Infrastructure Initiatives to Apply Connected- and Automated-Vehicle Technology to Roadway Departures

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FOREWORD

The overall goal of the Federal Highway Administration's (FHWA's) Roadway Departure (RwD) Program is to improve the safety of the Nation's highways through the reduction of RwD crashes. RwDs continue to account for more than half of U.S. roadway fatalities annually and nearly 40 percent of serious injuries, making such crashes a significant safety concern.

Connected vehicles and automated vehicles are complementary technologies with the potential to improve safety. The purpose of this research is to explore the role of highway infrastructure in enabling these technologies to reduce the number and severity of RwD crashes. This report identifies initiatives for FHWA and its State partners to consider and investigates how infrastructure may need to be adjusted to accommodate these technologies. This report includes a literature review on RwD crashes and conventional countermeasures. A series of Web meetings with interested stakeholders examined the gap between the state of the art of these technologies and their ultimate effective deployments. This document is intended for traffic engineers, highway designers and planners, and other transportation professionals to acquaint themselves with potential infrastructure changes that could accommodate these emerging vehicle technologies.

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16. Abstract
The Federal Highway Administration (FHWA) is investigating how emerging connected-vehicle (CV) and automated-vehicle (AV) technologies can address roadway-departure (RwD) crashes. The objective of this project was to develop a framework for FHWA regarding how the infrastructure components need to change to accommodate CV and AV technologies to help reduce the frequency and severity of RwD crashes. The project produced a list of initiatives that FHWA may use to support the deployments of CV and AV technologies in ways that will address RwD crashes. The initiatives were developed from a literature review and consultation with technology developers, vehicle manufacturers, State and local departments of transportation, infrastructure officials, and other stakeholders.

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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 AND SYMBOLS

3D	three-dimensional
AASHTO	American Association of State Highway and Transportation Officials
ADS	automated driving system
AV	automated vehicle
BSM	Basic Safety Message
Caltrans	California Department of Transportation
CSW	Curve Speed Warning
CV	connected vehicle
DSRC	dedicated short-range communication
FARS	Fatality Analysis Reporting System
FCW	Forward Collision Warning
FHWA	Federal Highway Administration
GAO	Government Accountability Office
GIS	geographic information system
GPS	Global Positioning System
HFST	high-friction surface treatment
HLDI	Highway Loss Data Institute
IHSDM	Interactive Highway Safety Design Model
ITS	Intelligent Transportation Systems
LDW	lane-departure warning
LED	light emitting diode
LiDAR	Light Detection and Ranging
LKA	lane-keeping assist
MDOT	Michigan Department of Transportation
MUTCD	*Manual on Uniform Traffic Control Devices*
NCHRP	National Cooperative Highway Research Program
NDS	Naturalistic Driving Study
NHTSA	National Highway Traffic Safety Administration
ODOT	Oregon Department of Transportation
Ohio DOT	Ohio Department of Transportation
RFID	radio-frequency identification

RSU	roadside unit
RwD	roadway departure
RWIS	Road Weather Information System
SAE	SAE International
SHRP2	second Strategic Highway Research Program
SPaT	Signal Phase and Timing
TIM	Traveler Information Message
TMC	traffic management center
USDOT	United States Department of Transportation
V2I	vehicle to infrastructure
V2V	vehicle to vehicle
V2X	vehicle to other (e.g., pedestrian)
VDOT	Virginia Department of Transportation
VTTI	Virginia Tech Transportation Institute
WTP	willingness to pay

EXECUTIVE SUMMARY

The Roadway Departure (RwD) Team at the Federal Highway Administration (FHWA) is tasked with preventing and mitigating RwD crashes—those "in which a vehicle crosses an edge line, a center line, or leaves the traveled way."[(1)] Recognizing that connected-vehicle (CV) and automated-vehicle (AV) technologies have the potential to enhance highway safety, the RwD Team is considering how these technologies can be included with the existing diverse set of RwD countermeasures. The purpose of this research is to understand how the infrastructure may need to be adjusted to accommodate these technologies.

CVs send and receive brief messages through dedicated short-range communication. Messages can be transmitted vehicle to vehicle (V2V) or vehicle to infrastructure (V2I). The messages enable various applications to enhance safety, mobility, and other goals. AVs have driving automation features that are responsible for lane keeping in at least some circumstances. An AV may receive a portion of its information through CV technology. CVs and AVs will interact with the infrastructure differently than conventional vehicles have since the earliest days of motorized transportation.

Research published in the past 3 years was examined. Applications of CV technology include warnings about curve speed, spot weather, and lane drops. Current AV systems typically use machine vision, and their performance is limited by lighting and weather conditions. Early driver-assistance systems are often deactivated by drivers due to false warnings and the systems' failures to adapt to individual drivers' habits. A vehicle's measurement of its position within the lane can be improved by several means: better lane markings, machine vision, and communication between those who place lane markings and those who engineer vision systems to detect them. Other approaches being researched include radar, improvements in satellite navigation, and detailed precision maps of the roadway.

Three Web meetings gathered input from industry, State departments of transportation, and the research community. A significant gap facing AV deployment is the lack of standardization. Pavement-marking patterns and advisory speeds can vary between and within States. V2I connectivity requires equipment on vehicles and infrastructure, posing a "chicken and egg" problem in which the two must be deployed together in a compatible fashion to be effective. Collaboration and frequent communication between infrastructure officials and developers of CVs and AVs are necessary.

FHWA is now considering research initiatives to fill the gaps identified by the research presented in this report. Some of the initiatives would assess the effectiveness of existing and future systems. Others would develop the Curve Speed Warning application to prevent vehicles from running off the roadway. Another set of initiatives would aid State and local agencies in preparing their infrastructure for CV and AV technologies. Others would improve the ability of AVs to recognize infrastructure cues. Low-priority and long-term items are included as well.

By promoting programs like those outlined here, the RwD Team at FHWA will further its goal of improving RwD safety and accelerating the deployment of CVs and AVs.

CHAPTER 1. INTRODUCTION

The Federal Highway Administration's (FHWA's) Safety Program features a roadway-departure (RwD) roadmap of activities to guide the portfolio of RwD-related research. FHWA's RwD Program focused on how connected-vehicle (CV) and automated-vehicle (AV) technologies can be considered alongside the diverse set of safety countermeasures developed to prevent and mitigate RwD crashes.

This project produced a framework in which FHWA can consider adjustments to the RwD roadmap. The framework includes recommendations on how the RwD Program can support the CV and vehicle-to-infrastructure (V2I) programs and how the RwD Program's focus may need to be adjusted to address these changes in the vehicles and infrastructure. This report describes activities that FHWA may undertake to prioritize RwD research activities for CV and AV safety issues. FHWA's RwD Team will use this information to support the CV and V2I programs and to adjust the RwD Program's focus to address these anticipated changes in the vehicles and infrastructure. The scope of this project is limited to light vehicles.

This document is organized into five chapters. Following this introductory chapter, chapter 2 is the literature review, which focuses on synthesizing information on the capability of CV and AV technologies to address RwD crashes. The review documents existing practices and knowledge on the topic from academic research, government studies, and national and international agency reports that were published after 2012 and are applicable to light vehicles. Chapter 3 presents the needs assessment, which addresses the gap between the state of the art of these technologies and their ultimate effective deployment. The needs assessment was conducted by organizing three Web meetings with CV and AV researchers and developers, vehicle manufacturers, State and local transportation departments and infrastructure officials. Chapter 4 discusses implementation of the research plan. It is a list of projects or initiatives that FHWA can consider as it endeavors to reduce the frequency and severity of RwD crashes through CV and AV technologies. The initiatives were identified through the findings of the literature review and the needs assessment. Finally, chapter 5 summarizes the overall findings of the project and presents concluding remarks.

BACKGROUND

CV and AV technologies have the potential to enhance highway safety by providing drivers with precise vehicle control and restoring appropriate driver attention to traffic and roadway conditions. CV technologies use dedicated short-range communication (DSRC) messages, vehicle-to-vehicle (V2V) communication, and V2I communication to provide drivers with timely safety information and warnings. AVs assist the driver or take full control of the driving task depending on the degree of their automation. Various levels of AVs have been defined—from the lowest level with simple cruise control, all the way up to vehicles with full driving automation. Such technologies can have a tremendous effect on the reduction of RwD crashes.

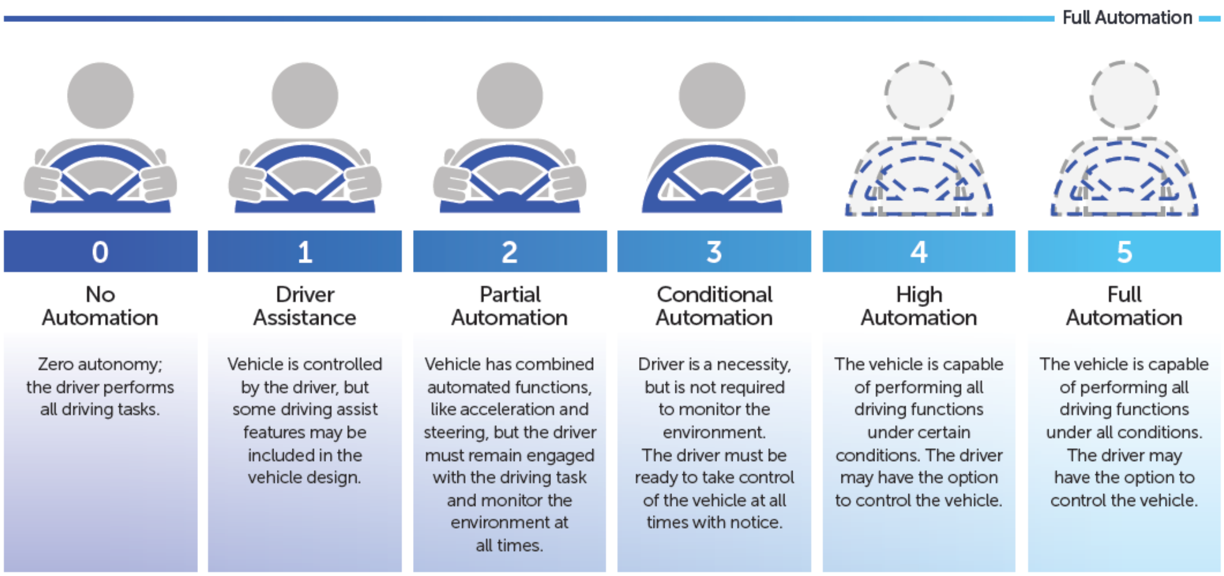
As the vehicle fleet transitions to include a greater percentage of these CV and AV technologies, it is important to understand how the infrastructure and safety countermeasures must adjust to these changes (e.g., rumble strips will become less important, while additional system striping may be needed). This project explores new and emerging technologies to determine which have the most potential benefits in reducing RwD crashes, how the RwD Program can support the CV and AV programs, and how the RwD Program's focus may need to readjust to address these changes in the vehicles and infrastructure.

DEFINITIONS

An RwD is a "crash in which a vehicle crosses an edge line, a center line, or leaves the traveled way."(1) As opposed to intentional lane-changing, merging, and diverging maneuvers, RwD refers to the unintentional departure or drift from a traveled lane.

CVs use wireless communication technologies to exchange mobility and safety information with other vehicles on the road (V2V), roadside infrastructure (V2I), and other features (vehicle to other (V2X), as in vehicle to pedestrian). The concept of CV technology is supported by DSRC. Using DSRC, equipped vehicles broadcast and receive mobility and safety messages (e.g., basic state information (location, speed, and acceleration), traffic signal status, and spot weather conditions).

The National Highway Traffic Safety Administration's (NHTSA's) *Automated Driving Systems 2.0: A Vision for Safety* adopted the SAE International (SAE) definitions for levels of automation.(2) The SAE definitions divide vehicles into levels based on "who does what, when."(3) *A Vision for Safety*, on page 4, summarizes the SAE Levels as shown in figure 1.(2)



Source: NHTSA.

Figure 1. Graphic. SAE automation levels range from 0 (no automation) to 5 (full automation).(2)

A Vision for Safety focuses on vehicles that incorporate SAE Automation Levels 3 through 5, or those with automated driving systems (ADSs). Page 2 reads, "ADSs may include systems for which there is no human driver or for which the human driver can give control to the ADS and would not be expected to perform any driving-related tasks for a period of time."(2)

A vehicle that receives messages from the infrastructure and has a human driver fully in control is a CV, not an AV. A vehicle operating at Level 1 or higher without any V2I or V2V communication is an AV, not a CV. A vehicle operating at Level 1 or higher that receives information about other vehicles or about the infrastructure via DSRC is both a CV and an AV; it is connected and automated.

PROJECT SCOPE

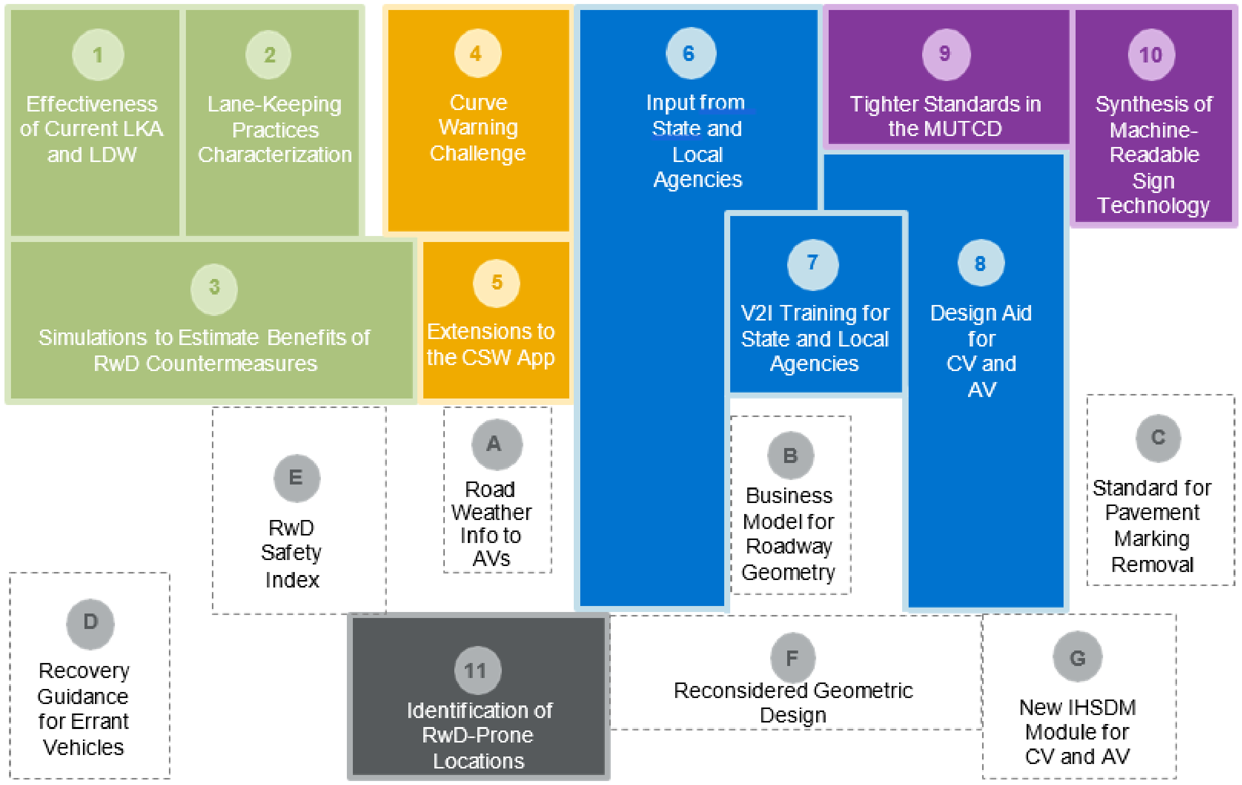
This project dealt with RwD crashes, specifically countermeasures that used CV or AV technology. It focused on FHWA, its partners at State and local transportation departments, and the highway infrastructure owned and operated by State and local entities. The study was limited to light vehicles, but some of its findings applied to heavy vehicles as well.

