough to allow a driver to pass through must be present. The distribution of gaps may be skewed toward smaller durations in areas where traffic is denser.	High	High
Gap and Lag	Drivers show a higher degree of variation (three times greater variance) in lag acceptance compared with gap acceptance when turning left; drivers have a tendency to reject lag and then accept the first gap.	High	Moderate
Maneuver	Average gap acceptance can be the same for right turns and left turns (from a median) but tends to be longer for through maneuvers (e.g., 6.7 s for turn and 7.9 s for through maneuvers; gap differences per maneuver may vary depending on the geographic location of the intersection.**	High	High
Number of Lanes to Cross	The accepted gap becomes larger as the number of lanes of opposing traffic increases.***	High	High
Number Of Rejected Gaps	The quantity of rejected gaps can reduce critical gap size (e.g., from 6.24 to 2.25 s after rejecting four+ gaps.**	Moderate	High
Point of Departure	Gap behavior tends to be more aggressive during median departures compared with stop-sign departures; left turns from a major road have shorter gaps than left turns from a minor road.**	High	High
Queue Presence	The presence of a queue behind a driver can reduce accepted gap size to 4.5 s, from 6 s.**	Moderate	Moderate
Rain Intensity	Rain intensity leads to longer gap acceptance, from 6.5 to 13 s as rainfall increased from 0 to 0.39 inches/h.*	High	High
Sight Blockage Caused by Waiting Traffic	Sight blockage from a left turning vehicle during an LTAP maneuver can double the amount of time drivers use to decide whether they want to turn (e.g., from 1.7 to 3.1 s).*	High	High
Time of Day	Drivers' acceptable gap may be larger in the morning compared with midday and evenings; peak periods affect gap acceptance relative to the constancy and availability of gaps.**	Moderate	Moderate
Wait Time	Increasing wait time can lead to smaller gap acceptance (e.g., 8 to 2 s gap after 100 s of waiting at a stop bar to turn left; longer wait times lead drivers to accept gaps that they previously thought were too short.***	High	High

*Data collected at a signalized intersection.
**Data collected at a stop or yield controlled intersection.
***Data collected at a stop/yield controlled intersection and a signalized intersection.

Discussion

Gap choice pertains to drivers deciding to accept or reject lags and gaps in traffic. The difference between the decision to reject or accept is straightforward, but the differences between gap and lag require explanation. Specifically, *lag* is the time interval between the arrival of a vehicle at the TCD on the minor road of an intersection (e.g., stop or yield sign) and the arrival of the first vehicle on the major road. *Gap* is the time interval between the passage of one vehicle and the arrival of the next, yet there is still uncertainty about the definition of gap because some practitioners include headway.(59,60) In addition, lag can be thought of as the remainder of a gap when a driver on a minor road arrives at the intersection. Lag and gap are measured to characterize how drivers coordinate their movements relative to their proximity to other drivers on the road. The size of a gap that drivers find acceptable to enter is probabilistic, and drivers change what they find acceptable depending on a variety of factors. (See table 9 and table 10.)

Table 10. Driver/vehicle characteristics that can affect gap acceptance decisions.

Driver/Vehicle Characteristics	Finding	Data Quality	Design Relevance
Driver Gender	There is some evidence of gender differences; there is also evidence that gender is not a significant factor.*	Low	Low
Driver Age	Older drivers tend to reject more usable gaps and accept longer wait times than younger drivers; teens display more aggressive gap acceptance than adults.*	High	Moderate
Vehicle Type	Motorized two-wheelers' gap acceptance is shorter than for passenger cars; drivers of older cars accept larger gaps than drivers of newer cars.*	High	High

*Data collected at a stop or yield controlled intersection.

Factors That Affect Gap Size Acceptance: The process by which drivers decide to accept any one gap is complex and has multiple considerations—some are observable (e.g., wait time), while others are not (e.g., internalized perception of risk that influences drivers' assessment of the value of accepting a gap).(61) The size of gaps and lags that are accepted by drivers vary as a result of many factors. While several published predictive factors at a population level (i.e., macroscopic gap selection factors) and at an individual level (i.e., microscopic gap selection factors) are available, it is prudent to assume that an individual's gap acceptance behavior will show widely varying differences. V2X, however, may provide an opportunity in the future to incorporate historical driver behavior (e.g., aggressive versus conservative gap acceptance) into system activation parameters. Another consideration is that some factors, such as the presence of queues and number of rejected gaps, are well established but may not always manifest in the same manner at every location.(56,61,62) For example, the data from Gorjestani et al. showed that aggregate measures reflecting 80th percentile rejected gap were different depending on the point of departure (i.e., from TCD versus from median) and geographic location.(52)

The distribution of gap sizes affects gap acceptance, and these distributions change throughout the day.[55] This dynamic nature of traffic flow can cause drivers to be less able to assess traffic for acceptable gaps. Logically, for drivers who are less familiar with the traffic flow of the opposing or cross traffic, any unstable and unpredictable changes in traffic flow may cause drivers to unwittingly wait until larger gaps become available. Drivers who are more familiar with (and thus better able to judge the utility of) the available gaps may accept comparatively smaller gaps (i.e., familiarity with the traffic distribution may allow drivers to be better able to identify passable gaps). Learning the operation of a traffic distribution allows drivers to change their perceptions of the value and utility of taking any one gap, and can occur while drivers wait for an acceptable gap the first time they drive through an intersection.[61,62]

Lag and Gap: Gap should be considered as fundamentally different from lag. Data from Gorjestani et al. show a tendency for drivers at two-way stop-controlled intersections to reject the initial lag and then immediately accept the first gap.[52] (In a sample of more than 16,000 intersection maneuvers, drivers on minor roads accept a following gap 78 percent of the time after rejecting the initial lag.[52]) In addition, Devarasetty, Zhang, and Fitzpatrick describe significant differences between accepted lags and gaps at 30 different sites located in Texas, New York, and Arizona.[51] They measured gap size when vehicles turned left and passed through traffic approaching from the opposite direction. They found that accepted critical lag times varied between 2.2 and 7.6 s, which was a much greater range compared with their measurements of critical gap (which is an estimate of the point at which rejecting or accepting a gap is equiprobable.[63] Critical gap varied between 5 to 6.8 s. This finding illustrates that gap and lag should be evaluated independently rather than unequivocally combined.

In addition to the situational factors described in the previous paragraph, factors related to drivers and vehicle types may also affect gap judgments. These factors are more difficult to accommodate through design, but the aspects warrant consideration if these factors will be overrepresented at a location (i.e., heavy truck traffic).

Design Issues

In most situations, the size of an accepted gap will actually change once a driver on a minor road enters an intersection. Specifically, observational data indicate that mainline traffic reduces speed and that there can be large reductions in mainline traffic speed (e.g., 31-percent speed reduction) at a very gentle rate (e.g., 2.2 ft/s^2) when drivers on minor roads are making maneuvers.[51,66] For left-turning drivers at a signalized intersection, approaching traffic may also change their speed, thus changing the gap.[5]

Note that there are multiple methods for measuring gap-acceptance behavior of drivers, and many of the methods result in different conclusions. Ashalatha and Chandra found that different estimation methods can produce critical gap values that vary up to 37 percent, even when using the same traffic data.[60] Therefore, practicioners should confirm the reliability of their gap-acceptance calculations using different estimation approaches.

TOPIC 8. INTERSECTION DECISION SUPPORT FOR STOP-CONTROLLED MINOR AND MAJOR ROAD JUNCTIONS

Introduction

This topic covers human factors considerations for intersection decision support systems installed at junctions between major and minor roadways. This topic primarily addresses SSA, which provides information for drivers on minor roads; however, pertinent information about communicating with drivers on major roads using freeway junction signs is also included because they can affect travel speeds on major roads in a complementary manner.(67,68) A few pilot systems are designed to assist drivers who are approaching a stop sign-controlled intersection, and while the function of each system is slightly different, the general purpose is the same.(67,68,69) Specifically, the objective of these systems is to reduce conflicts between higher-speed, major road traffic and slower-speed, minor road traffic.