This study generated 11 initiatives for consideration. Most of the initiatives and their implementation plans focus on how FHWA's RwD Program can benefit from the technical aspects of CV and AV technologies and how the infrastructure and standard practices of highway engineering can be modified to accommodate these technologies. Other initiatives focus on preparing State and local transportation department staffs to acquire the necessary skills to embrace these emerging technologies.

All the initiatives are either unique to RwDs or focus on an RwD element of a larger effort. The tasks focus on manageably sized initiatives that can produce results in the near term. Most of the items on this list can be accomplished in 1 to 2 years. The initiatives span a breadth of technical, outreach, and economic content. They address CVs, AVs, and AVs with CV support.

OVERVIEW OF THE RESEARCH IMPLEMENTATION PLAN

The 11 major initiatives and 7 supplemental ideas recommended in chapter 4 complement one another and fall in a loose sequence. Figure 2 graphically shows the relationships between them. The regions with solid outlines represent the 11 major initiatives. The regions with dotted outlines represent the supplemental ideas that may come later or support the major initiatives. The colors indicate how the initiatives can be grouped. Regions that touch each other show relationships between initiatives.



Source: FHWA.
LKA = lane-keeping assist; LDW = lane-departure warning; CSW = Curve Speed Warning; MUTCD = *Manual on Uniform Traffic Control Devices*;[(4)] IHDSM = Interactive Highway Safety Design Model.

Figure 2. Graphic. Recommended research topics are a diverse yet cohesive approach to improving RwD safety.

One of the criteria for selecting the 11 main initiatives was that they could begin in the near term, and most of them could. Figure 2 is arranged so that short-term projects appear at the top and long-term projects appear at the bottom.

Initiatives 1, 2, and 3 (the green regions) would analyze existing data to produce a basic understanding of driver performance and RwD countermeasure systems. The top two (initiatives 1 and 2) characterize the current status of driver lane-keeping practices under naturalistic conditions and the effectiveness of existing RwD countermeasures, respectively. These two initiatives would lead to simulations of existing and new countermeasure systems to predict their effectiveness. The simulations would benefit from input from the Curve Warning Challenge, and they would guide extensions to the Curve Speed Warning (CSW) application. Initiatives 4 and 5 (yellow) aim to enhance the CV CSW application. One would encourage States to deploy the application at a curve, and the other would enhance the application's capability in the long term. Initiatives 6, 7, and 8 (blue) call for communication with State agencies, seeking their input as key stakeholders and providing resources for them. Initiatives 9 and 10 (purple) are for improving the process of getting infrastructure information to a vehicle by means other than CV technology.

The lower levels in the graphic are long-term benefits for highway departments. They include ways to predict the RwD safety of geometric designs from simulations and passing vehicles, which could lead to new guidance for geometric designs and associated pavement markings and eventually a new Interactive Highway Safety Design Model (IHSDM) module to build a road suited for CVs and AVs.

CHAPTER 2. LITERATURE REVIEW

The literature review and technology scan evaluated technologies for their maturity and suitability to support RwD-related applications. Attention was given to emerging technologies in the fields of vehicle automation, CVs, and AVs with a specific focus on RwD crashes and their severity. Because this is a highly researched field, the literature review was limited mostly to post-2012 publications applicable to light vehicles. Relevant studies in naturalistic driving settings, pilot projects, and simulations were reviewed. The discussion centers on RwD crashes and how they could be reduced with emerging technologies.

CONTEXT

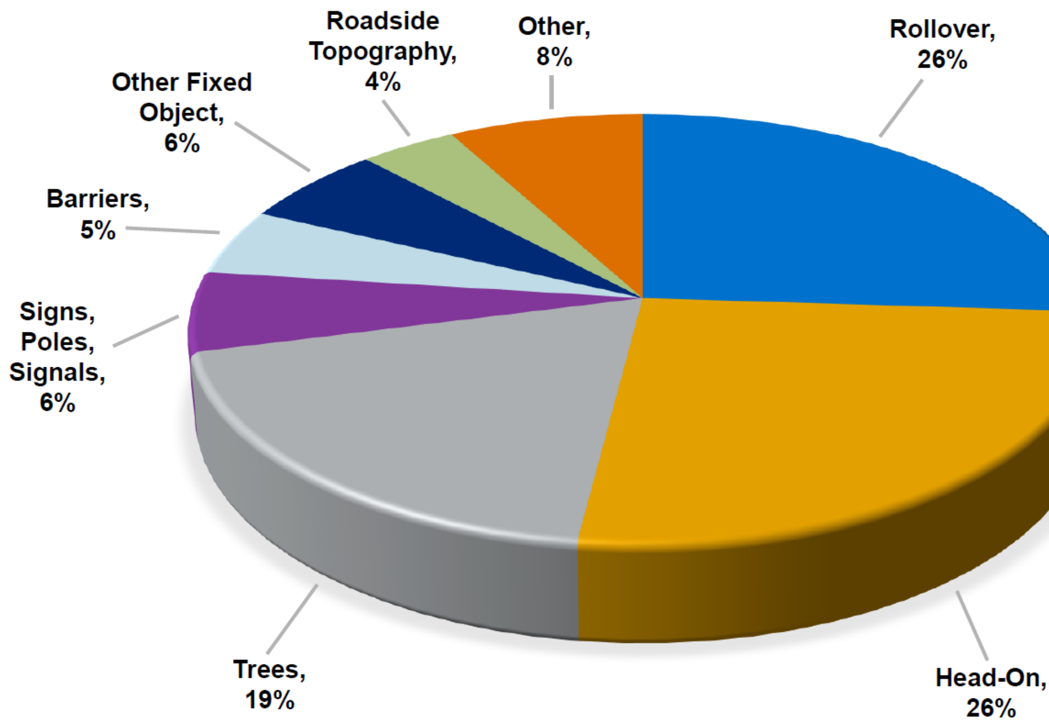
This chapter begins with an overview of RwD crashes, discusses the issue's criticality, and summarizes FHWA's strategy for preventing or reducing such crashes. RwD-crash statistics are presented, followed by a discussion of factors that cause RwD crashes. The discussion then proceeds to remedies that use CVs, AVs, and other enhanced infrastructure technologies and their implications for RwD-crash prevention and mitigation. Finally, the efforts of State transportation departments and other infrastructure stakeholders to promote CV and AV technologies are evaluated.

RwD-Crash Statistics

Roadway crashes are an epidemic considering the number of fatalities and injuries suffered as a result of surface transportation.(5) An international study on high-income countries that analyzed the social costs of these crashes showed that these costs range from 0.5 to 6.0 percent of their gross domestic product with an average of 2.7 percent.(6)

There were 37,461 crash fatalities on U.S. roadways during 2016.(7) FHWA's study of the Fatality Analysis Reporting System (FARS) database showed that RwD crashes accounted for more than half (53 percent) of all highway fatalities in 2016 (i.e., out of 37,461 deaths, approximately 19,676 were attributed to RwD crashes). Between 2014 and 2016, an average of 17,002 fatal RwD crashes occurred annually.

Figure 3 shows the breakdown of the RwD fatalities by the most harmful event of the crash based on an FHWA study of data in the FARS database from 2013 to 2015. Rollovers and head-on crashes each account for 26 percent of total RwD-crash fatalities. Impacts with roadside trees are responsible for 19 percent of RwD fatalities. Given these statistics, FHWA's RwD strategic plan provides a primary focus on addressing rollovers, head-on crashes, and roadside tree crashes and a secondary focus on signs, poles, signals, fixed objects, barriers, and roadside topography.(8)



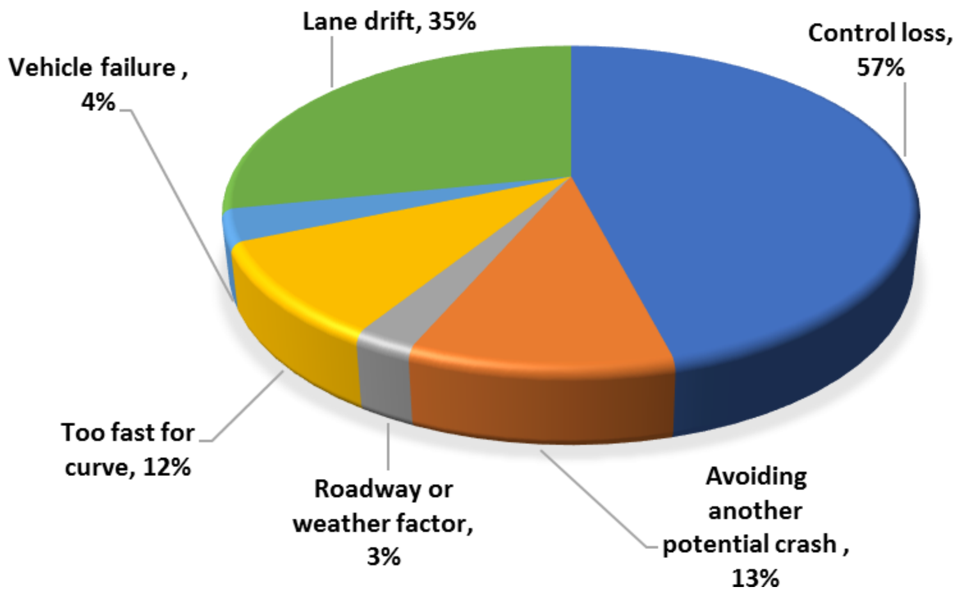
Source: FHWA.

Figure 3. Pie chart. Proportion of RwD fatalities by most harmful event of the crash.

It is important to make the distinction between crashes caused by intentional and unintentional lane departures. "Intentional lane departure" refers to the deliberate departure from a traveled lane due to a lane change. On the other hand, "unintentional departure" refers to the drifting of a vehicle from its traveled lane or road without a deliberate action by the driver. Citing prior U.S. Department of Transportation (USDOT) studies, Lee et al. reported that crashes that occurred when a driver was in the process of maneuvering the vehicle laterally from one lane into another accounted for 4 to 10 percent of all crashes and 0.5 to 1.5 percent of all motor vehicle fatalities.(9) These crash and fatality statistics are relatively small compared to the number of crashes and fatalities due to unintentional lane departures.

Factors Contributing to RwD Crashes

RwD crashes are caused by a variety of factors. A recent study by Cicchino and Zuby on factors leading to unintentional lane departures showed that the most common are loss of control, lane drift, avoiding another crash, speed too fast for curves, vehicle failure, and adverse road or weather conditions.(10) Figure 4 shows the breakdown of crashes resulting from unintentional lane departures according to that study. The least common reasons are mechanical failure and road weather conditions. The driver, by action or inaction, is responsible for the majority of RwD crashes. This presents CV and AV technologies with an opportunity to improve highway safety by assisting the human with the driving task.



Source: FHWA.

Figure 4. Pie chart. Most causes of passenger-car unintentional lane departures are driver actions or inactions.

Another study focused on identifying factors that contribute to RwD crashes using the United States Road Assessment Program dataset and road geometric features. This study found that the main contributing factors to RwD crashes were roadside severity, horizontal curvature, and shoulder width.(11) "Roadside severity" refers to the nature of and distance to the nearest roadside object that could injure vehicle occupants fatally or seriously.

Hallmark et al. provided a comprehensive review of factors that contribute to the occurrence and severity of RwD crashes.(12) These factors included flaws in geometric design of roads such as narrow lanes, narrow or absent shoulders, and substandard curves; driving too fast for conditions; attempting to avoid vehicles, debris, or animals; weather conditions that adversely affect road visibility and friction; distracted driving; impairment due to fatigue, sleep, or drugs; and others. The authors grouped these factors into four categories: roadway, environmental, vehicle, and driver.

Departing the traveled lane or road while negotiating a curve is another major factor of crashes. Torbic et al. reported that the crash rate for horizontal curves is approximately 3 times that of tangent sections, and about 76 percent of curve-related crashes were single-vehicle RwD crashes.(13) Hallmark et al. reviewed the literature and developed a toolbox of countermeasures for RwD crashes on horizontal curves.(14) The report highlighted that 25 to 50 percent of severe RwD crashes in Minnesota occurred on curves, though curves account for only 10 percent of the highway miles.

Goals of the FHWA RwD Team

In an attempt to reduce the occurrence of RwD crashes, the FHWA RwD Team developed a strategic plan to provide a common vision for research, policy, and implementation.(8) The plan describes the significance of RwD crashes, outlines the nature of the problem, and provides potential countermeasures. The vision of the strategic plan is to "pursue a proactive approach that will lead Toward Zero Deaths and serious injuries involving roadway departure events." FHWA seeks to accomplish this vision by deploying countermeasures that decrease the risk of RwD and promoting data-driven applications for safety treatments. The overall goal of the strategic plan is to reduce RwD fatalities by a minimum of 500 annually and reach the target of fewer than 8,500 RwD fatalities annually (a 50-percent reduction of the current rate) by 2030.

The goal of the FHWA's RwD Team is to actively develop and implement strategies for reducing RwD crashes and their severity. The RwD Team prioritizes its efforts with the following three objectives:(8)

- Keep vehicles on the roadway and in their appropriate directional lane.
- Reduce the potential for crashes when vehicles do leave the roadway or cross into opposing traffic lanes.
- Minimize the severity of crashes that do occur.

FHWA provided technical support to the Toward Zero Deaths initiative, through which a number of national transportation associations have produced a national strategy on highway safety.(15)

EXISTING COUNTERMEASURES

The countermeasures are systematically organized into current RwD countermeasures and the emerging technologies for reducing RwD crashes and their severity. The effectiveness and maturity of these technologies are presented, and their implications for RwD are discussed. The articles presented in this section are reviewed considering the advantages and limitations of existing technologies. In addition, this section presents how an FHWA initiative that includes a partnership with States and municipalities can help overcome limitations of emerging technologies.

Conventional RwD Countermeasures

This section lists conventional solutions and then proceeds to describe the literature on CV and AV technologies. CV and AV technologies may mimic, complement, or extend the capabilities of conventional approaches. For example, installing warning signs has been proven to have a significant effect on the reduction of curve-related crashes. Guardrails (longitudinal barriers) can reduce the severity of RwD crashes.

Several conventional countermeasures for RwD crashes have been identified by the American Association of State Highway and Transportation Officials (AASHTO).(16) Similarly, a team with a mission of scanning successful conventional engineering solutions to RwD crashes across several States identified the following countermeasures:(17)

- Shoulder rumble strips.
- Center line rumble strips.
- Edge line rumble strips.

- Safety Edge^SM.
- Paved shoulder widening.
- Edge line pavement markings.
- Pavement markings at curves.
- Additional signage, especially at horizontal curves.
- Dynamic signage (e.g., speed feedback).
- Cable median barriers.
- Removal of frequently hit objects.

There are typically three approaches to consider in reducing RwD crashes. The following approaches may be implemented alone or in combination:[18,19]

- *Systemic approach* considers the application of countermeasures that support crash reduction over a wide road network or number of sites that share a high risk factor for RwD crashes based on factors such as lane width, speed, traffic volume, road friction, horizontal curvature, and traffic control devices. Such an approach typically considers the application of conventional treatments to all segments of roadway or entire routes that share a specific risk factor.

- *Spot approach* focuses on reducing RwD crashes at a specified spot that has a high number of RwD crashes. Such treatment approaches account for locations that may not be addressed through the systemic approach (e.g., deteriorated pavement surface and poor geometric design such as sharp horizontal curves). Such locations require special treatments involving moderate- to higher-cost improvements (e.g., pavement rehabilitation and application of high-friction surface treatments (HFSTs)).

- *Comprehensive approach* intends to counteract those RwD crashes that cannot be addressed by systemic and spot approaches. This approach focuses on the concept of the four Es of safety: Engineering, Enforcement, Education, and Emergency medical services. In addition to infrastructure improvements, this approach attempts to promote safe driving behavior by addressing human factors issues such as speeding, impaired driving, distracted driving, seatbelt use, and enforcement.