Guidelines

Information Presented to Drivers on Minor and Major Roads: When possible, inform drivers who are approaching a limited sight distance intersection of potential hazards from cross traffic. The following list includes possible message information items for drivers on minor and major roads:

- Driver on minor road:
    - Presence of traffic on major road.
    - Proximity of traffic on major roads to intersection, or size of gap in traffic flow on major roads.
- Driver on major road:
    - Intersection ahead.
    - Presence of traffic on minor road.

Intersection, Maneuver, and Traffic-Flow Considerations: The SSA system should accommodate intersection- and maneuver-specific factors that affect driver gap acceptance, as well as aspects of traffic flow on minor and major roads (e.g., average daily traffic and vehicles per hour, distribution of available gaps).

System Activation Timing: When appropriate, the activation timing for messages to inform driver gap choices should incorporate a decision-making time interval (e.g., an activation parameter with an additional time component for message reading and comprehension).

DII Placement: DIIs should be located outside of approaching drivers' intersection sight distance (ISD) to avoid occluding portions of their line of sight of cross traffic.

Number of Stages in a Message: Limit the number of conditional stages or phases of a message (e.g., advise/inform, alert/warn, prohibit).

Figure 6 depicts examples of sign locations that consider ISD. Grey sight triangles are based on the location of the driver's eyes.[70] The slanted green line represents a location that does not negatively affect the driver's line of sight, and the vertical red line represents a sign position that occludes the driver's view of oncoming traffic.

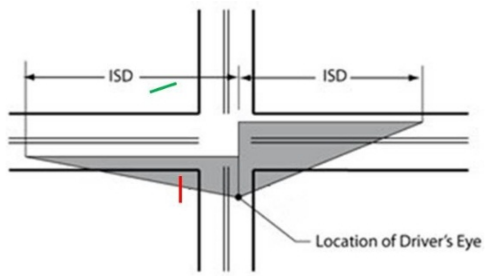
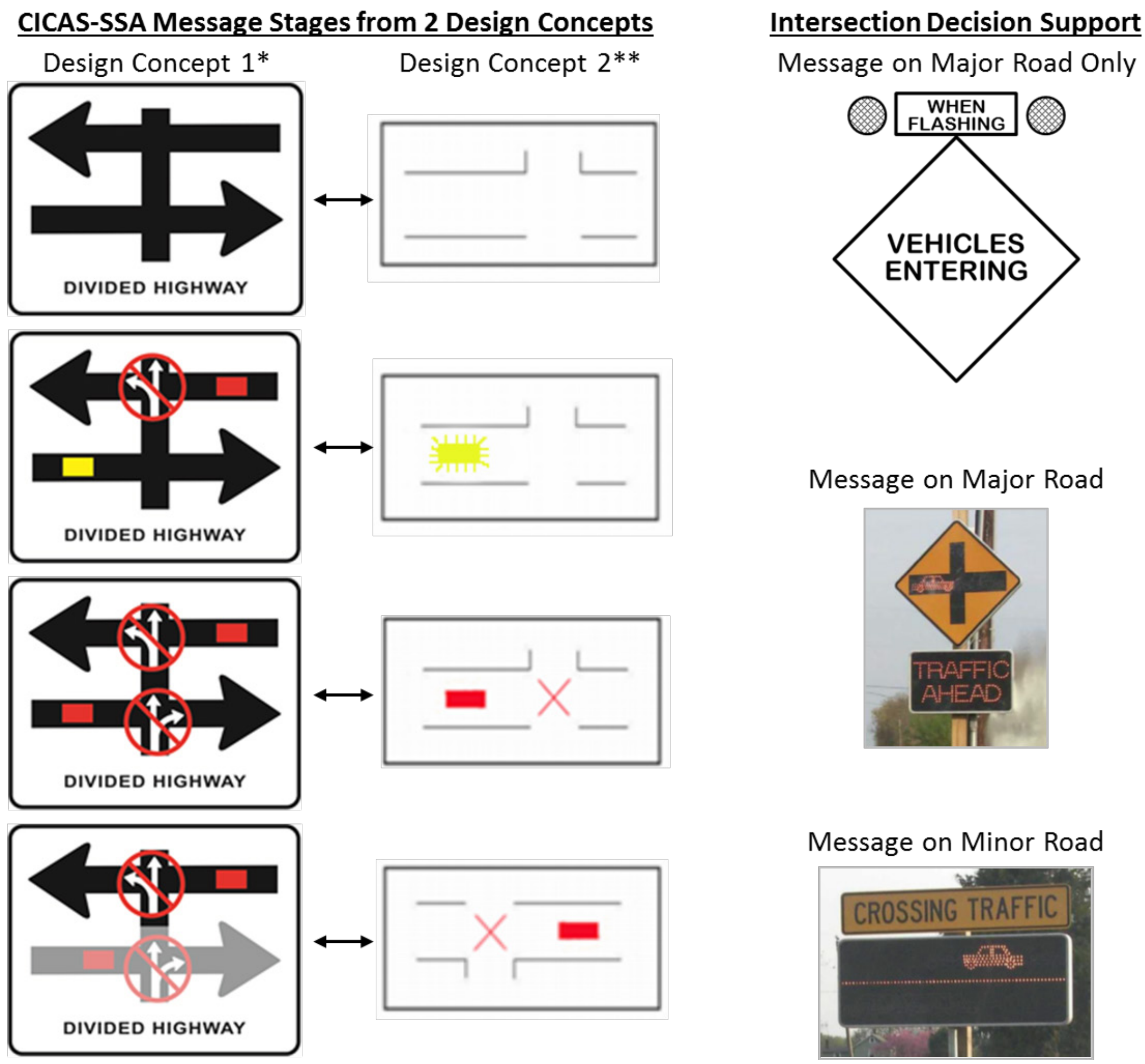


Figure 6. Illustration. Example sign locations that consider ISD.

Figure 7 provides comparison examples of graphical displays for intersection decision support systems.



Sources: University of Minnesota, Minnesota Department of Transportation, Transportation Research Board, Virginia Transportation Research Council.

*Example sign states are shown, the full set of sign states is not well documented in the research but there are more than a dozen elements that change as per descriptions of the systems.

**Example design states are shown for an in-vehicle version of CICAS-SSA. Arrows are used to show which CICAS-SSA graphics are intended to be identical.

Figure 7. Diagram. Comparison of graphical displays for intersection decision support systems that send messages to drivers on the major road, minor road, or both.(19,49,68,67)

Discussion

Only a few efforts have examined systems that provide information to drivers at both minor and major road junctions, specifically two-way stop-controlled intersections.(67,68) However, there is extensive documentation from a test implementation of CICAS-SSA, which was designed to assist drivers on minor roads in rejecting unsafe gaps. This system displays information about the proximity of traffic on the major road to the intersection. The available design information about CICAS-SSA includes documentation on initial design efforts and prototype testing.

Unfortunately, field test reports do not provide information about the CICAS-SSA's effectiveness.