Recently, the American Traffic Safety Services Association and Jalayer et al. provided an overview of safety countermeasures for RwD crashes based upon a comprehensive literature review and input from State and local agencies.[20,21] The objective of their work was to provide transportation practitioners with an understanding of the infrastructure-based, conventional RwD-crash countermeasures' effectiveness. The RwD safety countermeasures were classified into three categories: signs, pavement safety, and roadway design. Jalayer and Zhou reviewed conventional sign and pavement treatments to improve RwD safety.[22]

Signs

Signs inform drivers of horizontal curves and advisable speeds. Sign-based RwD countermeasures include chevrons, dynamic curve-warning systems, and advanced curve warning and advisory speed signs, as shown in figure 5. Installation of advisory speed signs and oversized chevrons at curves was found to yield greater benefits compared to sites without advisory speed signs.[23] Veneziano and Knapp provided guidelines for effective use of signs for horizontal road alignment and related warnings.[24]

Source: FHWA.

Figure 5. Photo. Arrow signs and chevrons can be used separately or in combination.[25]

Pavement Safety

Pavement-safety countermeasures focus on treatments to the pavement surface that increase friction between the tire and pavement surface, enhance visibility, and improve quality and depth of edge dropoffs so that a vehicle is stable and easily recoverable after encountering a dropoff. Pavement-based RwD countermeasures include HFSTs, raised pavement markers, edge line pavement markings, center line and shoulder rumble strips (figure 6-A), and the Safety Edge^{SM} (figure 6-B).

Source: FHWA.

A. Shoulder and center line rumble strips alert drivers to a drift.(26)

Source: FHWA.

B. Safety Edge^{SM} aids drivers in returning to pavement.(27)

Figure 6. Photos. Pavement treatments to improve RwD safety.

Roadway Design

Roadway-design countermeasures focus on designing better and more forgiving roadways, which include cable barriers, guardrails, shoulder widening, breakaway supports for signs and lighting, and improvements to the clear zones. The results of the study by Jalayer et al. identified pavement safety (i.e., rumble strips, etc.) as the most effective countermeasure for reducing total RwD-crash frequency and severity.(21)

Addressing RwD Through AVs

Although the conventional RwD countermeasures have been effective, the frequency and severity of RwD crashes can be further reduced by taking advantage of emerging AV technology. Most of the automated features in the current vehicle fleet are at Levels 1 and 2.(28) Functions at Levels 3 through 5 are almost all currently in the research and development stage.

Rau et al. developed a methodology to determine the target crash population that could be addressed by different levels of automation.(29) Their work was focused on identifying the target crash populations for each function and level of vehicle automation, estimating the overlaps of the target crashes among the different functions of vehicle automation, and accounting for incremental target crashes between the lowest and highest automation levels. The authors did so by mapping the functions of the automation to two comprehensive crash databases, the General Estimates System and FARS, by correlating the automation levels with key crash characteristics like crash locations, precrash scenarios, driving conditions, travel speeds, and driver conditions. Their results suggested that all levels and functions of vehicle automation have the potential to counteract RwD crashes on high-speed roads in all driving conditions. They also found that vehicle automation can address driver errors, such as recognition errors, decision errors, and erratic actions, that contribute to RwD crashes.

Predecessors to Automated Lane Keeping

Systems that warn the driver of a situation or that momentarily intervene are not automated; they are Level 0 in the SAE definitions. Even so, these systems, like automated systems, need to obtain information, particularly a vehicle’s location in a lane. Because these Level-0 systems are more widely deployed, they are a source of real-world experience in the needs of automated lane-keeping systems.

Lane-departure warning (LDW) is a driver-assistance system that provides warning to a driver whose vehicle is in danger of departing its lane. Lane-keeping assist (LKA) applies a momentary corrective torque to the steering wheel or differential braking to bring the vehicle back to its lane when it begins to depart.(30)

Driver actions and inactions contribute to a significant proportion of RwD crashes.(10) Therefore, driver-assistance systems that assist in reducing the demand of the driving task might greatly reduce crashes and mitigate their severity.

Lane-Departure Systems

Kusano et al. examined the potential of LDW systems to reduce occupant injury levels in single-vehicle crashes in the United States.(31) Their study was based on reconstruction of crashes and a comparison of the crash outcomes under two scenarios (i.e., as it occurred and as if the vehicles were equipped with LDW systems). The study found that the system could potentially prevent about 30 percent of all RwD crashes caused by a vehicle drifting out of its traveled lane. This is equivalent to a 25-percent reduction in seriously injured drivers. The study recommended modification of highway systems by expanding shoulders and regularly painting lane markings so that the benefits of the system are maximized.

Reports on field operational tests of LDW systems highlighted that the use of LDW systems has long-term benefits such as positively affecting the lane-keeping behaviors of drivers.(32,33) The studies reported that these systems resulted in improved lane keeping, fewer lane departures, and increased turn-signal use by drivers.

Cades et al. studied the performance of drivers with and without LDW systems.(34) Human subjects were asked to perform mental math as a distraction to their driving on a closed course. LDW systems did not affect the variation in the study's vehicle-control metrics. The study suggested that LDW systems may not fully compensate for the effects of a secondary task on vehicle control.

A system that expanded lateral driver-assistance systems, like LKA, was discussed by Lattke et al.(35) Their road departure–protection system did not depend on lane markings only but rather considered roadside curbs, guardrails, barrels, dividers, and road-surface edges (the transition from road surface to grass or gravel) to estimate the road alignment. The system detected the road course and lane markings and then detected possible lane departure or RwD. If departure was detected, the system monitored driver intentions, and if the departure was unintentional, then the kinematic and dynamic controls were applied to avoid the departure. In case the vehicle could not be brought back onto the road within the system's operational constraints, the system attempted to align the vehicle with the roadway so that the severity of the RwD was minimized.

A recent study by Cicchino and Zuby reported that 34 percent of drivers who were involved in a crash because they drifted from their lanes were sleeping or otherwise incapacitated.(10) The authors concluded that systems that provide only transient corrective actions to counteract lane drifting may not necessarily prevent crashes when drivers are sleep impaired and thus could be exposed to other higher-risk crashes when they try to regain control. The authors concluded that LKA systems may need to be combined with other in-vehicle driver-monitoring systems to identify incapacitated drivers and safely remove them from the road.

Estimated Benefits of Lane-Departure Systems

New vehicles are increasingly adopting advanced driver-assistance systems, such as lane-departure systems, that have the potential to decrease the likelihood of crashes and their severity by addressing human error and distracted driving.(36,37) Kockelman and Li estimated the safety benefits of advanced driver-assistance systems in terms of the savings due to crash avoidance and moderation of crash severities.(38) They valued the annual economic cost savings from driver-assistance systems that are relevant to RwD crashes to be in the range of $6.6 to $12 billion.

Lane-departure systems have the potential to prevent or mitigate 483,000 crashes per year, including 87,000 nonfatal injury crashes and 10,345 fatal crashes.(39) This represents about 8 percent of all crashes and 30 percent of all road fatalities in the Unites States. Such systems were found to be the most relevant technological intervention in reducing the most fatal crashes.(39,36) Similar statistics have also been reported by Jermakian.(40) Harper et al. estimated LDW systems to have an upper benefit of about $42 billion as the technologies become more effective and widespread.(36) Lateral driver-assistance systems (i.e., lane-departure and lane-change assistants) have the potential to decrease the number of crashes in the European Union by 14,000, assuming a 7-percent penetration rate in 2020.(41)

Gordon et al. suggested that LDW systems have a potential to reduce 47 percent of all lane departure–related crashes, which corresponds to a reduction of about 85,000 crashes annually.(42) Another study by Kusano and Gabler, which had the objective of estimating the expected number of crashes and injuries that could be prevented assuming all vehicles were equipped with lane-departure systems, found that 11 to 23 percent of RwD crashes and 13 to 22 percent of driver fatalities could have been prevented.(43)

The systems that prevent lane departure in Level-2 vehicle automation appear to significantly contribute to the reduction of RwD and other crashes. Analysis of mileage and crash data of two car models in the years 2014 through 2016 revealed that the crash rate of those models dropped by almost 40 percent after a steering-assistance system was installed. The system used information from forward-looking cameras, radar sensors, and ultrasonic sensors to detect lane markings and vehicles ahead to keep the car in its lane via an automated lane-centering steering control.(44)

A simulation study by Katzourakis et al. examined two systems' effectiveness in avoiding RwD crashes in emergency scenarios. The simpler system had haptic feedback and steering torque such that the human and the machine carried out the maneuver cooperatively. The second system, which corrected the front-wheel angle, overriding the steering-wheel input provided by the human, proved more effective in preventing RwDs.(45)

Another simulation study by Scanlon et al. attempted to evaluate the effectiveness of LDW and LKA systems in preventing RwD crashes, assuming all vehicles in RwD crashes in the U.S. fleet were equipped with either system.(46) The study found that LDW systems can reduce RwD-crash frequency by 26.1 percent and serious injuries by 20.7 percent. LKA systems were predicted to reduce the frequency of RwD crashes by 32.7 percent for the lowest four levels of intervention and by 51.0 percent for the highest level. The reduction in seriously injured drivers ranged from 26.1 to 45.9 percent. The baseline case had neither LDW nor LKA systems.

Effectiveness of Lane-Departure Systems

Though many studies have shown that lane-departure systems are beneficial, their practical effectiveness is not as great as their expected benefits. The most important reason for the lower effectiveness of such systems is the difficulty of correctly detecting lane markings. Lane markings must be identified in a noisy environment. The markings can be obscured by parked and moving vehicles or shadows from utility poles, trees, buildings, vehicles, and other objects. Also, sharp curves, irregular lane shapes, and merging lanes; writing and other markings on the road; unusual pavement materials; and poor lighting can make markings difficult to recognize. The markings themselves may be of poor quality. A recent review of lane-detection technologies suggested that more work needs to be done on developing better algorithms for detection of lane markings on straight and curved roads so that the algorithms are robust enough under different weather conditions.(47)

Kusano and Gabler evaluated the relevance of the LDW confirmation test to real-world RwD crashes.(48) The study was based on supplemental crash reconstructions of 890 RwD crashes from the National Automotive Sampling System. The results found that the system's confirmation test captures many of the conditions observed in real-world RwDs (e.g., the median speed of the vehicle at the time of the lane-departure crash was about 49 miles per hour, which is close to the 45 miles per hour specified in the test). However, there were some aspects of real-world RwDs not included in the test (e.g., the confirmation test is performed in daylight, while nearly half of all RwD crashes occur in the dark), and the confirmation test is only performed on straight road segments, while more than half of real-world departures occur on curves. In addition, the lateral departure speed specified in the confirmation test is 1.1 miles per hour, whereas the mean lateral departure speed of the real-world crashes was 9.5 miles per hour. The authors suggested that the design of future performance tests should be more representative of the real-world crashes.

The Highway Loss Data Institute (HLDI) analyzed insurance claim frequency of vehicles equipped with driver-assistance systems and found LDW systems to be ineffective at reducing the number of collisions.(49) The authors surmised that drivers are tempted to tune out the warning or completely turn off the system because they are getting too many false alarms. HLDI suggested that LKA systems that actively keep a vehicle in its lane without depending on the driver's response may be more effective than a mere warning. A similar study that was based on regression analysis of insurance claim data for vehicles equipped with advanced driver-assistance systems found that LDW systems were associated with increases in the number of damage and first-party injury claims.(37) Its analysis showed higher claims for two models equipped with LDW systems and an insignificant claim reduction for a third model. It suggested that the expected benefits of LDW systems may be overrated in the literature.

Driver Acceptance of Lane-Departure Systems

Partly because lane-detection systems suffer from many false alarms, driver acceptance of the systems is poor.

A recent study on activation rates (i.e., whether turned on or off) of LDW and Forward Collision Warning (FCW) systems at one manufacturer's dealership service centers revealed that the activation rate for FCW systems was much higher than that of LDW systems.(50) Of the 265 vehicles observed to have both systems, only 33 percent had the LDW system turned on, while all except one had the FCW system turned on.

A similar study revealed the experience of drivers of another make with FCW and LKA systems.(51) In this study, 88 percent of drivers drove with the FCW system turned on, while only 13 percent of the drivers turned on the LKA systems. Likewise, 46 percent of the respondents indicated that they sometimes used the LKA system, 29 percent of the respondents indicated they rarely used the system, and 12 percent never used it at all. Such low use of LKA systems could be due to LKA systems being turned off by default. In all, 71 percent of the drivers who owned vehicles with LKA systems before indicated they are less likely to have LKA systems activated again.

A study by Eichelberger and McCartt on the experience of drivers of a model with crash-avoidance systems reported that 59 percent of drivers left the LDW system activated, whereas more than 80 percent left the FCW system activated.(52) This higher percentage of drivers leaving LDW systems activated could be because this system is on by default.

The high rate of false alarms adversely affects acceptance of LKA systems.(53) In their study, 27 percent of survey respondents thought they received a false alarm from the LKA system on at least one occasion when they did not drift out of their lane. This happened in situations when there were old markings or stains on the road (43 percent); pavement markings other than lane markings, such as crosswalks (32 percent); exits, splits, and merges (29 percent); missing or unclear lane markings (14 percent); heavy rain or snow (11 percent); driving on curves (11 percent); shadows or brightness contrast (7 percent); and work zones (4 percent). On the other hand, 25 percent of drivers who used LKA reported that the system should have provided a warning but did not. This happened in situations when there were missing or unclear lane markings, inclement weather, and low-speed travels. The most frequent complaints about the LKA system were that it does not work consistently (21 percent) and is too sensitive (7 percent).

Despite these complaints, drivers perceive that lane-departure systems are useful. Drivers who used such systems reported that the systems have prevented them from crashing into a vehicle in another lane (4 percent) or running off the road (34 percent).(51) Recent studies by Navarro et al. on the effect of false warnings on full or partial lane-departure events revealed that even less reliable LDW assistance can be beneficial.(53,54) Imperfect LDW systems (i.e., systems with many false warnings and missed warnings) are able to significantly improve driving performance in terms of lane-keeping compared to no LDW systems at all. However, full lane-departure and highly unreliable warnings reduced assistance efficiency, and drivers tended not to trust the system.

Lane-Marking Recognition

While lane-detection and -tracking techniques have been used in LKA systems, little attention has been given to the development of lane marking–recognition systems and incorporating them with LKA systems. Lane marking–recognition systems acknowledge the color (white and yellow), shape (solid and dashed), and type (center, edge, lane, channelizing, merge, diverge, single, double, work zone, and permanent lines) of lane markings so that LKA systems fully understand the information that lane markings are intended to provide.

Sensors for lane-departure applications can be passive or active.(50) A video camera with a machine-vision system is a passive sensor. It responds to light from other sources. Passive sensors are useful for lane and vehicle detection, but their functionality depends on illumination conditions and is affected by high variation in the shape of vehicles and cluttered environments. On the other hand, active sensors transmit energy and respond to its reflection from surrounding objects. Radar and Light Detection and Ranging (LiDAR) are active sensors. Both are useful for vehicle distance and speed estimation and are functional in more conditions.

To decrease the false-positive rate of lane departures, lane marking–detection methods that used the direction of travel of the vehicle to enhance an initial lane-marking detection were proposed by Sao and Rajkamar.(55) The notion of this approach is that truly detected lane markings should be oriented to the direction of the travel; otherwise, lane detections are deemed false positives. This approach demonstrated a decrease of false positives by almost 90 percent. Similarly, to address the challenges of variation in lane structure, noise, and complex illumination, Nan et al. proposed a lane-detection algorithm that incorporates prior spatial–temporal knowledge of the lane markings and their appearances.(56) Their results indicated that this approach had a precision close to 100 percent. Such methods have the potential to decrease the processing time for lane detection. Huang et al. proposed lane-marking detection based on adaptive threshold segmentation with prior knowledge of the level of clutter on the road surface and the special geometrical features of lane markings, which provided a more accurate extracting of lane characteristics.(57) Incorporating prior information on the road geometry and lane-marking features can improve both the processing time and accuracy of LKA systems. Joo et al. have discussed lane-departure detection based on geographic information systems (GISs) and enhanced Global Positioning Systems (GPSs), which are called Differential GPSs and have a location accuracy of inches.(58)

The consequences of lane departures vary depending on the type of lane marking that was crossed. For example, the severity of crashes caused by departing a yellow, double, solid line that marks different travel directions is higher than the severity of crashes caused by departing a white, single, broken line. Accounting for such information in LKA systems would greatly benefit their performance. A study by de Paula and Jung focused on the real-time detection and recognition of lane markings by using onboard vehicular cameras in a fully automatic manner and using feature extraction and classification techniques.(59) Similarly, Rodríguez-Garavito et al. applied computer vision to recognize and classify lane markings.(60) A recent study by Lu aimed at incorporating the lane-detection and -tracking systems into lane marking–recognition systems for ADS applications.(61) The experimental work was conducted on highways and urban roads in Ottawa, Canada, and the system had an average accuracy of 95.9 percent for detecting lanes and 93.1 percent for recognizing lane markings. Recently, Hoang et al. developed a lane-detection system that can discriminate between dashed and solid lane markings using visible-light camera sensors.(62) Their system was tested with the Caltech open database, and the results outperformed the conventional methods of lane detection.(63)

A related area of research that is getting considerable attention is the detection and recognition of road signs painted on the pavement surface (e.g., arrows, turn-only lane signs, speed limits).[64,65] Incorporating such systems with LKA can be beneficial, particularly in urban-area driving.

To understand the effect of pavement-marking characteristics on the performance of machine-vision systems used in AVs, Davies has been conducting a study on suitability of width, color, and retroreflectivity of pavement markings under dry and wet conditions.[66] Though the study is ongoing, the preliminary findings indicate that the suitable range of machine vision is 30 to 40 feet, higher levels of retroreflectivity increase detection rates by the machine vision, white pavement markings are relatively easier to detect compared with yellow markings, wider pavement markings (6 inches wide) are detected better than narrow markings (4 inches wide), and wetness severely reduces the detection of lane markings by machine vision.

Several researchers have worked on improving the methodology used for detecting lane markings in LKA systems (i.e., enhancing the speed and accuracy of the system). For example, Bhujbal and Narote developed an LDW system based on the Hough transform and Euclidian distance.[67] Xu et al. developed an algorithm for lane detection and tracking using vanishing points and particle filters.[68] Mammeri et al. examined various algorithms and outlined their advantages and disadvantages.[69] Kalaki and Safabakhsh applied lane-matching mechanisms to detect current and adjacent lanes to facilitate obstacle avoidance for ADSs.[70] Yang et al. developed a lane-detection algorithm based on classification of the geometrical features of lanes, which can overcome the problem of lane detection under uneven lighting conditions.[71] Kawamura et al. developed a lane-support system using radio-frequency identification (RFID) tags that contain lane information buried under the road surface.[72] Davis and Donath developed a sensor platform that is useful for producing high-accuracy maps (with position accuracy of less than 4 inches) of lane markings, which can enhance the effectiveness of LKA systems.[73] Additionally, Siegel suggested encoding lane information by adding fluorescent pigments to roadway lane-marking paints so that a vehicle equipped with light transmitters and receivers would able to detect the lane markings.[74]

An experimental study that assessed drivers' detection of roadside targets compared the effectiveness of adaptive and fixed headlights and fixed halogen headlights.[75] The benefits of adaptive headlights were greatest with low-reflectance targets placed on the insides of curves. The study unexpectedly found that adaptive headlights better detect targets of low reflectance than those of higher reflectance. This indicates a need for more research on the best placement and reflectivity of signs and pavement markings to accommodate adaptive headlights of manually driven vehicles or AVs.

ADSs Relevant to RwD Crashes

ADSs are emerging vehicle technologies that take full control of the driving task under certain conditions. Vehicles with these systems are expected to have superior safety benefits though they are faced with some engineering, legal, and institutional challenges.

Challenges of ADSs

A finding from a 3,400-mile study of a vehicle equipped with ADS was that inconsistency in lane markings between States poses significant problems to AVs. The difference between white and yellow markings challenged the ADS.[76]

To support the navigation sensors of ADSs, it would be ideal if such vehicles were provided with information regarding the static characteristics of the infrastructure through which they are being driven (e.g., number of lanes, lane width, degree of curvature, gradient of the road, shoulder width, pavement type, and others). For example, Benine-Neto et al. and Gao et al. discussed an optimization algorithm that determines a safe approach speed for curves to avoid RwD crashes based on the combination of expected road alignment, shoulder and lane width, surface friction, and vehicle dynamic features that can be used for navigation by ADSs.[77,78] Such an algorithm could be supported by providing it with archived information on static features of the infrastructure (e.g., radius of curvature as well as the number and width of lanes). Edelman et al. explored how a vehicle can estimate the friction between its tires and the pavement.[79]

Some aspects of ADSs remain not fully addressed (e.g., liability issues, security concerns, and privacy standards). In addition, the moral implications of machine decisionmaking in the event of unavoidable crashes are also a concern. Machine ethics and its applications to AVs are discussed by researchers who claim such cars need to replicate (or possibly exceed) the human decisionmaking process.[80,81]

Benefits of ADSs

Several researchers, government agencies, consulting firms, and other private enterprises conducted studies with the objective of predicting the successful deployment and market-penetration rates of vehicles with ADSs. Such vehicles are expected to significantly reduce the frequency of crashes. Considering that 40 percent of fatal crashes involve alcohol, distraction, drugs, or fatigue, Fagnant and Kockelman observed a potential for ADSs to reduce crash frequency by at least 40 percent. If other crash causes are considered (e.g., speeding, aggressive driving, overcompensation, inexperience, slow reaction times, inattention, and various other driver errors or limitations), the potential for crash reduction can be more than 40 percent. Fagnant and Kockelman predicted vehicles with ADSs to be 50 percent safer than vehicles without at the stage of 10-percent market-penetration rate and 90 percent safer at a 90-percent market-penetration rate.[82]

The safety advantage of ADSs relies on two main components: shorter perception–reaction time and longer sight distance. West highlighted that the onboard computer in such vehicles takes only 0.2 second to detect an object on the road, while human drivers take an average of 1.2 second.[83] Similarly, the LiDAR laser beams and cameras in these vehicles have a safe sight distance (safe visibility range) of 650 feet, compared to only 150 feet for human drivers.

Bansal and Kockelman forecasted the long-term adoption rate of CV and AV technologies in the United States based on survey data on willingness to pay (WTP) for these technologies and the assumptions of 5 and 10 percent annual drops in technology prices and of 0, 5, and 10 percent annual increments in Americans' WTP.[84] Their study also revealed that more than half the respondents were not willing to pay anything to add high levels of driving-automation technologies, and the average WTP of all respondents and of those with nonzero WTP were found to be $5,551 and $14,589, respectively. Their long-term fleet-evolution estimate was that Level-4 automation is likely to be adopted by 43 percent of the vehicle fleet in 2045. The authors suggested that, as the public learns more about the benefits of such vehicles, the perception of the cost of the technologies may change.

Fagnant and Kockelman predicted that the social effects of ADSs in the form of crash savings, travel-time reductions, fuel efficiencies, and parking benefits are likely on the order of $2,000 per year per vehicle.[82] If comprehensive crash costs are accounted for, the benefits could increase to $3,000 to $5,000 per year. Assuming only 10-percent market penetration, the annual U.S. economic benefit from ADSs could be around $25 billion. When including broader benefits and high penetration rates, such vehicles may save the U.S. economy roughly $430 billion annually.

A study by Blanco et al. compared the crash rates of an AV in on-road tests with crash databases, drawn from police-reported crash data and crash data from the second Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (NDS).[85] The overall crash rate of the self-driving car operating in automated mode was found to be 3.2 per million miles, while the national crash rate was 4.2 per million miles after applying controls for unreported crashes and crash-severity levels. The results suggested that ADSs have the potential to promote safety of the roads. However, the authors were not able to draw firm conclusions about relative effect on injury and fatality crashes since such vehicles are not driven enough miles to make or be involved in a crash with a serious injury or fatality.

Considering that crashes are rare events and that vehicles with ADSs have been introduced only recently and are driven far fewer miles than conventional vehicles, quantifying the safety benefits of ADSs unequivocally would be difficult. Kalra and Paddock conducted a study that aimed to determine how many miles of driving it would take to evaluate the safety of ADSs reliably and make statistical comparisons with the performance of human drivers without any ambiguity.[86] Their results suggested that demonstrating the safety of such vehicles would take tens or even hundreds of millions of miles of driving. A hypothetical fleet of 100 vehicles with ADSs being driven 24 hours per day and 7 days per week at an average speed of 25 miles per hour would require years to accumulate this many miles. Their finding implied that ADSs' safety performance could not be practically evaluated based on real-world testing but should focus on methods like accelerated testing, virtual testing and simulations, mathematical modeling and analysis, scenario and behavior testing, and extensive tests on hardware and software systems.

Addressing RwD Through CVs

CVs use wireless DSRC to exchange mobility and safety information with other vehicles on the road (V2V), with roadside infrastructure (V2I), and other features (V2X). This exchange of information is expected to provide significant benefits in safety, efficiency, mobility, infrastructure, and fuel consumption.[28]

Equipped vehicles broadcast their information (e.g., location, speed, and acceleration) 10 times per second in a format known as the Basic Safety Message (BSM). CV technology provides a platform for critical safety and mobility messages to be tailored for an individual vehicle. Some of the CV safety applications are in forward-collision avoidance, blind-spot detection, lane departure, electronic brake lights, and intersection conflict avoidance. NHTSA indicated that CV technology could address up to 80 percent of the crash scenarios involving nonimpaired drivers.(87) Richard et al. provided some guidelines on the design of safety warnings for V2V and V2I applications.(88)

Bansal and Kockelman forecasted the long-term adoption rate of CVs based on WTP.(84) The average WTP for adding connectivity to a vehicle was found to be $110. Their fleet evolution estimate was that 60 to 80 percent of U.S. vehicles will have CV technology in the year 2045, assuming NHTSA issues no regulation mandating the technology.

In the context of RwD crashes, CV technology can be beneficial to warn drivers of traffic and roadway conditions that can give rise to RwD crashes. For example, CV technology can be used to warn of upcoming curves, lane drops or closures, merge situations, spot weather conditions, speed reductions around work zones, and the presence of debris on roadways. Chang et al. discussed the benefits of CV applications in greater detail.(89) Altan et al. also discussed the application of CV technology for integrated warning systems for lane drifts, lane changes, and blind spots.(90)

The effectiveness of V2V connectivity might not be as good as V2I on low-density roads because the transmission range of DSRC-based messages might be negatively affected due to network fragmentation. In addition, the communication range may be shortened due to foliage and building effects. Considering that RwD crashes commonly occur on low-density, rural highways and at specific road locations, like curves and lane drops, V2I can be advantageous over V2V. The study by Shagdar and Muhlethaler demonstrated how DSRC-based V2V and V2I connections can be used to support vehicle merge control.(91) The result of their study indicated that, for the merge-warning application, V2I-based communication is preferred over the V2V-based systems due to its ability to reliably provide information at consistent time intervals.

Speed-Management Applications

Speed management using CV technology involves advanced vehicle-control algorithms that adjust the approach speed of vehicles based on real-time traffic and infrastructure information. In the context of RwD crashes, speed-management applications of vehicles using V2V and V2I technologies can be used for warnings related to curves, lane drops, work zones, and spot weather. In such applications, CVs are warned of the downstream traffic and infrastructure statuses and are advised to maintain a suitable speed to avoid RwD crashes.

CSW Applications

The CSW application of V2I technology is intended to reduce RwD crashes by alerting drivers if their approach speed is expected to cause loss of vehicle stability in the curve. Stephens et al. wrote a concept of operations for the application.(92) An ongoing project at the University of Minnesota is developing a warning system for lane departures and curve speeds that can be integrated in an onboard, V2I unit that uses ordinary GPS receiver technology and commonly available mapping data.(93)

Dahmani et al. developed a methodology for warning of curve departure by integrating vehicle dynamics with an estimated curvature of the roadway.(94) The system works based on inputs from a fuzzy observer that estimates the road curvature and compares the estimate with the curvature of the vehicle's trajectory. In addition, input from steering dynamics is considered. The difference between the estimated road curvature and vehicle-trajectory curvature is used as an indicator of the risk of RwD crashes; if the risk is found to be greater than a given threshold, an alarm is triggered.

Precrash scenarios that are addressed by the CSW application lead to 169,000 crashes and 5,000 fatal crashes annually, which have a total estimated cost of $29,080 million.(89,95)

These applications require a road inventory with the locations and degrees of the curves and current information on the surface conditions or, at least, the weather.

Applications for Temporary Speed Restrictions

The speed of traffic may be temporarily reduced by factors such as work zones, adverse weather, traffic queues, and incidents. The application of CV technology for warning drivers of upcoming reduced-speed areas has been demonstrated by many researchers. For example, Timcho et al. showed the use of V2I technology for weather-warning and reduced-speed-zone-warning applications.(96) Drivers are warned of the upcoming adverse spot weather conditions and are advised to reduce their speed through V2I messages. A similar application of CV technology provides drivers with pertinent lane and speed guidance to navigate safely through an incident area or work zone.(97) Stephens et al. demonstrated that CV technology can be effectively used to recommend an optimal speed for harmonizing with other traffic.(98)

Road Weather–Performance Management

CV applications in development provide for two-way communication of weather and surface conditions between vehicles and infrastructure.(99) The Motorist Advisory Warnings based on Pikalert® data were used by the road weather–performance management application to provide drivers with assessments on visibility, road conditions, and road precipitation. Information on road and weather conditions is taken from connected snowplows or other agency fleet vehicles. The data are processed and then pushed to travelers as in-vehicle advisories and alerts in near real time as well as through Web-based user interfaces (computers, tablets, and smartphones). The mobile application keeps drivers abreast of changing road-weather conditions. Hill developed a concept of operations for how vehicle connectivity can be used to warn of adverse road-weather conditions.(100)

Lane-Level Localization Using CVs

Applying CV technology to prevent RwD crashes requires lane-level localization of vehicles (e.g., applications for lane-encroachment warning and merge warning due to lane drops). DSRC-based positioning systems satisfy the need for accuracy, availability, continuity, and low cost, all of which can be useful for collision avoidance, LDWs, and AVs' lateral or longitudinal control.

Alam et al. conducted a study on the use of the DSRC carrier frequency offset for the instantaneous lane-level positioning of CVs.(101) The system is based on V2I technology, through which two roadside beacons broadcast their positions and the geometry of the roadway lanes and a CV uses the data contained in these signals and odometer-based speed to estimate its instantaneous position along the road and the lane. The accuracy of the proposed system increases with the speed of vehicles, with the probability of false alarms and missed detections being almost zero. Such systems can be used for guiding traffic on highways, lane-level management of traffic, and LKA applications. Liu et al. also demonstrated the use of roadside units (RSUs) as fixed-position references to improve positioning accuracy.(102)

Similar studies by Ansari and Wang developed a V2V and V2I DSRC-based vehicle-positioning platform that enhances vehicle position for the use of critical transportation safety applications that require accurate position of vehicles (e.g., LKA applications).(103,104) Wang et al. developed a DSRC-based methodology for vehicular positioning using a distributed multiple-model Kalman filter.(105) The vehicle-location error in their system was 35 to 72 percent less than that of the standalone GPS method, depending on different traffic intensities and the CV penetration rates.