Information Presented to Drivers on Minor Roads: The CICAS-SSA attempted to allow mainline traffic to remain largely unaffected by cross-traffic, which was meant to aid drivers on the minor road with their gap choices. (See references 49, 52, 69, 71, and 72.) This decision support was provided using DIIs that delivered the following information about vehicles on major roads: (1) notification of vehicles that were arriving at the intersection soon, (2) information about the direction of the approaching vehicles, and (3) notification if crossing traffic was close enough that drivers on minor roads should avoid crossing. (See figure 7.) The behavioral objective of the system was to encourage drivers to reject short gaps, and the warning level was based on 80th percentile rejected gap size for all maneuvers measured, with a time component added to accommodate reading and comprehension of the DII message.(52)

The major road in this field test was a divided roadway with sufficient space for vehicles on minor roads to stop at the median. As shown in figure 7, the CICAS-SSA DII provided information about each direction of travel on the major road, which resulted in a display that was information dense. However, during initial testing, participants typically indicated that the CICAS sign was easy to understand, and they were able to describe its purpose to tell them about the presence of approaching vehicles.(19,49,69) Unfortunately, field test data do not provide clear results regarding the effectiveness of this system. However, a related driving simulator study from Becic et al., showed that there was a benefit in gap acceptance for a CICAS-SSA in-vehicle display that used a display that operated in a similar manner, but with a simplified visual design.(19)

Information Presented to Drivers on Major Roads: In contrast to the inconclusive data regarding what information to present to drivers on minor roads, the findings related to presenting information to drivers on major roads are more definitive. Specifically, systems that inform drivers on the major road about the presence of cross traffic on the minor road have been shown to be effective at reducing driver speed on the major road and possibly crashes.(67,68) One type of message sign that has some documented benefit is a static sign on the major road that simply indicates the presence of a crossroad (e.g., freeway-style junction signs). A study that examined this type of signage found a reduction in crash rates.(73) Similarly, the CICAS-SSA study by Gorjestani et al. found that there were overall reductions in mainline speed because of cross traffic, but only for large trucks entering from the minor road.(52) The reduction was moderate, between 0.5 and 3.5 mi/h for small and large gaps There was no reduction in mainline speed when smaller vehicles entered from the minor road. Visibility may have been a factor at this location, however, because smaller vehicles could be occluded by the undulant topography of the mainline roadway, whereas larger vehicles could still be seen.

Intersection, Maneuver, and Traffic-Flow Considerations: SSA systems that only inform drivers of the presence of other vehicles can be simple to implement for mainline traffic.(67,68) For example, at two-way stop-controlled intersections, the presence of a driver at the stop sign can be used to activate the message for drivers on the major road. Informing drivers on the minor road about approaching traffic, however, is more complex because criteria related to proximity on crossing traffic are required to determine relevant distance from the intersection to activate the message. Hanscom activated their message on the minor road when drivers on the major road were within the ISD.(67)

Alternatively, field measurements of gap choice have also been used to determine when to activate SSA messages to drivers on minor roads. The activation parameters for CICAS-SSA were determined using field data on drivers' 80th percentile rejected gap on minor roads.(52) The resultant 6.5-s value was used as the system timing for all stop-controlled intersections tested. Note that the observed rejected gap size was different across locations and for different maneuvers. It is possible that using the same timing for these different scenarios may have undermined the effectiveness of this system by making the system timing seem unreliable or inaccurate.(10) Consequently, developing system timing based on aggregate driver behavior for a specific maneuver and at a specific location should be considered during implementation.

It is important to recognize that gap choice is highly variable and may depend on many factors. (See topic 7.) Accordingly, using gap choice as a basis for selecting a system activation parameter should be considered to be a complex approach. It requires significant effort to measure, assess, and determine what elements of gap choice are relevant to include as activation parameters.(52) Available research on factors that affect gap choice suggests that no universally applicable value for gap acceptance or rejection exists. In particular, gap choice has been shown to be different for left, right, and straight-through maneuvers.66,53) The number of lanes a driver must cross is also a factor. Drivers tend to wait for larger gaps when crossing or entering multilane roadways.(54,55) The distribution of available gaps is also an important factor to consider because some intersections have dense traffic with fewer passable gaps.(50) When traffic is dense, drivers may reject more gaps before accepting a gap, but the gap they accept may be smaller than many of the rejected gaps. Thus, situational factors associated with specific locations and movements should be considered when selecting system activation parameters.

System Activation Timing: The CICAS-SSA activation timing parameter was based on field data collected on 80th percentile rejected gap size across multiple test sites.(52) This value was subsequently modified by adding an extra 1-s delay to account for the perceptual processing time needed to read and comprehend the message before initiating a crossing maneuver.(49,69) Laboratory research shows that prohibitory signs (e.g., left-turn arrow with prohibitory overlay that indicates left turns are not allowed) are associated with high error rates and can take more than a half-second for people to understand, although there is no estimate for real-world situations.(74,75) Note that an assessment of the amount of time required to comprehend the full array of images across the various CICAS-SSA states has yet to be done.

DII Placement: DIIs should not block the minor-road driver's line of sight of traffic on the major road. Early efforts to determine placement of the DIIs for CICAS-SSA found that test subjects reported that the DII message boards blocked their view of major road traffic when placed adjacent to the minor road.(76) Placing the DIIs outside of ISD triangles (see figure 6) allows drivers to see approaching traffic on the major road.

Number of Stages in a Message: The messages that were designed to inform drivers on the major road about the presence of drivers on the minor road were two-stage systems (e.g., "vehicles entering when flashing"; see figure 7). There has been considerable research on how to graphically present CICAS-SSA information to drivers on minor roads. Earlier efforts culminated in a multistaged message that consisted of over a dozen changing elements.[49,69] Later efforts found that less complex graphics and fewer stages may be practical options.[19,71]

Design Issues

There is a lack of research on how the presence of traffic in the same driving lane (e.g., lead vehicles) affects the comprehension of messages and whether drivers will understand if messages are intended for a lead vehicle or themselves.[76] This fact is relevant for systems that activate messages contingent on where the driver on the minor road is positioned. In the case of a CICAS-SSA type system on a median divided highway, a driver located at the stop sign could misinterpret a message intended for a driver in the median.

TOPIC 9. SLTA

Introduction

This topic discusses the factors that should to be considered when presenting left-turn gap-assist information to drivers making unprotected left turns at signalized intersections. The primary goal of SLTA systems is to provide decision support to drivers making permissive left-turn movements with oncoming traffic.[5] LTAP-OD crashes are primarily caused by errors made by the left-turning driver. The SLTA system has the potential to reduce the frequency and severity of LTAP-OD crashes by providing drivers with information about the presence of oncoming vehicles, which can address driver errors related to detecting traffic and judging gaps.[5] An SLTA system is an alternative to other left-turn safety countermeasure at intersections such as protected left turns, which typically lead to reductions in traffic flow and which sometimes also require dedicated lanes to implement.[5]

Guideline

The following design guideance is applicable when designing systems to provide SLTA information to drivers:

- The decision to provide SLTA information should consider intersection characteristics and the safety record of the specific intersection. SLTA is most useful at a location where there is a high volume of oncoming traffic, high pedestrian and bicyclist density, and persistent limitations on sight-distance/visibility.
- The timing algorithm of the SLTA alert/warning should incorporate factors related to intersections, such as geometry, SPaT, traffic volume/density, and speed.
- The SLTA information can be presented either using a DII, a DVI, or both. Implementing a DII display for SLTA has advantages because the display is available to all drivers making a left turn (i.e., the subject vehicle does not require CV technology), and it permits drivers to maintain their gaze on the roadway environment.
- The DII and DVI display locations should be integrated with locations where drivers would typically be scanning while performing the gap judgment task.

- If SLTA information is presented on multiple displays (DII and DVI) simultaneously, then the activation timing of the both displays should be the same.
- The meaning of the message elements and symbols used on SLTA DII/DVI displays should be consistent with the allowable movements.

Source: Knodler and Noyce

Figure 8 depicts a typical area that drivers scan when they are making a left turn. The two small ovals indicate drivers' preference for the SLTA-DII display location in their driving environment.(10)

Source: Knodler and Noyce

Figure 8. Photo. General region drivers scan when making an LTAP of oncoming traffic.(77)

Discussion

The most frequent causal factor in LTAP-OD crashes is a left-turning driver who inadequately perceives the gap required to make a safe left turn.(78) Other factors that also contribute to LTAP-OD crashes include failure to judge speed of closing vehicles, failure to see oncoming traffic, and obstruction of the driver's view by an oncoming opposing vehicle.(5) From 2005 to 2008, there were an estimated 200,212 LTAP-OD crashes at signalized intersections based on weighted National Automotive Sampling System-General Estimates System (NASS-GES) data, which accounted for an estimated annual cost of more than $10.3 billion.(79) The objective of the SLTA system is to reduce the frequency and severity of these crashes by providing drivers with information that will help them better assess oncoming traffic and discourage them from making left turns with inadequate gaps in opposing traffic.(5)

Intersection Characteristics: An earlier SLTA concept of operations (ConOps) by Misener et al. investigated a large set of intersection factors to identify the following characteristics that should be considered when implementing an SLTA system:(5)

- Left-turn pockets.
- Left-turn lane.
- Intersection geometry.
- Line of sight.
- Pedestrian levels.
- POV volume and speed.
- POV number of lanes.
- Percentage of left-turning vehicles.
- Percentage of heavy-duty vehicles.
- Clustered/dispersed traffic flow.