Identification of High-Risk Locations Using CVs

Crash-prone locations have traditionally been identified by the high incidence of crashes over a period of years. Smith et al. demonstrated the use of data from CVs for crash-prone locations using the near-crash events in which drivers took last-second and extreme evasive actions (such as swerving or skidding) to avoid imminent crashes.(65) Such evasive maneuvers, extracted from data logs of CVs, along with the GPS location can be used as a surrogate for crashes in general and for RwD crashes in particular due to poor infrastructure design (e.g., sharp curves, low friction, poor visibility, lane drops, and others). Transportation agencies can then use such data for identifying hot spots and implementing corrective actions without waiting for significant numbers of crashes to occur.

A similar application of CVs identifies roadway spots with temporary hazards by reporting vehicles with their hazard lights turned on and low-friction spots to other vehicles and road-maintenance agencies.(106) Traffic-management agencies can use the real-time information to optimize traffic lights, vary speed limits, and reroute traffic.

TECHNOLOGY TRENDS TO WATCH

A few topics do not fall into the category of conventional RwD countermeasures or the emerging technologies of CV and AV. Lessons from these topics have the potential to advance the effectiveness of the conventional RwD countermeasures and support emerging CV and AV technologies.

Understanding Lane-Keeping Behaviors of Drivers

Drivers' lane-keeping behaviors are directly relevant to the occurrence of RwD crashes. Therefore, understanding how drivers maintain their lanes and what factors lead them to deviate from their traveled lanes is critical for designing RwD countermeasures. Studies on lane-keeping behaviors of drivers that used naturalistic driving data are worth exploring because they shed light on the actual behaviors of drivers and on how they interact with lane markings on straight road segments and horizontal curves.

Johnson et al. conducted a study on lane-keeping behaviors of drivers using data from the 100-car NDS.(107) The objectives of the study were to understand the distribution of the lane-keeping position during normal driving, derive a relationship between the lateral velocity and lateral distance of lane boundaries, and examine correlations of lane-keeping position with lane width and radius of curvature of the roadway. Their findings indicated that drivers have higher lateral velocities and deviate further from the lane center as the width of the lane gets narrower and road curves are sharper. In addition, as drivers approach the lane boundary, their lateral velocities tend to decrease. The authors indicated that this could be the cause of premature warnings in LDW systems that lead to driver annoyance. The result of the study suggested that, to improve the timing and driver acceptance of lane-departure systems, the system should be able to learn and be calibrated based on individual driving behavior rather than using information from an entire driving population. Similarly, the normal lane-keeping behaviors of drivers may vary from country to country based on the lane-width and road-curvature standards of the countries, and thus, lane-departure systems may need to be calibrated accordingly.

To address the interaction between driver behavior, roadway environment, and the likelihood of lane departure at rural horizontal curves, researchers conducted several studies with the objectives of determining what environmental, roadway, driver, and vehicle factors influence whether a vehicle departs its lane and what factors influence the outcome of the lane departure at curves.(12) Hallmark et al. conducted a study that used the SHRP2 NDS and Roadway Information Datasets.(108) The results of the study suggested that the simple presence of curve-warning signs does not mitigate RwD crashes. Right-side lane departure is 6.8 times more likely on the inside of a curve than the outside of a curve. Males are up to four times more likely to have left-side lane encroachment than females. Guardrails may provide feedback to the driver about the sharpness of the curve, delineating the curve more clearly. Raised pavement markers decreased the probability of exceeding the posted speed limits, resulting in better speed selection and decreased risk of an encroachment. The study also found that driver age and upstream approach speed have significant effects on speed within the curves. This implies that countermeasures for RwD crashes at curves should address speed management, not only at a curve, but also upstream of the roadway before entering a curve.

A similar study by Oneyear et al. found that initial lane position, distraction, shoulder width, and curve delineation affect the likelihood of lane departure on two-lane, rural curves.(109) The results indicated that the lane position within the curve was correlated with the lane position upstream of the curve; drivers who glanced down were found to drift about 1 foot from the center of the lane toward the inside of the curve; in left-hand curves, large paved shoulders were associated with drivers drifting toward the outside of the lane more than small paved shoulders; and lower visibility delineation was correlated with drivers driving more toward the center of the two-lane roadway on left-hand curves.

One shortcoming of advisory speed signs is that they cannot consider variability in the driver’s actions, vehicle dynamics, and road characteristics. An infrastructure-based dynamic curve–speed warning was developed by Rey et al. for light vehicles based on probabilistic RwD-risk assessment, which considered the variability in approach speed, lateral speed, lateral acceleration, and lateral position.(110) Data were collected using low-cost sensors for measuring speed 150 feet before the curve entrance as well as sensors for measuring speed and lateral position at the curve entrance. The methodology triggers an alarm in the case of potential RwD due to loss of vehicle control given the longitudinal and lateral speed and vehicle acceleration while negotiating a curve. The study found that lateral position and speed at the curve entrance have a significant influence on the RwD risk. Their study was tested on multiple two-lane, rural curves in France.

A recent study by Ghasemzadeh and Ahmed analyzed the complex effects of weather, speed limit, and traffic conditions on drivers' lane-keeping behaviors.(111) The study found the standard deviation of lane position in heavy rain conditions was 3.8 times more than during clear weather. In addition, the standard deviation of lane position when traveling on low-speed roads (speed limit less than 55 miles per hour) was found to be 15 times more than that of high-speed roads. The lane position's standard deviation was found to decrease as traffic density increased (i.e., the standard deviation of lane position was 4.8 times more in free-flow conditions than in congested traffic conditions).

RwD-Crash Risk Index

Several models have been developed with the objective of predicting the frequency and severity of crashes on highways per the *Highway Safety Manual* and safety performance functions.(112) Such models function based on the relationship between crash histories, volumes of traffic, speed limits, and key infrastructure features. For example, Brimley et al. developed a methodology for calibrating the models used for estimating the crash frequency and severity in the *Highway Safety Manual*.(113) In a similar fashion, RwD-crash risk indices could be developed to identify the key infrastructure features related to RwD crashes and also provide an RwD risk score for highway segments; this information could be coupled with navigation and LDW systems to enhance these systems' performance.

Similarly, Miaou developed a model for predicting RwD-crash frequency and severity on rural, two-lane, two-way roads and rural, multilane highways.(114) In order to develop a roadway crash-risk model that is independent of crash-history data, Leur and Sayed and Leur and Hill developed a methodology for presenting a road-safety risk index to quantifiably assess safety performance.(115,116) The index was the product of the exposure to unsafe situations (i.e., the number of vehicles), the probability of the occurrence of unsafe events (i.e., the chance of a vehicle being in a crash), and the consequences of the unsafe events (i.e., the severity of a crash). This safety-evaluation technique potentially identifies roadway segments that experience low crash frequency but high crash severity.

Rosolino et al. developed a road-safety performance index that estimated the risk derived from infrastructure features, namely crash history, intersection or on–off ramp densities, pavement anomalies, horizontal and vertical curves, and roadside and safety barrier deficiencies.(117) The risk associated with the specific traveled road segment is given to drivers based on their driving speed. The system uses multiplatform mobile applications and GPSs to deliver the warning.

More recently, Jalayer and Zhou conducted a study on estimating the safety risk of roadside features by treating clear zone width and side-slope as two continuous variables rather than as discrete binary variables.(22) The study quantitatively evaluates the practical benefits of clear zone widths and side slopes. It enables road-safety audits and road-segment risk evaluations for prioritizing infrastructure treatments. A similar study by Carrigan and Ray described a methodology for predicting the severity risk of RwD crashes based on the combination of crash-based and encroachment-based approaches with the objective of improving highway safety.(118) The authors claim that their methodology was suitable for developing jurisdiction-specific models.

It is evident that the severity of an RwD event strongly depends on the characteristics of the infrastructure's static features where the departure occurred. Developing a map that contains the information regarding the degree of hazards on and near the road (e.g., road geometry, presence or absence of guardrails and ditches, and the nearby terrain) can significantly increase the effectiveness of LKA systems. Arora et al. conducted a study on improving a current lane-departure system by integrating it with a preprocessed map that contains relative severity levels of anticipated RwD events based on the characteristics of the static near-road hazards.(119) Their work built on the severity index developed in the Roadside Safety Analysis Program as an indicator for the risk of the RwD severity.(120) They accounted for barrier types, locations of trees and utility poles, pavement-edge dropoffs, outside-edge foreslopes or backslopes, and median widths and slopes. These indices are preprocessed and mapped. Given the RwD-hazard map and indices, road segments are then categorized as low risk, medium risk, or high risk for an RwD event. Based on the anticipated severity of RwD events, the type and intensity of the warnings and compensations applied by LKA systems can be adjusted to make them responsive to anticipated risks. The preprocessed hazard map and indices eliminate the need for expensive onboard sensors for detecting the permanent objects on or near the road.

Road-Information Inventory

Road-information inventory is the process of identifying objects on the road or in its proximity. Such objects include the road surface itself, signs, road markings, guardrails, curbs, poles, trees, and structures near the road. Information (e.g., the types, positions, and conditions of objects) stored in a GIS in the form of various map layers can be easily retrieved for many uses.

Advanced road-information inventory can be stored in high-resolution, three-dimensional (3D) maps. In the context of RwD crashes, an inventory can be useful for many purposes (e.g., providing navigation during adverse weather conditions and deriving an RwD-crash index), which smart vehicles can further utilize to drive more cautiously at high-risk segments and try to minimize the outcomes of RwD crashes if they occur.

Previously, the process of compiling a road inventory required a substantial amount of manual work to collect data from field measurements and postprocess the data, making it time consuming and expensive. Motivated by the need for an economic solution with improved capabilities, many researchers attempted to develop a system for an automatic or semiautomatic road inventory, using remote sensing technology for detecting and extracting road surfaces and objects. The process includes feature extraction from images and data fusion. Though automatic road inventory is appealing, some traffic signs could be heavily obstructed, making automatic detection difficult.

Automatic road inventory is conducted with image-based and laser-based mobile mapping systems. Recently, more attention has been given to laser-based mobile mapping since the performance of image-based mapping systems is limited by illumination, lighting and weather conditions, and shadows cast by buildings and trees. These systems suffer from distortions. One type of laser-based mobile mapping applies LiDAR.(121)

LiDAR can rapidly collect enormous volumes of highly dense, irregularly distributed, accurately georeferenced data in the form of 3D point clouds. Landa and Prochazka worked on developing a semiautomatic road inventory–registry process, using LiDAR for traffic signs, road markings, and general pole-shaped objects (e.g., street lights and trees). The successful detection rate of signs was 93 percent.(122) A similar study by Sairam et al. developed a mobile mapping system for 3D road-asset inventory.(123) A recent study by Zhang applied LiDAR for rapid inspection of pavement markings.(124) Gargoum et al. have successfully used LiDAR point-cloud images for automatic extraction of highway signs along with their conditions, coordinates, and elevations with a high precision and success rate, ranging from 93 to 100 percent.(125) Guan et al. reviewed literature on LiDAR and its application for road-information inventory. Their detailed review demonstrated that mobile LiDAR technology has a great potential for automatic road information–inventory registry through accurate 3D geospatial information on roadways, including road markings, signs, road surfaces, pole-like objects, and structures such as manholes, sewers, culverts, and tunnels.(121)

To improve the capability of ADSs in adverse weather conditions (e.g., snow and rain), researchers developed a solution based on road-information inventory, which is a high-resolution, 3D, digital map that includes detailed data about road markings, signs, geography, topography, and landmarks.(126) The effectiveness of high-resolution, 3D, digital maps has been demonstrated in a simulated urban environment known as Mcity through the University of Michigan's Mobility Transformation Center. The team demonstrated the ability of its ADSs to navigate effectively in snowy and other poor weather conditions.

High-resolution, 3D maps have been created for locations in Silicon Valley, Michigan, France, Germany, and Japan; these maps have also been made available to ADS developers.(127) LiDAR-equipped fleets of cars and advanced processing technologies are used to create these high-resolution maps. These high-resolution, 3D maps must be regularly updated to capture the changes in the conditions of the road and its environment (e.g., new road additions and detours due to work zones). These maps can be updated in real time so that a vehicle can react to road changes in a timely manner. High-resolution maps have been developed for Mcity in Michigan; parts of Route 101 and Interstate 280 in San Francisco, CA; part of Autobahn A9 in Munich, Germany; and a freeway stretch on Francilienne (N104) between A6 and A10 in France. Figure 7 presents a high-definition 3D map created for Mcity.

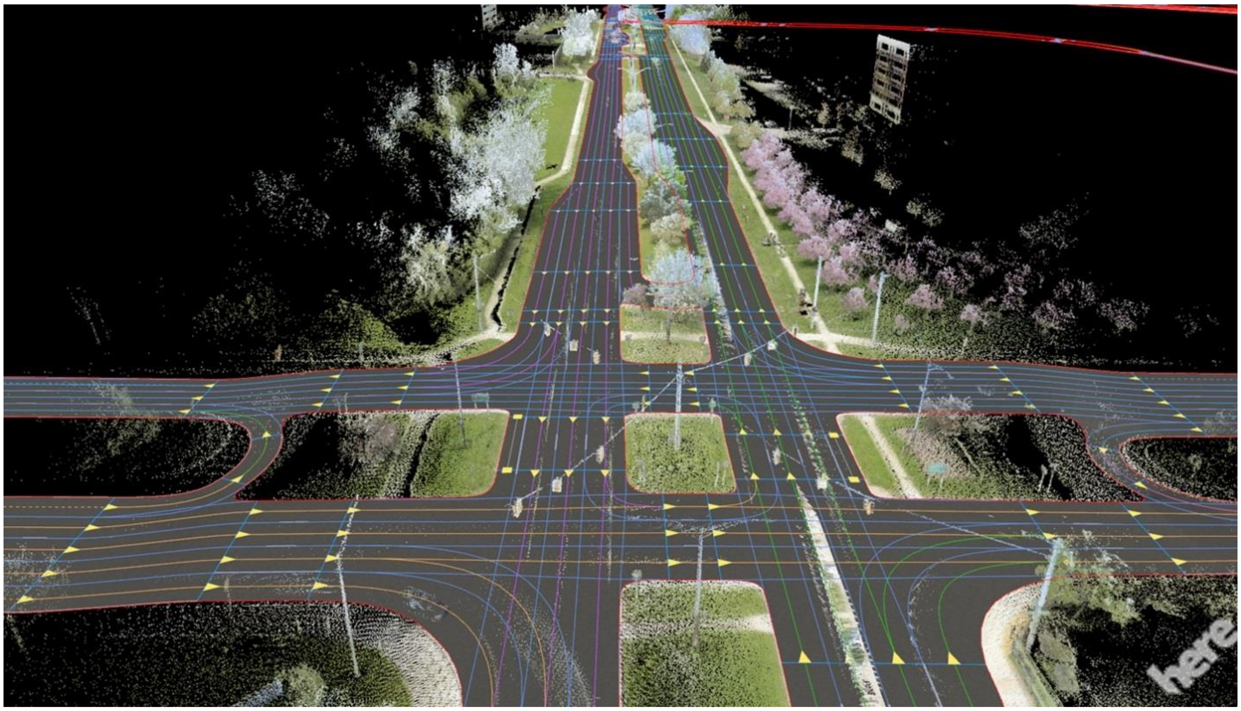


Image © HERE Technologies; used with permission.

Figure 7. Photo. High-resolution, 3D map for use by AVs in Mcity.[127]

Similar to the LiDAR-based, high-resolution, digital maps, Du and Tan developed an effective image-based road-information inventory using stereo 3D reconstruction to estimate vehicle localization.[128] Based on image sequences taken under different conditions, the experiment's results showed that the proposed system can identify lane markings with an accuracy of 98.6 percent. Considering that correct lane-marking detection supports AV navigation, such high-resolution, digital maps of road-information inventory are crucial for supporting AV navigation under clear and adverse weather conditions.

Public and private vehicles drive the roads gathering information on the infrastructure for various purposes, ranging from mapping features, to recording sign messages, to assessing conditions. The Ohio Department of Transportation (Ohio DOT) uses the van in figure 8 to collect data on roughness, pavement distress, rutting, and surface macrotexture.[129]

Source: Derek Troyer, Ohio DOT.

Figure 8. Photo. Ohio DOT van precisely tracks its position relative to the roadway as it gathers data on pavement conditions.

Addressing RwD Through Enhanced Infrastructure

Simple and futuristic developments in lighting and pavement might affect RwD crashes. CVs or AVs could benefit from adaptations of these innovations.

Enhanced Lane Markings

To make lane markings more visible to the human eye and machine-vision techniques, many researchers have developed variations of lane markings. Such markings could be beneficial to rural roads, where the frequency of RwD crashes is relatively high.

Light emitting diode (LED) raised pavement markers are solar-powered, illuminated markers that provide better visibility of roadway edge lines and center lines during nighttime driving and poor weather conditions.[(130)] These markers are similar to standard retroreflectors but contain small LEDs and sensors that can automatically turn on the LEDs when ambient light is below a specified threshold. Such LED markers can be set to flash to warn drivers when their speed is excessive. One LED raised pavement marker costs approximately $50, including material and installation. A similar technology is the flush-mounted, snow-plowable LED pavement marker.[(131)] Such markers provide over 30 seconds of reaction time, whereas conventional retroreflective road studs provide 3.2 seconds at 62 miles per hour.

Lane markings that glow in the dark are being introduced in the Netherlands on N329 in Oss.[(132)] Their objective, as part of the Smart Highway project, is to increase visibility and safety. The paint used for the lane marking contains photo-luminizing powder, which releases a green glow in the dark for up to 8 hours after being charged during the day. However, such lane markings were found to be sensitive to moisture, and their effectiveness declined drastically during rainfall.

Like the glowing lane markings, dynamic paint has been proposed in the Netherlands.(133) The temperature-sensitive paint contains thermochromatic pigments that become visible when the surface is unusually cold.

Given the limitations of vision-based systems, radar-based systems could be advantageous for their high range, high resolution, and functionality in more weather conditions. A recent study by Clarke et al. investigated the possibility of using a vehicle-mounted, synthetic aperture radar to detect radar scatters embedded in the road infrastructure.(134) Preliminary simulation results indicated the technique can fully resolve both clutter and radar reflectors.

Smart Roadway Lighting

The relationship between safety and roadway lighting is strong. Standard street lighting provides constant illuminance regardless of roadway conditions or real-time roadway usage. Smart roadway lighting provides adequate levels and quality of lighting in response to where and when it is needed and adjusts to current weather conditions. Its uniformity of lighting and controlled glare benefit visual perception. Gibbons et al. analyzed the relationship between levels and quality of lighting and crash rates and provided guidelines for adaptive roadway lighting design.(135) Foote and Woods developed LED-based smart roadway lighting with communications and lighting network–management software.(136) The Rhode Island Department of Transportation installed LED-based roadway lighting on the Sakonnet River Bridge. This lighting can adjust its color and brightness as needed.(137)

The Virginia Tech Transportation Institute (VTTI) developed and implemented on-demand lighting—an adaptive, overhead roadway lighting that uses CV technology, which is suitable for roadways with little traffic at night and higher crash rates.(138) The system uses DSRC, CV infrastructure, centralized wireless lighting controls, and LED luminaires. The concept is that a CV sends its location, speed, and route to a central traffic management center (TMC) through DSRC. Based on this information, the TMC will be able to identify which luminaires are required to be lit in front of the vehicle. Participants in the pilot project felt that the system provided a safe driving environment and did not find the on-demand lighting distracting. However, VTTI did not consider what level and quality of lighting to use.

The concept of interactive lights was proposed in the Netherlands.(139) The idea is that sensors detect the motion of vehicles, light their ways, and then gradually turn off to reduce energy consumption. In addition, the interactive lights can change color to give feedback on the speed of vehicles.

Navvab et al. examined dynamic lighting conditions in automobiles due to roadway and in-vehicle lighting conditions in terms of illuminance, luminance, and spectral outputs of several roadway-lighting systems as well as the drivers' gaze direction and pupil dilation under mesopic conditions with application in Smart Cities and Intelligent Transportation Systems (ITS). Such lighting enhances visibility.(140) In general, smart roadway lighting can benefit rural and low-volume roads.

Specialized Pavement Surfaces

The concept of smart pavement surfaces is to communicate with smart vehicles.[141] Preliminary projects in the United States and the European Union attempt to make the road infrastructure more suitable to CVs and AVs.

One such surface is tempered safety glass with the ability to harness energy from the Sun.[142] The panels are said to support the weight of a commercial vehicle and have a traction equivalent to asphalt. LEDs replace the traditional painted markings, providing better nighttime visibility. Permanently embedded microprocessors with fixed longitude and latitude offer exact vehicle location. The Missouri Department of Transportation has a 200-mile pilot project on Interstate 70 and the historic Route 66.[143]

Another concept consists of interlocking, precast concrete slabs embedded with digital sensors that provide wireless connectivity to vehicles.[144] The pavement includes a digitizer layer that can identify vehicle tire position, weight, and speed. The pavement can precisely locate a crash on the road and can recognize if a vehicle departs the roadway and call for help. Demonstration projects are planned in Missouri and Colorado.[145]

The Forum of European Highway Research Laboratories has initiated the Forever Open Road Programme.[146] It is designed for adaptability (i.e., to respond to changes in road users' demands), automation (i.e., to be fully integrated with intelligent communication technology applications between road users, vehicles, and traffic management), and resilience (i.e., to be able to maintain functionality under extreme weather conditions). This concept is expected to provide support to CVs and AVs. The "5th Generation Road" (Route 5ème Génération) and the "Roads in the 21st Century" (Straße im 21. Jahrhundert) are other similar concepts being developed in France and Germany, respectively.[147,148]

EFFORTS OF STATES AND INFRASTRUCTURE STAKEHOLDERS ON CV AND AV TECHNOLOGIES

States and local transportation agencies as well as other infrastructure stakeholders need to be ready to accommodate changes. This section briefly discusses how States and other infrastructure stakeholders are preparing for the arrival of CV and AV technologies.

Efforts of States on CV and AV Technologies

Many States have embraced CV and AV technologies and have developed pilot programs; permitted ADS tests on their public roads; or planned programs, projects, and deployments for CV and AV technologies. As of August 2016, seven States and the District of Columbia have enacted ADS legislation and are actively anticipating changes.[149] A few of the States that showed interest in CVs and AVs are California, Michigan, Virginia, Nevada, Florida, Washington, and Louisiana.[85,150] California, Michigan, and Virginia have been involved in the CV and AV arena for a while.

A report by the U.S. Government Accountability Office (GAO) provided a variety of information and guidance for State and local agencies interested in implementing V2I technology, including a description of benefits, various State and local scenarios for deployments of V2I technology, underlying infrastructure and communication needs, timelines and activities for deployment, estimated costs and workforce requirements, and challenges that need to be addressed.(151)

The deployment of ADSs is at an early stage in the United States. Though this is a great achievement by itself, it may be unfavorable for wider deployment due to inconsistencies across States on deployment policies. A national framework for wider adoption of CVs and AVs would accelerate their deployments.(123,149)

California

California, in collaboration with its academic and research organization partners, has been one of the leading States to develop and deploy CV and AV applications. The California Department of Transportation (Caltrans) plans to address its challenges of safety, mobility, environment, and agency efficiency of its growing population through deployment of emerging transportation technologies. Recently, Caltrans proposed the One California program for deployment initiatives of CV and AV technology.(152,153)

Michigan

The Michigan Department of Transportation (MDOT) along with the University of Michigan and industry partners hosted the USDOT Safety Pilot Model Deployment for CVs. MDOT has initiated and completed numerous CV and AV projects, has integrated mobile-observation and vehicle-based data-collection systems, and is planning on the United States' largest deployment of CV and highway technologies.(154) In addition, MDOT has recently formed a collaborative initiative for CVs and AVs called the Smart Belt Coalition.(155)

Texas

Texas has shown interest in CV and AV technologies and assessed the implications of CV and AV deployments for the State's local government agencies.(156,157) Considering that the Texas Department of Transportation is responsible for the Nation's most extensive State-level road network, its interest in CVs and AVs can have significant benefits. The State has initiated projects that developed different scenarios for CV and AV penetration rates. For example, Kim et al. discussed the potential benefits of these technologies in Texas and their implications on travel behavior, safety, congestion, and leisure during travel.(158) The result of their study indicated that the largest benefit for Texas would come from crash savings, which is equivalent to 57 percent of the total expected benefits at a high market-penetration rate of 90 percent.

Virginia

The Virginia Department of Transportation (VDOT) has been active in the field of CV and AV technologies along with its main partners, VTTI and the University of Virginia. It has planned, executed, and evaluated many CV and AV applications. Recent initiatives by Virginia include the Connected Vehicle Pooled Fund Study, which is expected to prepare the State's local transportation agencies for the deployment of CV technologies in Virginia.(159) In addition, the State has initiated programs like Virginia Automated Corridors and Virginia Connected Corridors, which seek to address the safety and mobility challenges of the State's highways through CV and AV technologies and integrate the applications with the operations of VDOT.

Oregon

Recently, the Oregon Department of Transportation (ODOT) conducted a study on preparing the State for CVs, AVs, and other cooperative applications.(160) The study resulted in a roadmap that contains 94 recommended actions under 12 categories in the arena of CV and AV technologies.

Efforts of Infrastructure Stakeholders

A National Cooperative Highway Research Program (NCHRP) report for AASHTO outlined an infrastructure-research roadmap on the research and planning needs for CVs and AVs at the State and local transportation agency levels.(16) The report identified a number of CV and AV projects that address infrastructure design and operations, institutional and policy issues, planning issues, and modal applications. (See the appendix for a list of the projects and brief descriptions.)

Carlson and Poorsartep discussed how infrastructure stakeholders should adapt to accommodate advances in the field of transportation.(161) The authors highlighted that many of the vehicle technologies (e.g., machine vision) are designed with little consultation with infrastructure experts. To accelerate the safety and mobility benefits of the emerging technologies, they suggested an improved collaboration between infrastructure officials, research organizations, and automotive industries to devise a common understanding of how the physical infrastructure may be modified to better accommodate vehicle technologies.

CHAPTER 3. NEEDS ASSESSMENT

The previous chapter, Literature Review, discusses the safety issues of RwD crashes and the capabilities CV and AV technologies offer. This chapter assesses the needs of CVs and AVs so that the gaps between the states of these technologies and their effective deployments are identified. The needs were assessed based on three stakeholder-engagement Web meetings that promoted discussion and experience sharing. The Web meetings are described in the appendix.

CV and AV technologies that counteract RwD crashes have multiple stakeholders. These include CV- and AV-technology researchers and developers, vehicle manufacturers, State and local transportation departments, and infrastructure officials. As evidenced in the literature review, many CV and AV technologies and their applications are designed and developed with minimal consultation with State transportation departments or infrastructure officials. To accelerate the safety benefits of CV and AV technologies, improving communication and collaboration among these stakeholders is important. This communication would lay down a common understanding of how the physical infrastructure may be modified to better accommodate the emerging transportation and vehicle technologies. The needs assessment will explore the possibilities of CV and AV technologies in reducing RwD crashes, how FHWA's RwD Program can support CV and AV deployment, and how the Program's focus may need to adjust to address these changes in the vehicle and infrastructure technologies. Assessing the needs of CV and AV technologies can effectively clarify problems and identify appropriate interventions to be implemented by FHWA and other infrastructure entities. The assessment supported the development of the research implementation plan, which is discussed in chapter 4.

DISCUSSION POINTS AND LESSONS LEARNED

For systematic presentation of the main discussion points and findings from the needs assessment, the subject matter addressed in the three Web meetings are combined and summarized by topic in the following sections.

Standards

New standards are needed to cover new developments; in some cases, more precise standards of current systems are needed.

Signage and Lane Markings

Observations related to signage and lane markings included the following:

- Well-maintained lane marking can be the most effective short-term solution to the challenges of AVs.
- The *Manual on Uniform Traffic Control Devices* (MUTCD) contains standards, guidance, and options, all of which might be subject to interpretation. Tighter standardization within and between States would make manufacturers' jobs easier as this would increase the probability of the lane markings being recognized by AVs' machine-vision systems.[(4)]

- A supplemental notice of proposed amendments that proposes a revised set of standards to be incorporated in the MUTCD, including the federally required minimum levels of retroreflectivity for pavement markings, was brought to the attention of the participants during the second meeting. Website links were distributed to participants after the call.[162]

- White stripes on new concrete can be difficult to see for both humans and machines. Though it is not required by the MUTCD, some States supplement the white stripes with black paint, which AV manufacturers have found useful. The trouble is that there are at least 13 different ways the black paint is applied.[4]

- As with lane markings, styles of signs can vary. AV manufacturers must deal with this variety. For example, advisory speeds for curves have different margins across the country.

- Machine-readable signs are being developed through different, incompatible approaches. Treatments that would be invisible to a human, such as infrared markings and RFID tags, have been proposed. Quick-response codes and bar codes have also been proposed.

- Road-sign and -marking standards (e.g., the MUTCD) are based on human factors. The MUTCD or a supplement can account for machine-vision systems and support the perception and intelligence algorithms they use.[4]

Mapping

New electronic mapping technology offers advantages to travelers and transportation agencies. Findings include the following:

- Public and private entities are making maps for various purposes. Among other reasons, State and local agencies need maps to do the following:
    - Maintain inventories for asset management.
    - Design improvements based on maps of existing conditions.
    - Evaluate sites visually before visiting.

- Sometimes States and manufacturers buy mapped information from private sources. Private funding has its advantages but comes with unanswered questions of ownership and responsibility for maintenance.

- Given that there is no mapping standard, there may be differences in the ways the maps are produced and the information they contain.

- Navigation needs much more precision than an asset inventory. The condition of the road and roadside can change hour by hour, so a map or inventory must be refreshed almost continuously.

DSRC, V2I Applications, and Messages

Uncertainties for V2I communication are many and include the following:

- More than one State is already investing in V2I equipment such as signal controllers. They need assurance that their systems will be compatible with the standards that will be implemented. The systems must be interoperable with the DSRC equipment on all vehicles.

- Some States are considering deploying RSUs to support V2I communication. However, States face questions with uncertain answers: Who will develop the applications for V2I? How do they ensure that V2I applications function the same in all States? What features will vary and require that the applications differ by State?

- The messages sent and received through V2I communication are still under review. For example, the contents of a Traveler Information Message (TIM) and the MAP message, which contain information about road geometry to aid navigation of CVs and AVs, are being reviewed by the SAE committee, which welcomes more participation by transportation departments and other infrastructure stakeholders.

Infrastructure Differences for CVs and AVs

CVs and AVs will require different infrastructure than conventional vehicles. Examples include the following:

- The design requirements of infrastructure components, such as signs, markings, and medians, would be different for CVs or AVs. Human drivers are in control of CVs, so conventional signs would still be necessary. Virtual signs, through V2I communication, would supplement information available to both types of vehicles. Better pavement markings would benefit both human and machine vision.

- Manufacturers said that State transportation departments do not need to do anything differently to accommodate AVs, but the departments should do a better job of what they currently do (e.g., uniform lane marking and signs within and between States).

- Redundancy of information is valuable for many reasons: machine vision is reaching its limits, signs can be obscured by weather or other vehicles, and pavement markings fade. One manufacturer preferred DSRC; another, also desiring a broadcast, was technology neutral. Broadcast information with real-time updates for work zones and traffic incidents was preferred over maps.

- Providing the absolute location of infrastructure components is not necessary, but relative location is. For example, if a vehicle obtains information about the number of lanes and their width, then it can be positioned within its lane relative to a road edge or guardrail.

- Participants believe that CV and AV capabilities are complementary and that both will be part of the long-term solution. Automakers are perceived to be investing more in AV technology than in CV technology.