This ConOps did not provide specific criteria for these intersection characteristics, but it did identify a shortlist of design consideration for SLTA systems based on these factors. (See table 11.) However, no data indicate which characteristics are most critical for implementing the SLTA system, or which observed levels constitute a "high" indicator. Accordingly, these considerations should only be used as a general reference. Note that design consideration for the systems will not be uniform across intersections, and adjustments would need to be made based on the characteristics of the specific intersections. More information is available in Misener et al.(5)

Table 11. General design considerations for intersection characteristics.

Intersection Characteristics	Design Considerations
• High traffic volume in the primary direction. • High concentration of LTAP crashes involving a vehicle turning from primary corridor onto cross streets. • High speeds.	CICAS–SLTA systems require capability to monitor a large number of vehicles at relatively high speeds.
• Multiple lanes of oncoming traffic. • No left-turn pockets.	CICAS-SLTA systems need to consider the turning time needed for completing left turns, based on the size and/or number of crossing lanes. This variable is essential for determining the warning threshold.
• High pedestrian presence.	CICAS-SLTA systems need to consider/ design needs to include pedestrian-sensing capabilities.

Line of sight, geometry, and visibility represent other considerations when implementing SLTA. Divekar et al. found that drivers did not use an SLTA system when they had a clear view of oncoming traffic.(10) In this situation, drivers preferred to rely on their own judgment based on observing oncoming traffic; however, drivers used the system when their view of oncoming traffic was obscured by a truck in the opposing left-turn lane.(10,80) This fact suggests that the system may be more appropriate at intersections where the drivers' view of the traffic is frequently limited by sightline restrictions or other vehicles.

System Timing: Determining the timing for the SLTA message alert is challenging because no guidance or documentation about the message timing requirements or about suitable approaches for determining message timing exists. Misener et al. suggest that factors such as intersection geometry, traffic volume and speed, and signal phasing should be considered when determining system timing, and that the timing of the message activation should be calibrated for the specific intersection where the system is deployed.(5) For example, the timing of the message will be longer if the driver must cross multiple lanes of traffic compared with crossing a single lane.

The unequivocal priority of the SLTA system is to improve safety by reducing LTAP-OD crashes. Therefore, the message timing of the system must be designed to provide all drivers with sufficient time to safely execute a turning movement. This approach leads to conservative system timing parameters biased toward larger gaps in traffic. However, there is a tradeoff between larger gap sizes and drivers' perception of credibility of the system. In particular, drivers tend to ignore SLTA information if it provides a "don't go" (no left turn) indication for gap sizes that drivers are normally comfortable turning through.(10) Moreover, drivers seem to rely on the system more and perceive a system to be more accurate, if the message alert timing matches their comfortable gap size. For example, in a simulator study by Divekar et al., drivers ignored the SLTA system when the alert was presented for gaps that were 2 s longer than the gaps that drivers frequently accepted.(10) In contrast, when the alert timing matched the gap sizes drivers frequently accepted, a higher proportion of drivers used the system. While it is critical that SLTA systems do not encourage potentially unsafe gap acceptance, it is still important to recognize that designing a system that is highly conservative runs the risk of being underutilized.

Display Type: The SLTA message can be presented either on a DII, a DVI, or both. The type of display does not seem to affect driver use of the SLTA information in meaningful ways. Misener et al. found that there was no difference in the drivers' turning rate and braking response as function of the location of SLTA display type (DII or DVI).(5) Divekar et al. found that drivers used whichever SLTA display was available in the driving environment to inform their left-turn gap judgment and that the performance across the two display conditions (DII versus DVI) was the same.(10) In both studies, however, drivers indicated a general preference for the DII because it had a distinct advantage of being located on the roadway and was perceived as more authoritative than the DVI. This preference is consistent with a report by Rephlo in which participants consistently demonstrated a preference for information presented on the DII in responses to questions about reliability of the SSA system.(80)

Display Location: Another factor that needs to be considered when implementing the SLTA system is the location of the displays in the environment. Specifically, the displays should be integrated with drivers' normal visual scanning behavior during left turns. Incorporating the displays within or near the drivers' typical scanning zone will make it easier for the drivers to acquire the information and to respond appropriately.(10) Drivers making a left turn maneuver tend to scan the intersection from the right to left, and they generally take a first look at the relevant traffic light and then focus on oncoming traffic.(77) Drivers also use the stream of oncoming traffic as their base point from which they then distribute their glances between any objects in their path of travel (pedestrians, bicyclists, etc.), other sources of information at the intersection, and the traffic light.(77,81)

DII-DVI Coordination: When presenting information on both DII and DVI displays simultaneously, it is important that the timing of the message between the two systems is the same. (See topic 3.) Divekar et al. examined the effect of the DII and DVI having different timing when presenting SLTA gap-assist information.[10] In one condition, when drivers used just one display and were essentially able to ignore the other, there was no evidence of interference. In another condition, however, when it was more difficult to simply ignore a display that had longer timing (i.e., DVI was near the drivers' line of sight), there was evidence that interference might have occurred because this display showed conflicting information as a result of lag in display timing. From a simple human factors perspective, this situation should be avoided because providing conflicting information when drivers are making a decision about whether or not to turn is likely to interfere with their decision-making process.

Message Elements and Symbols: Finally, there needs to be consideration of which message symbols are used on the DII and/or DVI displays. Existing symbols have a distinct advantage of familiarity (see topic 5), but drivers also have a learned meaning for these symbols. If the symbol's commonly accepted or understood meaning does not match the function of the system, then drivers' understanding of the message may be reduced. For example, Divekar et al. examined drivers' understanding of two MUTCD symbols in an SLTA scenario: "No Left Turn" and "Left Turn Yield" symbols presented on a DII.[10,7] (See figure 9 and figure 10.) Almost half of drivers misinterpreted the "No Left-Turn" message on the DII as a permanent restriction rather than a temporary restriction based on immediate traffic conditions. On the other hand, the "Left Turn Yield" sign in the same context had a much higher initial comprehension rate. These findings suggest that it is important that message elements and the symbols used on system displays should be consistent with the purpose of the system.

Source: MUTCD.

Figure 9. Illustration. MUTCD symbol for "No Left Turn" that was presented on the DII to examine drivers' understanding of the SLTA system.[7,10]

Source: MUTCD.

Figure 10. Illustration. MUTCD symbol for "Left Turn Yield" that was presented on the DII to examine drivers' understanding of the SLTA system.[7,10]

TOPIC 10. RLVW

Introduction

This guideline discusses the presentation of notifications and warnings for RLVW systems. The objective of this application is to warn potential red light runners so they can take action to avoid entry into the intersection. Violators are drivers who are on a trajectory that will result in them crossing the stop bar and entering an intersection when they do not have the right of way. Violator causal factors include both unintentional acts such as missing the signal because of low conspicuity or inattention and intentional violations such as trying to "beat the yellow." RLVW holds the potential to reduce the frequency of unintentional violations. This information is presented with the assumption that other means of reducing right-of-way violations have been undertaken, such as reviewing the signal's visibility and timing based on MUTCD requirements and investigating ways of increasing conspicuity (e.g., optimizing signal placement).[7]

Guideline

The following design guidance applies when determining the presentation of notifications and warnings for RLVW systems:

- Use an RLVW to address red light running due to inattention or poor signal visibility.
- Present the RLVW in a period that is detectable and actionable by the driver.
- Avoid activating the RLVW while the driver is in the dilemma zone. When a traffic signal turns yellow, a dilemma zone region is created upstream of the intersection, encompassing distances in which drivers can neither safely stop at the stop line nor completely pass through the intersection before the light turns red.
- Base RLVW timing on a consideration of several factors, including driver perception reaction time (PRT), current travel speed, the distance to the intersection, deceleration required to perform a nonviolating stop, and road surface conditions.

Table 12 provides a list of timing factors with their respective effects on driver responses to RLVW.

Table 12. Timing factors that affect RLVW compliance.

Factor	Effect on Driver Response to RLVW
PRT	Distracted or inattentive drivers generally display longer reaction times.
Current travel speed	RLVW compliance may increase if the driver can decelerate at a comfortable level.
Distance to intersection	RLVW provided earlier, at greater distances, typically results in greater compliance.
Deceleration required	Required decelerations should be at or below 0.5 g to facilitate RLVW compliance.
Road surface condition	Inclement weather and broken/uneven road surfaces may negatively affect RLVW compliance.

The choice of DII for the RLVW depends on the salience of the signal and associated visibility conditions, as well as the cause of red light violations. Table 13 provides a list of technologies that have been examined for or are applicable to RLVW. All are of low salience in their nominal state and activate only when providing the RLVW.

Table 13. Example DIIs for the RLVW as a function of condition/utilization.

Condition/Utilization	DII	Description
Low signal visibility and/or contrast	Signal Head, alternating flashing beacon	Lights placed on either side of the red signal lens that flash in an alternating pattern.
Low signal visibility and/or contrast	LED backplate	Illuminated backplate for the signal head. Not MUTCD compliant, and wind/weight load must be considered when adding to existing span wires or mast arms.
Low signal visibility and/or contrast, or cluttered visual scene around signal head	Blank-out sign, strobe lights	Blank-out sign that displays an illuminated octagon with STOP written inside. May include strobe lighting at the corners of the sign.
Signal head potentially obscured (e.g., obscured by a leading large truck)	In-pavement lighting	Conventional or LED lighting installed in-pavement at the stop bar. Illuminates when triggered to provide the appearance of a lighted line across the road.

LED = light-emitting diode.

Discussion

Right-of-way violations at intersections extract a great toll in regard to cost and well-being. Eccles et al. estimated that 234,881 crashes led to a total annual cost of $13 billion (using NASS-GES data, 2005 to 2008).[79] Furthermore, approximately 45 percent of these crashes resulted in fatalities or injuries. Therefore, intersection applications such as RLVW have potentially large safety benefits concerning crash involvement. Red light violations may result from intentional and unintentional factors. Hendricks, Fell, and Freedman characterized three different causal factors for these types of collisions: (1) looked and did not see, (2) driver inattention, and (3) crossed intersection with an obstructed view.[82] Other causal factors that have been identified include trying to beat the yellow, mistaking the phase of the signal, and intentionally violating the signal. Of these factors, RLVW holds the potential to reduce the frequency of violations from all but those arising from intentional violations.

A number of engineering countermeasures for reducing the frequency of right-of-way violations at signals have been identified and tested. Summaries of these are provided by the Institute of Transportation Engineers (ITE) and by Antonucci, Hardy, Slack, Pfefer, and Neuman.[83,84] Methods such as improving the signal visibility and conspicuity, providing advance notice of the upcoming intersection to increase the likelihood of stopping, and eliminating unnecessary signalized intersections are all potential countermeasures to right-of-way violations at intersections. The information presented in this section assumes that other engineering countermeasures were considered prior to the implementation of an RLVW.

Considerations Regarding Driving Inattention or Signal Visibility: The RLVW presentation can involve several different DII elements.[85] DII evaluations have examined both RLVW and DII intersection warnings oriented to the potential victims of red light violators. Although targeted at different drivers (with different assumptions about driver state), both are discussed here because all have the same intended effect of preventing entrance into the intersection. Furthermore, many of these countermeasures were not designed to target violators; instead they were designed to augment the visibility of the existing TCD and infrastructure. While these countermeasures were implemented as a supplement to existing DII, their use as a warning (i.e., not activated until a potential violation is identified) may be supported.

Beacons are used to draw attention to the signal head in low visibility or contrast scenarios. For notifications to an intersection, these have typically been examined in the form of alternating flashing lights on either side of the signal head. A blank-out sign can provide additional information when the signal may be of low visibility. These signs can be mounted with the signal heads. They are blank in the nominal state and provide a replication of a stop sign when activated. Strobe lights may be included on the sign that, when activated, can assist in attracting drivers' attention to a signal or sign in cluttered visual scenes. These elements have been examined (largely in conjunction with each other, preventing any detailed discussion of individual DII element effects) by both Neale et al. (in conjunction with a blank-out sign and strobe lights) as well as Inman, Davis, El-Shawarby, and Rakha.[6,86] Results from both examinations found generally high but not complete compliance with these warnings. A distracted driver, however, may still miss these signals, and Inman et al. note that higher compliance was found with additional and more conspicuous DII elements (such as in-pavement lighting).[86]

A light-emitting diode (LED) backplate can serve as an attention attracting element to a signal. The MUTCD specifies that signal backplates should have a dull black finish to enhance contrast or, optionally, a yellow retroreflective strip for enhanced nighttime appearance.[7] While not in compliance with the MUTCD, an LED surround used instead of the retroreflective strip can allow a more conspicuous illuminated outline of the signal head. Tydlacka, Voight, and Langford reported that LED backplates are associated with a reduction in red light running violations.(87)

In-pavement lighting is generally described as being used to enhance, or attract attention to, lane markings. This type of lighting can also be useful when the signal head may be obscured, for instance if a driver is following a large leading vehicle. Inman et al. describe a simulator experiment that included in-pavement lighting along the travel lane and the stop line; however, these were examined in conjunction with intelligent rumble strips that could be triggered, so the effectiveness of the lighting alone cannot be assessed.(86) Tydlacka et al. reported on the installation of in-road lights installed with the stop bar at an intersection.(87) The stop bar lights provided an improvement in right turn on red violations (a prohibited maneuver at that particular intersection) but had no effect on red light running violations. In-pavement lighting should also be considered in relation to the cost of installation and maintenance. Carson, Tydlacka, Gray, and Voight describe many of the installation and maintenance costs associated with this DII, as well as report on some jurisdictions' operation experiences.(88) In addition, depending on the installation, in-pavement lighting may be visible to nonviolating drivers and could possibly lead to unintended responses from nonviolating drivers.

Message Presentation Period: Determining the timing of the RLVW is difficult because of the direct relationship among the warning time, driver response time, speed, and deceleration required to achieve a stop. Identifying a violator can only be done very close to the intersection entrance, yet presentation of violation warning must be actionable (beyond the PRT and physical limits of stopping the vehicle). Thus, the RLVW must be presented within a period that is detectable and actionable by the driver. For instance, if a driver can only be identified as a violator 180 ft from an intersection, then a driver approaching at 45 mi/h will only receive a warning 2.75 s prior to violation. Assuming an immediate reaction from the driver, this action would require an average deceleration of approximately 0.75 g, a value that some drivers may not be able to sustain. In this case, the driver may pass through the intersection in violation or come to a stop beyond the stop bar if he or she attempts to comply with the RLVW. Further, factors such as driver distraction can increase the PRT, increasing the required RLVW timing.

Avoid Dilemma-Zone Activation: Because an RLVW system has not been extensively tested in highway conditions, some potential unintended consequences should be noted. First is the potential for driver confusion (and thus delayed response) if RLVW is presented in the dilemma zone. Neale et al. note that this confusion may result in a conflict if the potential violator is given the warning while the signal is yellow, stating that "…while the warnings were meant to elicit a stopping response, the [yellow] light provides a choice to drivers, who must decide whether they feel more comfortable stopping or trying to make it."(6) (p. 162) Drivers' individual resolutions to this conflict could result in a number of different, potentially undesirable actions that may negate the benefits of the RLVW.