- Work zones that have bright lights in unconventional arrangements can be difficult for AVs to interpret. Virginia Tech recently finished a study on lighting needs for humans and recommended a follow-on for machine vision.

Signage, Roadside, and Friction Information

V2I offers the opportunity to deliver valuable information to vehicles in new ways, including the following:

- Broadcasting sign information in a TIM or encoding it in a MAP is possible. DSRC is probably less expensive than maintaining actual signs. Adding RFID tags to current signs is not expensive. Replacing signs for those with machine-readable fonts would be tremendously expensive.

- If geocoded information on roadside conditions and roadway inventory were available, AV manufacturers would use it for crashworthiness.

- Real-time surface information, including road-surface friction, is very difficult to estimate. AV manufacturers would readily use the information if they had it.

Sparse, Rural Areas

Sparse, rural areas present different challenges than urban areas. Such challenges are as follows:

- Providing electrical power to remote RSUs is a problem. Solar energy is not always the answer.

- The Wyoming Connected Vehicle Pilot Deployment Program is using traveling vehicles to carry information to other vehicles. That works on an interstate but not on a less-traveled road. In rural areas, V2I can be more effective than V2V communication.

- The optimum density of RSUs to support V2I applications in rural areas is not known. There is a trade-off between the crash-reduction benefits from V2I applications and deployment costs.

Staff Training

Issues regarding training new staff are the following:

- Transportation departments do not always know what new skills their employees and contractors need to learn.

- Education and outreach will be especially important to smaller county and local agencies that do not have staff dedicated to keeping up with CV and AV technologies.
- State-level decisionmakers need to be kept aware of developments in CV and AV technologies. Executives need to be shown that CV technology is cost-effective in reducing crashes before they invest in wide-scale deployment.

Collaboration

FHWA and other stakeholders will need to collaborate in the following new ways:

- All participants agreed that vehicle manufacturers, FHWA, and State transportation departments should work more closely on common interests.
- Manufacturers are working with NHTSA, which is doing much to advance V2V technology. FHWA could play a similar role in promoting research, standards, and outreach for V2I technology.
- Wide deployment of V2I systems requires that both transportation departments install RSUs and manufacturers develop applications on vehicles to use the information. This is like the "chicken and egg" metaphor as it is unclear whether transportation departments should first install RSUs or manufacturers should first develop and perfect V2I applications.
- Infrastructure agencies can play a key role in facilitating the deployments of CV and AV technologies (e.g., AASHTO's Signal Phase and Timing (SPaT) challenge was a step toward successful deployment of V2I applications for signalized intersections). Efforts could also be applied to other V2I applications relevant to RwD crashes (e.g., curve-warning applications).

IDENTIFIED GAPS

Transportation agencies maintain the infrastructure, and manufacturers produce vehicles that drive on it; both have roles in deploying CV and AV technology. A major gap seen from both perspectives is the need for collaboration so that their respective products can operate together. The two stakeholder groups, having complementary roles in highway safety, face different sets of challenges in realizing the benefits of CVs and AVs in reducing RwD crashes.

A Gap Common to States and Manufacturers

State and manufacturer representatives alike recognized the need for better collaboration.

Collaboration. Infrastructure officials, vehicle manufacturers, and State and local transportation departments need to work jointly toward common goals and objectives. Doing so will require frequent and open communication among stakeholders. Vehicle manufacturers have worked more closely with NHTSA on V2V and AV technology than they have with FHWA. To advance V2I technology, FHWA and vehicle manufacturers can increase their collaboration and benefit from the increased levels of commitment, integrated objectives, clearly defined roles and responsibilities, shared understandings, and common assumptions. Frequent and continual collaboration would provide a means to answer the stakeholders' questions. This would reduce uncertainty, which can possibly reduce costs as miscommunication and work duplication are avoided.

Gaps as Perceived by Transportation Departments

Representatives of State transportation departments brought several needs to the attention of FHWA.

Justification for the Investment. Executives and decisionmakers at State and local levels need to be shown the safety, mobility, and environmental benefits of CV and AV technologies. They need to justify the initial, operating, and maintenance costs. Participants observed that the challenge for justifying investment in these technologies is that many of the benefits are demonstrated through experimental, small-scale, or short-term pilot programs. Decisionmakers would like to see benefits demonstrated in large-scale and long-term deployments. These large-scale demonstrations in real-world scenarios can be time-consuming and resource-intensive tasks.

Assurance of Future Compatibility. Some State transportations departments are installing equipment that supports V2I communication and others are considering installing it soon. However, States are concerned whether the equipment will be compatible with future V2I communication standards. Another compatibility issue is whether V2I equipment and applications will work across different States. This poses a critical challenge to States' investments in the technologies and their wider deployment. The gap is, as emphasized by one participant, the lack of standardization of V2I equipment and applications. Guidance is also needed on how to install the equipment and what density will support current and future efforts.

Funding and Guidance. Though some State transportation departments are willing to deploy and support advanced vehicle technologies, they lack the funding needed for the equipment and training their staffs on how to install, operate, and maintain the equipment. Participants highlighted that this challenge can be greater for local and small county agencies that lack resources and staff dedicated to monitoring developments in CV and AV technologies. State transportation departments need guidance to answer the questions or reservations they have at all levels of their organizations.

Gaps as Perceived by Vehicle Manufacturers

Vehicle manufacturers noted several actions that could be taken by the FHWA and its State and local partners to facilitate the deployments of CVs and AVs.

Clearly Visible Lane Lines. Foreseeable AVs rely primarily on edge lines for navigation. Therefore, readily detectable and unambiguously interpretable lines are paramount. Gaps preventing further expansion (or proper operation) of AVs are lines that are difficult to detect in certain circumstances or ambiguous. Pavement seams or linear patches, in some cases, run nearly parallel to travel direction but do not demarcate the lane. Temporary lines for work zones may not be recognized as such, or former lane lines that have been milled may be misinterpreted as current. These challenges need to be addressed by transportation agencies responsible for the markings, automakers, or collaboration between the two. The MUTCD presents two challenges. The impossibility of anticipating every roadway situation has led the MUTCD to include standards, guidance, and options.[4] The flexibility of the guidance and options presents a host of markings to automakers. Furthermore, a long deliberation time (one participant observed that the rulemaking on visibility maintenance began more than 2 decades ago) will delay deployment of AVs that rely solely on longitudinal markings. A participant remarked that machine vision is nearing its capability limit. Much of the burden for improvement, then, will fall on the agencies responsible for the markings. Because pavement markings alone cannot convey full information in all geometries and weather conditions, there is a need for a second source of information—redundancy.

Redundancy. In this context, redundancy means that a second set of information is available to AVs in addition to the existing pavement markings and signs. A static map or inventory of road features is one way to provide a redundant source. However, participants observed that maps quickly go out of date (one even said the situation can change by the hour), so broadcasting current information is necessary. There is more than one way to do this. DSRC is a commonly cited medium. Road geometry and other information can be in the TIM or MAP message. There is some expectation that fifth-generation (also known as "5G") cellular communication technology will have adequate latency for V2V safety messages. Cellular technology has the advantages that capital investment will be borne by private industry rather than State transportation departments and that the Federal Communications Commission will maintain the spectrum availability. It has the disadvantages that it is not yet available and that it may not be able to incorporate existing DSRC equipment.

Additional Data. Successful use of CV and AV technologies for improving safety requires availability of dynamic data relevant to weather conditions, visibility, and surface friction. Some of the data are difficult to collect from in-vehicle sensors. Others that can be collected by in-vehicle sensors are only local. Some participants from vehicle manufacturers highlighted that, if they could obtain up-to-date data about the infrastructure and environment downstream of traffic, they would incorporate these data into their safety applications. However, there was no consensus on how such data would be collected and shared.

Consistency. The characteristics of lane markings and traffic signs are not uniform in all locations (e.g., in urban areas, in rural areas, and across States). One participant mentioned that various road-sign designs and styles serve the same purpose (e.g., traffic-control signs around work zones and advisory speed signs for curves that have different margins across the country). Participants agreed that, though the MUTCD provides standards and guidance, many of its aspects are left to the subjective discretion of engineers and operators.[4] Lack of maintenance funds can further induce inconsistencies in signs and lane markings due to replacement costs. This would make navigation for AVs more difficult. At the same time, AVs should be designed to handle the existing inconsistencies in their worst-case scenarios to be considered a safe and reliable mode of transportation.

In conclusion, most of the findings from the current needs assessment are consistent with the findings of the literature review. These conclusions provide a solid ground for the following chapter, Research Implementation Plan.

CHAPTER 4. RESEARCH IMPLEMENTATION PLAN

The safety issues of RwD crashes, the benefits of CV and AV technologies, and the gaps between current infrastructure capabilities and the deployments of these technologies are established in previous chapters. The objective of this chapter is to present a list of projects and activities that FHWA can consider to reduce the frequency and severity of RwD crashes through CV and AV technologies. Implementing the research topics will lead to appropriate interventions to be carried out by FHWA and other infrastructure officials.

The research-implementation plan addresses how the physical infrastructure may be modified to better accommodate emerging transportation and vehicle technologies, what activities FHWA's RwD Program can promote to support CV and AV deployments, and how the Program's focus may need to adjust to address these changes in the vehicles and infrastructure technologies.

Eleven initiatives, spanning a breadth of technical, outreach, and economic content, are fully developed, and their details are discussed in this chapter. All initiatives are unique to RwDs or focus on an RwD element of a larger effort. Each initiative is described in the format of an NCHRP research statement.(163) General background information on the initiative is first presented. This is followed by the specific objectives and the potential benefits the initiative provides. The initiative's relationship to the existing body of knowledge is discussed by referring to research that has been recently published or is currently underway. A possible research approach is outlined by task.

The initiatives are grouped according to the ideas they address, as in figure 2. Following the fully developed initiatives, existing and smaller efforts are listed.

The following criteria were considered to identify the research initiatives:

- Each initiative is specific to RwDs or provides the RwD portions of a larger effort.
- Initiatives were designed to be completed in 1 to 2 years. Most will have a tangible benefit after that time. Many will lay the groundwork for follow-on or are contributions to long-term efforts.
- The initiatives focus on the role of the infrastructure or the perspective of State and local transportation departments.

INITIATIVE 1. EFFECTIVENESS ESTIMATES OF CURRENT DRIVER ASSISTANCE

Background

Onboard electronic systems to assist drivers in lane keeping have been on the market for more than a decade. They take two forms. LDW systems are an electronic version of longitudinal rumble strips. They sense when a vehicle is at risk of an inadvertent lane departure and alert the driver. LKA systems are more sophisticated. They aid the driver in steering the vehicle. Some apply a steering torque as the vehicle nears the edge of the lane but no torque when the vehicle is aligned with the lane; they give the driver the feeling of being in a lane with the cross-section of a bathtub. Other LKA systems provide a continuous steering torque to keep the vehicle centered in the lane, which is Level-1 automation by the SAE definitions, which have been adopted by USDOT.[3]

Although several auto manufacturers' systems have their unique distinctives, they have accumulated enough exposure so that statistics can be analyzed to estimate their effectiveness. These systems can be enhanced by CV technology, and they are, in some ways, precursors to CVs and AVs. Lessons from their initial years of deployment will provide valuable insights regarding the implications of CV and AV technologies for preventing RwDs.

Objective

The objective is to estimate the crash reduction enabled by current LDW and LKA systems. A secondary objective is to document other lessons learned from the deployments of these systems that may be useful in applying CV and AV technologies to prevent and mitigate RwDs.

Potential Benefits

This work will help both current and future technologies prevent RwDs. Benefit estimates for these systems will enable comparisons of onboard, electronic systems with other approaches, old and new, for avoiding RwDs. Insights into how these systems perform and their shortcomings can reveal how infrastructure can better support their operations.

Relationships to the Existing Body of Knowledge

Many researchers have studied lane-departure systems from various perspectives. A simulation-based study by Scanlon et al. attempted to evaluate the effectiveness of LDW and LKA systems in preventing RwD crashes, assuming varying levels of compensation.[46] Kockelman and Li estimated the safety benefits of advanced driver-assistance systems in terms of the savings due to crash avoidance and moderation of crash severities.[38] NHTSA analyzed the mileage and crash data of passenger vehicles in the years 2014 through 2016 with and without a steering-assistance system.[44]

Tasks

This initiative comprises three tasks, each with associated activities.

Task 1. Develop a Research Plan

- Review prior studies in estimating the benefits of vehicle-based lane-departure countermeasures.
- List and categorize LDW and LKA systems that are on the market.
- Develop a data-sampling and -analysis plan that will build on existing knowledge and estimate the effectiveness of representative countermeasures.

Task 2. Develop Driver Models

- Obtain and analyze crash data for vehicles equipped with various implementations of LDW and LKA systems along with suitable control vehicles.
- Estimate the ratio of crashes in vehicles equipped with the countermeasures to those without. Present the results in a form that can support a benefit–cost ratio estimate.
- Note and describe instances in which real-world performance was less than predicted.

Task 3. Write Recommendations for Future Vehicle-Based Countermeasures

- Compile the lessons that can be learned from the initial rollout of previous countermeasures.
- Describe the principles of countermeasures that were the most effective in avoiding RwDs.
- Describe how these lessons and principles can be applied to countermeasures that take advantage of CV and AV technologies.

INITIATIVE 2. CHARACTERIZATION OF LANE-KEEPING PRACTICES

Background

Human drivers do not follow a perfectly straight line but move slightly back and forth within a lane. A person's lane position is affected by their level of vigilance as well as by the wind, play in the steering mechanism, cross slope on the road, and other factors. LDW-system manufacturers have made, at least implicitly, assumptions about normal lane-keeping practices, but drivers have been known to disable those systems. The aversion to the warnings is presumably because drivers' personal practices fail to match manufacturers' expectations; that is, the alarms are too frequent, and drivers find them a nuisance.

When lane drift is excessive, it becomes a departure. The vehicle can encounter another vehicle, a fixed object, or an unrecoverable slope, and the departure becomes a crash. Knowing which lane-position features indicate an impending crash would be valuable.

Objective

The objective of this research is to develop a better quantitative understanding of drivers' lane-keeping behaviors in naturalistic driving.

Potential Benefits

Modifying LDW and LKA algorithms so they warn only when a danger is truly present would enhance their acceptance by drivers. Knowledge of normal and precrash lane-keeping behavior will enable more realistic vehicle simulations, which could be used for benefit estimates and other purposes.

Relationship to the Existing Body of Knowledge

Ghasemzadeh and Ahmed used SHRP2 data to analyze the complex effects of weather, speed limits, and traffic conditions on drivers' lane-keeping behaviors.(111) Pape et al. used quantitative lane-keeping behaviors to develop a driver model.(164)

Although Sayer et al. found that an LDW system can have a beneficial training effect in pilot deployments, Reagan and McCartt and other studies have documented that vehicle owners tend to disable LDW systems, apparently due to nuisance alarms.(33,50)

Hallmark et al. found that the frequency of lane encroachments and RwD crashes occurring on left and right curves differ significantly.(108) Understanding the differences in how drivers negotiate curves in opposite directions can lead to improvements in both onboard and infrastructure-based departure countermeasures.

Tasks

This initiative would involve two tasks.

Task 1. Review Available Resources

- Compile available sources of lane-keeping behaviors.
- Summarize findings of prior studies on lane-keeping behaviors.
- List existing driver-steering models, and assess each for its suitability to produce naturalistic behavior.

Task 2. Develop a Model for Generating Naturalistic Paths

- Determine which characteristics should affect the model (including, for example, driver demographics, driver condition, roadway classification, road curvature, surrounding traffic, and weather).
- Determine which properties of the path the model should produce (including, for example, mean lane position, variance of lane position, and peak excursion from the lane center).
- Select an appropriate form of the model, develop it, and then demonstrate the fidelity of its paths.