Timing Considerations: In this topic, warning timing is discussed in regard to the required deceleration and what deceleration levels a driver may accept. This discussion is necessary because of the relationship among speed, distance, time, and the resultant deceleration, as described by the American Association of State Highway and Transportation Officials (AASHTO).(89) AASHTO presents design values for stopping sight distances of a "comfortable deceleration" level ranging from approximately 0.27 to 0.34 g. Gates, Noyce, and Laracuente examined drivers passing through different intersections and found that the travel time to the intersection following activation of the yellow light was the greatest single predictor in determining whether a driver would continue through the intersection.(90) For drivers approaching the light at a faster speed, Gates et al. identified decelerations ranging from approximately 0.29 g (15th percentile) to 0.42 g (85th percentile), suggesting the AASHTO values may be slightly conservative.(89)

Compliance is generally greater when warning times are longer and thus lower decelerations are required of the driver. A simulator examination by Inman et al. used timing between 2.75 and 3.3 s; these values resulted in decelerations between 0.65 and 0.85 g.(86) In a complementary closed-course test track experiment, Inman found that slightly lower values of 0.78 g were typical. Compliance with a DII-provided warning was higher when longer warning periods were provided (thus involving lower required decelerations). However, these findings, when viewed alongside collision avoidance research reported by Keifer et al. and the AASHTO standards, suggest that drivers may not perform decelerations above 0.5 g.(91,89)

Another factor that may influence RLVW compliance is the road surface condition. Although the effect of road surface condition on RLVW compliance has not been systematically evaluated, other efforts to reduce right-of-way violations at signalized intersections have identified pavement surface conditions as a concern.(83,84) ITE notes that lower friction forces arise from issues such as older or damaged pavement, certain road surface types, and the presence of surface water. These may all lead to intersection violations by making a driver less likely or able to comply with a yellow signal and should be accounted for in an RLVW.

Design Issues

Research has suggested potential benefits to presenting RLVW information through both the DVI and DII. Both Neale et al. and Inman and Davis concluded that simultaneous DII and DVI presentation of an intersection collision warning message was more effective than individual presentation through either individual method of communication.(6,92) Therefore, the coordinated presentation of RLVW messages should be considered when possible.

Beyond the benefits of presentation via DVI, obtaining information from V2I communication can help improve the performance of the RLVW prediction algorithm by providing the information contained within the basic safety message. Combining the current vehicle parameters (as contained in the basic safety message) with SPaT information could allow more accurate, precise, and directly targeted presentation of RLVWs. These V2I-enhanced RLVW messages could also benefit from other vehicle information, such as the braking ability of vehicle or load status of commercial vehicles.

The effect of surrounding traffic on RLVW compliance is unknown. Inman and Davis examined compliance with a DII-based warning of a red light violator (i.e., warning the potential victim prior to entering the intersection) in a driving simulator task with no surrounding traffic, lead vehicle, and following vehicles.(92) The presence or absence of a following vehicle was found to have no effect, and the presence of a leading vehicle affected response time to the yellow light but not compliance with the signal. In an examination of DIIs for intersection collision avoidance, Neale et al. noted that some participants commented on the presence of a following vehicle in their responses to a warning and that the following vehicle presence may have had an effect on the driver's comfort with performing the stopping maneuver.(6) Pending further investigation, implementation of an RLVW should consider the likelihood of surrounding traffic modifying the likelihood of a driver response.

A final potential issue is the possibility of the RLVW message being visible to nonviolating drivers. The driver of a lead vehicle that could enter the intersection legally and exit during the red clearance interval could slow in response to the message, thereby becoming a violator. Related is the issue of following vehicles. Driving simulator studies have suggested that the presence of lead or following vehicles will not affect driver braking likelihood; however, this possibility has not been investigated extensively or outside of simulated environments.(92) Some evidence does suggest that drivers receiving the RLVW message may hesitate to engage in the hard braking required to avoid violating the right of way if another vehicle is following.(6) Conversely, the potentially violating driver's braking may lead to a rear-end collision from inattentive drivers in following vehicles.

TOPIC 11. CSW

Introduction

This guideline addresses the use of DIIs in CSW applications, including advanced warning signs, vehicle-activated signs, and DCWSs. The corresponding DII elements advise drivers of an upcoming horizontal curve and provide a warning and information regarding the safe approach and traverse of the curve. Eccles et al. estimated that almost 169,000 annual crashes occur as a result of unsafe speed at curves or ramps, with 44 percent resulting in injuries or fatalities and a cost estimated to exceed $29 billion.(79) Horizontal curves can also be a challenge for large combination vehicles (LCVs), which must approach curves at different speeds than automobiles. LCV crashes in curves typically involve improper speed and inattention.(93) This guideline is intended to supplement MUTCD standards for problematic horizontal curves and V2I applications in addressing certain vehicle types with higher risk of crash involvement.(7)

Guideline

The following design guideance applies to the use of DIIs in CSW applications:

- Use a combination of advance warning signs and DCWSs to target at-risk drivers with information about the safe traversal of a horizontal curve.

- Locate advance warning signs based on table 2C-4 of the MUTCD.(7) Present CMS information in accordance with MUTCD legibility recommendations (for speeds above 55 mi/h, 600 ft in nighttime conditions (7.4 s at 55 mi/h) and 800 ft (9.9 s at 55 mi/h) in daytime conditions). Advanced warning sign placement should consider passenger vehicles and LCVs separately. Consider using vehicle-specific or separate DIIs if a single DII cannot accommodate the kinematics of these different vehicle types.

- Include the advisory speed for the vehicle in DCWS message elements. DCWS messages may include the vehicle's current speed, the risk type, and any driver corrective action needed.

- Follow guidance from section 2L.05 of the MUTCD regarding how to format information presented on a CMS that is part of a DCWS.[7]

- Permit the advance warning window for an LCV to overlap with that for a passenger automobile; however, the time and distance for some types of LCVs (e.g., empty tractor-trailers, vehicles pulling loaded liquid tanker trailers, etc.) may be considerably greater than that of a passenger car.

- Enhance a CSW with V2I communication. Include vehicle characteristics in CSW algorithms to reduce false alarms. Use the DVI to provide a salient audio or visual CSW notification.

Table 14 provides a list of DII elements which support horizontal curves.

Table 14. DII Elements to support horizontal curves.

DII Element	Description
Advanced warning signs	Notification sign, including an indication as to the type and direction of the forthcoming horizontal curve. These indications can include an advisory speed and/or warnings specific to LCVs.
Vehicle-activated advanced warning signs	An advanced warning sign that activates based on an approaching vehicle traveling above a predetermined threshold. Signs can include blank-out signs or a static sign with flashing beacons.
DCWSs	CMS triggered by approaching vehicle. These signs typically include a vehicle detection system and can be connected to weigh-in-motion systems for LCVs. A DCWS should be used in conjunction with advanced warning or vehicle-activated advanced warning signs.

Discussion

CSW DII elements supporting LCVs in horizontal curves should provide information about the advisory speed for the curve (relative to the rollover threshold) and be visually salient. LCVs have a reduced rollover threshold and must traverse horizontal curves at lower speeds than passenger vehicles. Improper speed and driver distraction are contributing factors to many LCV crashes in curves.[93] A CSW can address these factors by targeting specific drivers with actionable information about the curve in an attention-getting manner through both DII and DVI elements.

Multiple DII Elements: A CSW should be provided via multiple DII elements, including advanced warning signs or vehicle-activated advanced warning signs and a DCWS. When used alone, static signs may not be an effective method for providing this information. Chowhurdy, Warren, Bissell, and Taori noted that many drivers ignore or otherwise do not comply with advisory speed signs because of overly conservative advisory speeds compared with the capabilities of modern vehicles.[94] Assuming that advisory speeds are properly calibrated, vehicle-activated signs can help draw attention to an advisory sign by increasing the sign salience. The highest salience, however, comes when these are used in conjunction with a DCWS.

Location and Presentation: The location and presentation of the CSW DII is dependent on factors such as the posted or 85th percentile speed, the difference between posted and advisory speed, typical conditions, and the expected driver PRT. The MUTCD provides guidance on the placement of advance warning signs.[7] Advanced warning signs may be supplemented by beacons or may use blank-out signs activated by approaching vehicles (i.e., vehicle-activated advance warning signs) to increase conspicuity.

The CMS message should be presented for a sufficient duration of time for the driver to read the message. The MUTCD provides the following criteria for legibility distances (provided in table 15 as seconds of visibility):[7]

Table 15. Criteria for legibility distances by seconds of visibility.

Design Criteria	55 mi/h Design Speed	70 mi/h Design Speed
Daytime condition legibility distance (800 ft)	9.9 s	7.8 s
Nighttime condition legibility distance (600 ft)	7.4 s	5.8 s

A minimum message presentation time of 4 s is recommended.[95] If the message must involve two phases of presentation, then the cycle time should not exceed 8 s. Information targeting LCV drivers may be presented earlier than information targeting passenger vehicle drivers; however, a distracted driver may not notice the CMS when the message is first presented. Because the system targets distracted drivers, longer presentations are preferred. In all cases, the placement should be based on engineering judgment, balancing the benefits against drivers' potential to forget or ignore the message.

Driver Workload: DCWS message elements should be provided far enough in advance of the curve so as not to increase driver workload. Driver workload at curves becomes elevated at curve discovery and is highest at curve entry and negotiation.[11] CSWs may reduce workload and uncertainty by providing information about the curve, no closer than 246 ft or 4 s from the curve. information includes MUTCD-specified information about the curve such as the horizontal curve's direction and the advisory speed.[7] A DCWS can incorporate information from speed/height sensors, machine vision, or weigh-in-motion systems to provide more targeted information and reduce instances of false alarms.

Message Comprehension: Format information of a DCWS CMS to facilitate message comprehension. When presented on a CMS, messages should be presented with a limited number of information units to ensure rapid extraction of the message by the driver. MUTCD provides guidance for phrasing messages on CMS in section 2L.05; the simplest message that provides the needed information is the best.[7]

Presentation for LCVs: The advance warning window for an LCV may overlap with that of a passenger vehicle. However, the time and distance required for some configurations of LCVs to slow to an appropriate speed (e.g., when the LCV is either empty or heavily loaded, pulling a liquid tanker trailer, etc.) may be considerably greater than that of a passenger car. DCWS signs can be implemented at greater distances when specifically targeting LCVs. Therefore, the information from a DCWS CMS may be more beneficial for LCV drivers when presented earlier.

Advisory Speed Calculation: Use V2I communication to enhance CSW applications by determining optimal approach speeds based on vehicle characteristics and horizontal curve characteristics. For instance, the rollover threshold for an LCV with a high center of gravity will be much lower compared with an automobile. Thus, the safe entry speed of the two vehicles will likely be different for a given horizontal curve. Calculating an appropriate advisory speed based on both sources may provide a more accurate value. V2I also allows coordinated presentation of a CSW via DVI and DII, which may provide further benefits to the CSW. The use of the DVI will allow auditory presentations of a CSW, which may be very beneficial for distracted drivers (who are a large contributing factor to crashes at curves).[96]

Design Issues

DCWS information should provide accurate advisory speed information because false alarms can negatively affect drivers' trust in the system.[97] (See topic 6.) CMS information targeted to a specific vehicle should be clearly indicated as such to avoid unintended consequences such as nontargeted drivers suddenly braking in front of other vehicles. Previous field trials have examined the use of transponders and weigh-in-motion systems to identify vehicles for CSW messages.[98] Presenting information targeted specifically to a driver by providing identifying information (such as the driver's given name or the freight carrier), however, is not recommended because this public display of personal information may foster driver resentment.

The information provided in this guideline is primarily oriented to the issue of horizontal curves. With appropriate sight distances and proper signage, horizontal curves are unlikely to present a problem to most passenger vehicle drivers. With certain types of curves, however, such as compound curves or certain sag vertical sections, drivers may improperly judge appropriate entry and negotiation speeds.[99] In these situations, different DII elements (such as those discussed within this section) may be advisable.

TOPIC 12. ROAD WEATHER: GENERAL HUMAN FACTORS CONSIDERATIONS

Introduction

This topic discusses guidance for road weather messaging on DIIs and DVIs. The primary purpose of these road weather applications is to provide warnings regarding current or near-term adverse conditions that require drivers to adjust speed as opposed to providing information about forecasted conditions.[9] The weather conditions of primary interest include high winds, flooding, adverse road surface conditions, and reduced visibility. These applications would be most relevant in areas that have a history of weather-related crashes.

Design Guidance

The following design guideance is applicable when developing DIIs and DVIs with road weather messaging:

- Provide relevant weather information that conveys the nature of the weather hazard, location of the hazard, and appropriate driver responses to maintain safe vehicle operations.
- Make the decision to communicate weather information via DII or DVI with the consideration of the factors covered in table 16.

Table 16. Differences in presenting weather information via DII and DVI.

Factor	DII	DVI
Content Presentation	Messages should be primarily text on a CMS, dynamic message sign, blank-out sign, or a static sign with beacon(s).	Multimodal possible, including visual graphics, icon, or text.
Targeted Messaging	Messages should apply to vehicle classes or all road users.	Targeted messaging via DVI is appropriate; message can be suppressed if not applicable to known route.
Location Information	Message should be presented in terms that road users who are unfamiliar with the area will comprehend.	More detailed information or additional context may be provided.
Message Framing	Both warnings and prohibitions are appropriate.	Both warnings and prohibitions are appropriate; any information should be mirrored on the DII.
Advisory/Regulatory Speed	Both advisory and regulatory speeds are appropriate.	Advisory speeds appropriate; regulatory speed updates should be mirrored on the DII.

Table 17 provides examples of weather information presented via DII and DVI.

Table 17. Presenting weather information via DII and DVI.

DII Message Targeting All Road Users	DVI Message Targeting Individual User
"Flooding at US-301" "Washington DC Use Route 210"	"Flooding at US-301" "Road Closed Ahead" "Turn Left: Berry Road"

Discussion

This topic discusses guidance for road weather messaging on DIIs and DVIs. Analyses of crash data have estimated that 211,304 annual crashes may involve weather-related factors.(79)

Applications such as SWIW-RS can provide road weather information and help reduce the incidence of these crashes by warning drivers of the need to reduce speed because of hazardous road conditions. These applications are mainly intended to provide warnings regarding current or near-term adverse conditions rather than forecasted conditions.[18] The weather conditions of primary interest include high winds, flood conditions, adverse road surface conditions (e.g., ice, snow, or rain) and reduced visibility (e.g., fog or smoke).[18] These applications would be most relevant in areas that have a history of weather-related crashes, such as icy roadways or areas prone to flooding.

Road weather messaging on a DII is most likely to take place on CMSs, dynamic message signs, blank-out signs, or static signs with a dynamic element (such as a warning sign with a flashing beacon). Information presented on the CMS will likely be primarily text-based, and design guidance is available in other sources.[9,34] The road weather messaging on a DVI is able to increase the salience of the message through multimodal presentation (i.e., use multiple sensory channels to attract drivers' attention), and to filter road weather information that is not applicable to the vehicle. As V2X market saturation increases, providing coordinated information via DII and DVI will likely become of greater importance. (See Design Issues.)

In addition to these general factors, some specific factors have an effect on presenting road weather information via DII or DVI. Table 16 provided a comparison of these factors: content presentation, targeted messaging, location information, message framing, and advisory/regulatory speeds. These are discussed further in the following paragraphs.

Content Presentation: The content presentation of a message refers to how the message is formatted and displayed to the road user, such as text, icons, other graphics, or (in the case of a DVI) audio-visual presentation. Messages should be presented via DII in accordance with best practices and available guidelines.[9,34] A CMS can be an effective DII element for presenting hazard warnings regarding road weather concerning speed and headway as well as general hazard awareness.[100,101] However, DIIs are spatially fixed in the environment. Information presented should account for this fixed location and the single exposure of limited duration that drivers will have with the DII, which can be achieved by providing concise, relevant, and well-formatted information to drivers, with complementary road weather information presented via DVI or available through 511 systems or similar means.

Targeted Messaging: Messages may be targeted, meaning that they are intended for specific road users or classes of vehicles or may be applicable to all road users. Messages presented via DII are typically visible to all road users. Information presented via DII should be applicable to either all road users or classes of road users specifically identified on the DII (e.g., high crosswind advisories for trucks). The same information may be provided via DVI. If the DVI is used, then it may be to provide road weather information to all users or to target individual vehicles or classes of vehicles. This level of targeting may be particularly useful for vehicles with a known route (i.e., to suppress irrelevant updates or provide updates for a specific planned route).

Location Information: Road weather information provided via DII is visible to all road users at that location. Because drivers may not be familiar with the area, however, providing drivers with information relevant to a specific landmark, location, or route supports better driver compliance than general messages (e.g., “Fog Delays to Boston, Use Route I-295” is preferred over “Major Delays, Use Other Routes”).[9] The DVI may be used to provide more specific information. Because road weather information involves three locations (the sensor location, the DII location, and the current location of the driver/DVI), providing highly specific information for a given location is challenging.[102] Therefore, it may be necessary to convey uncertainty in weather likelihood, location, timing, and impact to drivers.[9] This uncertainty may be provided as a percentage or qualitatively (e.g., “possible”) but should avoid being inaccurate, irrelevant, obvious, repetitive, or confusing.[34]

Message Framing: Message framing refers to the type of message provided to the driver. In the case of road weather information, messages are typically framed as advise/inform (potential weather-related hazard), alert/warn (active weather-related hazard), or prohibit (road closed because of a weather event). Providing drivers with weather-related warnings and prohibitions via DIIs and DVI is appropriate. Examples of these types of information include hazardous conditions (e.g., high winds) and road closures. Presentation using both DII and DVI allows redundancy. The DVI can provide additional information in a more salient fashion (e.g., multimodal messages that combine visual notifications with auditory and/or haptic presentation); however, the message should adhere to existing design principles that stress the importance of keeping drivers’ visual attention directed to the road.[14]

Advisory and Regulatory Speeds: Presenting advisory and regulatory speeds related to adverse weather conditions is an appropriate use of a DII.[7] DIIs, especially those that resemble existing regulatory signs and devices, may be viewed as regulatory devices by drivers.[23] Presenting both advisory and regulatory information via DII (such as a CMS) can assist drivers in maintaining an appropriate speed in challenging conditions.[103] DII presentation of both advisory and regulatory speeds has demonstrated effectiveness.[104,105] Results from investigations of speed advisory systems have demonstrated safety benefits from DVI presentation of speed messages.[106] These results suggest that DVI presentation of weather-related speed notices may be effective. However, little research has examined this specific use of a speed advisory system. Regardless of presentation method, any information presented via DVI that is not vehicle-specific should be reflected on the DII as well.

Design Issues

One important aspect of road weather messaging in the CV context is the congruence between DVI and DII messages. Although both systems may provide information from the same RSE sensors, DIIs are only available at fixed locations, while DVIs are available at any driver location. DVIs may provide targeted messages, while DIIs typically present messages suitable for all road users. In addition, there may be an update delay because of the weather event message verification cycle.[18] When coupled with the fixed location of the DII, it is possible for information presented via DVI to reach the driver before information presented on a DII. This incongruence in timing could lead to driver confusion, especially if the messages give distances that reference the driver’s location or trajectory (e.g., flooding in 4 mi, 20 min delay).

This issue has been considered for providing travel time information via DII, with the ultimate recommendation that information that is highly susceptible to change or that is calculated from rapidly changing conditions should provide either a timestamp or a range that captures the potential variation in conditions.[34] As a new concept, drivers' tolerance for relatively small timing incongruencies between DII and DVI is unknown. Providing targeted messaging to vehicles or providing a measure of the certainty of the information on either DII or DVI may eliminate this concern

CHAPTER 4. SUMMARY AND CONCLUSIONS

This report is part of the HFCV research program, whose goal is to minimize driver workload by eliminating CV device-related distractions. The research described in this document is part of an effort to develop initial design guidance for V2I safety messages provided using DIIs and DVIs. Emerging CV technologies and applications have the potential to significantly improve safety on U.S. roads; however, it will take many years for CV technology to reach sufficient penetration levels in the US vehicle fleet for those benefits to be realized. In the meantime, DII displays can effectively communicate safety messages even for vehicles that do not have integrated CV applications. Thus, DII-based approaches provide an important transition to the CV future, in addition to providing additional countermeasure options to address local safety problems. The current report provides a starting point for roadway engineers and other DOT personnel considering developing and implementing infrastructure-based safety measures that include DII components.

Although there is sufficient general and application-specific research related to using DII displays to communicate safety messages to drivers, this area of investigation is still in an early stage. The current effort drew upon on the best available research information to provide initial design guidance for developing effective DIIs. Existing HFCV research, in addition to previous research from related domains, was used to develop this preliminary design guidance. A total of 12 guidelines were developed using this approach.

A clear finding throughout the report was that although there was only a limited body of research covering specific CV applications, a substantial amount of research has been conducted on intelligent infrastructure-based safety applications in general. Therefore, for most of the guideline topics, there was sufficient existing research to develop useful design guidance, typically by adapting research findings obtained from non-CV safety systems that had key operational characteristics in common with the relevant CV applications. This approach was particularly effective for the general design guidance topics presented in the first part of the document (topics 1 through 7).

The application-specific guidelines (topics 8 through 12) also contain more specific design information that relates to individual applications; however, these guidelines should generally be considered preliminary design references at the time of this publication. While every attempt was made to use the most recent information about how these systems are intended to work, their full operational specifications are still being developed. Also, it should be noted that the basic strategy for guideline development in these topics employed an opportunistic approach with regards to the specific type of guidance provided in each topic. That is, the content for each topic was largely determined by focusing on the best available research information. This enabled the inclusion of at least some design information on each topic, and for all the key systems; however, this information was not as uniform across topics. It would be valuable to identify key information gaps that currently exist across the topics, so that they could be addressed in future research. Moreover, real world implementation and evaluation information about these technologies is largely missing.

Consequently, an important avenue for future research is to investigate driver behavior and responses to infrastructure-based CV applications under more realistic driving conditions. This research would be particularly relevant if DII messages were examined in combination with other in-vehicle safety information, since this will likely represent future operating environment in a CV world. These safety systems must strike a fine balance in terms of augmenting drivers' understanding of their situation with relevant safety information, while at the same time avoiding annoying or distracting drivers with information that is unneeded, presented at the wrong time, or in conflict with other more important safety information. Examining how drivers manage infrastructure-based safety information in the context of the full range of on-road driving tasks, and the priorities that drivers assign to them, represents an important step for ensuring that these systems are developed and implemented in a way that maximizes the benefits to drivers.

In the meantime, the current document provides some of the most comprehensive and detailed design guidance for infrastructure-based CV systems. While individual guidelines discuss key design issues and the associated Human Factors considerations, they also serve as a useful starting point for users to find relevant research sources that provide more detailed information about specific topics or design issues. Importantly, the guidelines presented in this document compliment other Human Factors design references and address key information needs. In particular, the NCHRP Report 600: *Human Factors Guidelines for Road Systems* provides human factors design guidance for infrastructure, but it does not address connected infrastructure elements.(11) Similarly, the *Human Factors for Connected Vehicles Driver-Vehicle Interface Design Principles* focuses exclusively on in-vehicle safety applications, and do not cover infrastructure-based systems in detail. Thus, the current guideline document provides useful and complementary information to other recent State transportation department design documents.

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