Follow-On and Implementation Activities

This model can be used to improve the effectiveness of LDW systems. When driver responses to warnings are incorporated in the model, its simulations can be used to evaluate in-vehicle or CV lane-departure warnings. These evaluations would support system development and contribute to estimating benefits.

An extension to the model would be to include speed selection and deceleration practices, which would aid in evaluating curve-warning algorithms.

INITIATIVE 3. SIMULATIONS TO ESTIMATE THE BENEFITS OF CV COUNTERMEASURES FOR RwDs

Background

State and local transportation departments will have new installation and maintenance responsibilities to accommodate CV deployment. Expenses will include installing, powering, maintaining communication equipment (such as RSUs), as well as providing the RSUs with current information and handling the information they produce. Those responsible for State transportation budgets need to justify these costs by documenting the expected benefits from improved safety and mobility and the decreased departmental operating costs. There is a role for researchers who study RwD crashes to provide benefit estimates to the larger effort of infrastructure management. Existing data and tools can estimate benefits through simulations.

Objective

The objective is to demonstrate and document the economic justifications of CV deployment from the perspective of State transportation departments. This will include unambiguous and quantitative estimates of the benefits and costs of CV deployments.

Potential Benefits

This work will support the larger effort to develop an economic analysis from a State or local perspective to justify CV deployment. It will also guide further research in developing specific applications.

Relationships to the Existing Body of Knowledge

A recent GAO report observed that, although CV deployment benefits and costs have been estimated through simulations and a small number of pilot studies, the actual benefits and costs of large-scale implementation remain largely unknown.(151) Chang et al. provided quantitative information on crash reductions expected from CV deployment.(89) Kockelman et al. provided the safety and operational benefits of CV and AV deployments in monetary units for various penetration rates.(165) More specifically to RwD, Ghasemzadeh and Ahmed used SHRP2 data to analyze the complex effects of weather, speed limits, and traffic conditions on drivers' lane-keeping behaviors.(111) Cicchino and Zuby quantified the causes of lane drifts.(10) Pape et al. used quantitative lane-keeping behaviors to develop a driver model and then combined the driver model with models of RwD countermeasures to estimate their benefits.(164)

Tasks

This initiative would involve four tasks.

Task 1. Develop a Research Plan

- Survey the factors leading to RwDs.

- Survey present and forthcoming CV-related countermeasures for RwDs.
- Associate countermeasures with departure precursors and then develop a plan for estimating the countermeasures' effectiveness.

Task 2. Develop Driver Models

- Use naturalistic driving data to develop models of human lane-keeping behavior in normal and near-crash circumstances.
- Develop models of human responses to current and proposed countermeasures.

Task 3. Simulate Development and Prevention of RwDs

- Combine the driver model with a model of a vehicle and a countermeasure.
- Simulate cases of impending departure to estimate the countermeasures' effectiveness.

Task 4. Integrate the Results

- Use crash and traffic statistics to estimate the number of RwDs that are preventable in representative circumstances.
- Report the countermeasures' effectiveness in a way that can be incorporated in a benefit–cost analysis.

Follow-On and Implementation Activities

The results of this effort will contribute to the RwD portion of benefit–cost estimates for CV and AV infrastructure modifications. Going forward, the model can be used to evaluate candidate designs of vehicles, infrastructure, and their interactions.

INITIATIVE 4. CURVE-WARNING CHALLENGE

Background

To facilitate V2I-technology deployment, AASHTO issued the SPaT challenge to State and local transportation-infrastructure owners and operators to incorporate SPaT broadcasts in at least one coordinated corridor in all States by 2020. In the same way, a curve-warning challenge can be the successor to AASHTO's SPaT challenge. This initiative would encourage States to identify ramps and curves with high counts of RwDs (or rollovers for heavier vehicles) and complement existing advisory signs with CV technology. A TIM for curve warning already exists and is being deployed, thus requiring minimal technical development. The challenge would be to standardize advisory speeds. The AASHTO Green Book allows considerable latitude in advisory speeds.[(166)] Differences vary according to agency practice or even regional driving culture. More advanced demonstration projects would include information, perhaps from a Road Weather Information System (RWIS) or prior stability control activations, on the weather and road surface conditions.

Prime candidates for early deployment are locations with a history of RwD incidents, tight curves at the bottom of a hill, and curvatures that are difficult to see.

Objective

The objective is to encourage State and local transportation agencies to start deploying V2I-communication equipment. An additional objective is to counteract RwD crashes at horizontal curves using V2I applications.

Potential Benefits

The initiative will be a step toward deploying V2I applications. The short-term benefit is that State and local transportation agencies will acquire valuable experiences and lessons about DSRC-based V2I communication and identify sites suitable for curve-warning applications. Another long-run benefit is that larger V2I curve warning–application deployments will have significant safety benefits.

Relationships to the Existing Body of Knowledge

Stephens et al. developed the concept of operations for the CSW application.[(92)] Pilot deployments include various versions of the application. Many aspects of AASHTO's SPaT challenge and lessons learned from the program can also be used to support this initiative.

Tasks

This initiative would involve three tasks.

Task 1. Literature Review

Conduct a comprehensive review of literature on DSRC-based curve warning. This will provide an understanding of this V2I application's current development stage. Any missing links or knowledge gaps will be identified, and appropriate remedies can be implemented.

Task 2. Identify the Requirements of the V2I Curve-Warning Application and Provide Guidance

This task will solidify the application's technical requirements and provide guidance to State and local transportation agencies to ensure that they accomplish their objectives. This will include completing the communication standard and assistance on site selection, ensuring DSRC equipment acquisition and compatibility, and developing reference materials. The task may also include training State and local transportation department staffs on how to install and maintain the equipment and collect and analyze the application-generated data.

Task 3. Outreach to Transportation Agencies and Supervision

Meet with existing stakeholders and State and local transportation departments to establish consensus on the curve-warning challenge. Provide a followup or supervision for the challenge.

INITIATIVE 5. EXTENSIONS TO THE CSW APPLICATION

Background

The V2I CSW safety application alerts vehicles if they are approaching a curve too fast. Some current implementations treat the application as an electronic version of the advisory speed sign. It alerts a driver, who may have missed the advisory sign or has not realized that the vehicle speed is higher than the posted advisory.

This feature can be expanded to benefit both CVs and AVs. The AASHTO Green Book allows considerable discretion in establishing an advisory speed.(166) Transmitting the curve's geometric information along with current surface conditions would allow approaching vehicles to make more pertinent speed choices.

Information necessary to select a maximum safe speed for a curve comes from three sources. The first source is fixed information about the infrastructure: the curvature and superelevation. Second is current information about the surface. Information on weather or road weather can come from existing sources available to transportation departments. Currently available products infer surface conditions from humidity and temperature measurements. A possible application extension would include information that the HFST is known to have deteriorated and has yet to be restored. Reports of loss-of-control messages can also be included. Information from the infrastructure can be packaged in the RSU and transmitted to the vehicle. The third source of information is on the vehicle itself, such as cornering ability (or roll threshold for a heavy vehicle), and the tire-tread condition and holding ability (i.e., for futuristic systems). This is sufficient information for speed selection in an AV. The more meaningful advisory speed would prove beneficial despite the complications of the CV's driver's skill and preference.

Within a few years, nearly all light vehicles will have automatic emergency braking. This function is designed to detect fixed objects in a vehicle's path and automatically apply the brakes. Conceivably, the enhanced application on a vehicle with no other automation could engage the brakes when it approaches a curve at an excessive speed.

Objective

The objective is to take full advantage of the CSW application, benefitting both CVs and AVs as they approach a curve.

Potential Benefits

The enhanced message will remove the inconsistency and uncertainty AVs face as they interpret existing advisory speed signs. The additional contents on road surface conditions will benefit human CV drivers.

Relationship to the Existing Body of Knowledge

A concept of operations for CSW applications developed for the ITS Joint Program Office envisioned transmitting geometry and current road-weather information.(92) Some early implementations have been simpler, transmitting only a fixed advisory speed or an advisory accounting for geometry and traffic.[167] This initiative would lead to transmitting more information and extend the use to AVs.[168]

Tasks

This initiative would involve three tasks.

Task 1. Document the Opportunities Offered From an Enhanced CSW Application

- List the functions that the application can perform.

- Consult with stakeholders, including AV manufacturers and standards committees, to develop a concept of operations and identify any changes to standards needed for initial testing.

Task 2. Develop an Application to Demonstrate

- Select an appropriate subset of features.
- Write and test code to be implemented in an RSU.
- Demonstrate the features with vehicles in a controlled environment.

Task 3. Test the Enhanced Application in a Deployment

- Identify a CV program through which the application can be demonstrated with real traffic. This would most likely be an existing or previously planned deployment. Preferably, both CVs and AVs would participate.

- Collect data on the application's performance and its effect on RwDs.

- Recommend further action, which might include revised standards or continued research.

INITIATIVE 6. INPUT FROM STATE AND LOCAL TRANSPORTATION DEPARTMENTS AND OTHER STAKEHOLDERS

Background

A working relationship among all stakeholders—Federal agencies, State and local transportation departments, research organizations, vehicle manufacturers, and others—is crucial to CV and AV success. Therefore, promoting understanding and coordination facilitates increased interaction between vehicle manufacturers and infrastructure officials. Ideas include encouraging AASHTO to send delegates to SAE committees, supporting State and local agency staffs to attend vehicle manufacturers' CV and AV demonstrations and vice versa, and delivering workshops and webinars dedicated to sharing experiences between public and private agencies. Issues can be identified and addressed collaboratively. Better communication can also lead to a common understanding of the technologies, and what they can do and what they cannot do.

This is a broad topic with many activities already underway. Topics of interest to the RwD Team would include support for better virtual rumble strips, advance notice of lane closures, availability of road weather information, and implementation of the CSW application.

Objective

The primary objective of this initiative is to cultivate a platform for better communication among stakeholders to facilitate a strategic roadmap for planning and implementing actions in CV and AV technologies. A secondary objective is to clearly identify CV- and AV-technology requirements from the infrastructure officials' and vehicle manufacturers' points of view and to work toward achieving them.

Potential Benefits

Developing a strong relationship among State transportation departments, infrastructure officials, the private sector, and other stakeholders is important for mutual benefits to these organizations as well as efficient and successful CV- and AV-technology deployment. Better communication allows experiences to be shared and the priorities, challenges, and opportunities of CVs and AVs to be identified, as perceived by all interested parties. This also has the potential to create educational and outreach opportunities for the staff.

Relationships to the Existing Body of Knowledge

A survey-based study by Zmud et al. that developed a strategic CV and AV roadmap for transportation agencies outlined how local agencies plan to include these technologies, but also revealed that they are not sure how to incorporate them in their current and future transportation planning activities.(157) Carlson and Poorsartep suggested improved collaboration among infrastructure officials, research organizations, and automotive industries to devise a common understanding of how the physical infrastructure may be modified to better accommodate CV and AV technologies.(161) Shladover and Gettman observed that the vehicle industry has yet to fully align with the agencies that own and operate the roadway infrastructure with respect to CV and AV technology despite the obvious synergies between them.(169) Their recommendation 2.4 deals with the technical aspects of DSRC communication and its associated institutional issues; this initiative recommends communication on broader topics.

Some State agencies are actively engaged in advancing CV and AV initiatives. This recommended effort facilitates engagement among other States and smaller agencies that are not early adopters.

Tasks

This initiative would involve three tasks.

Task 1. Identify the Stakeholders and Develop Customized Communication and Engagement Approaches

Stakeholder interests and concerns are varied and, therefore, require a customized approach to communication and engagement. This task will identify any gaps in the relationships and communication among stakeholders.

Task 2. Define Each Stakeholder's Roles, Responsibilities, and Engagement Level

Up front planning for each stakeholder's roles and responsibilities allows the organization to understand how it fits into the overall CV and AV picture. Outlining the benefits an organization will gain from participating in communication will lead to better commitment and ensure successful CV and AV deployments.

Task 3. Conduct Outreach Meetings

Meetings can be a combination of online and in-person events. Ideally, they will be advertised and held in forums familiar to the target audience (such as Every Day Counts, AASHTO, and regional organizations).

Follow-On and Implementation Activities

This initiative will continue, and the training content will evolve as deployment progresses.

INITIATIVE 7. V2I TECHNOLOGY–AWARENESS TRAINING FOR STATE AGENCIES

Background

The expanding deployment of CVs and, to a lesser extent, AVs will lead to new staff roles and responsibilities at State transportation departments. To accommodate future needs, some State and local agencies are working to involve their staff in CV and AV technologies. However, many agencies do not have the resources to devote staff to keeping up to date on these technologies. Some are only beginning to learn about new developments. Transportation departments need support to make decisions such as which V2I services to provide and where RSUs should be located. Therefore, developing a guidebook to cover the basics of DSRC and the infrastructure's role in providing services is important. It would explain how agencies can get help from State transportation departments or find FHWA resources to plan and deploy CV infrastructure. Further in the future, training modules for technicians who install and maintain CV equipment will aid local agencies that are responsible for deploying communication equipment in the infrastructure. If the guidebook is online with the Federal-Aid Highway Program Policy and Guidance Center, it can be updated as technology advances. Early education, engagement, and outreach to these agencies will ready their staff to contribute to the actual deployments of these technologies and be part of the overall process.

Overviews of CV principles will enable agencies to deploy V2I systems; certain components will be specific to RwD. A pertinent training module might demonstrate how to select locations to protect with the CSW application and how to construct a TIM for a location.

Objective

The objective is to educate and train the staff of small county and local agencies on CV technology. This will determine how the roles and responsibilities of transportation staff will change as CVs become widely deployed. It will result in identifying which skills are lacking and how these skills could be introduced to an agency. The initiative would promote awareness and participation in small county and local agency staff for CV technology in general and V2I technology in particular so that would be better prepared to deploy communication equipment and operate the system.

Potential Benefits

As part of the overall professional development benefits, this initiative will increase local agencies' staff capacity to adapt to emerging technologies. This will improve the effectiveness and efficiency of wider V2I-application deployments. This initiative will have multiple implications, like increased opportunity for innovation and strategic planning and increased capacity to meet CV methods and operational needs. Trained staff will monitor industry changes and increase their contribution to the overall business processes at local agencies by being proactively prepared for these emerging technologies.

Relationships to the Existing Body of Knowledge

A recent survey-based study by Bertini et al. examined the perception and preparedness of the ODOT staff for CV and AV technologies.(170,171) The study revealed that most respondents knew about these technologies and were in favor of their application. However, many (up to 34 percent of respondents) had concerns about training, education, and outreach to ODOT's personnel.

Tasks

This initiative would involve three tasks.

Task 1. Identify Who Needs What Skill Sets

Local agencies will need staff that know how CV technology works and how functions can be integrated with daily traffic operations and management. The roles of transportation engineers, planners, and operators will change from routine design, construction, and maintenance to new technology-driven operations. The need for enhanced information technology, wireless communication, and data management will rise. As local agency staff transition from passive to active roles, they must gain a clear understanding of the skills required to complete their duties. This task will identify the new skills that traffic engineers, operations staff, and field technicians must master.

Task 2. Identify How and When These Courses Will Be Delivered

Outline the frequency of the courses to achieve short-, medium-, and long-term improvements. In addition, delineate the courses' appropriate development (scope and content) and delivery method, such as direct staff training through various methods like online resources or workshops or "training the trainer."

Task 3. Develop Suitable Courses

Having identified what skill sets are lacking, develop structured courses that complement the skill needs of State and local transportation department staff. Each course should consist of practical applications and be designed with specific objectives and learning outcomes that can be used by individuals in State and local agencies.

Follow-On and Implementation Activities

This initiative will continue, and the training content will evolve as deployment progresses.

INITIATIVE 8. SOFTWARE AID TO DESIGN FOR ACCOMMODATING CVs AND AVs

Background

Highway designers will have to apply new principles when designing for CVs. AVs may impose requirements on designs as well. A software aid can serve many functions in preparing and evaluating a highway design to support CVs and AVs.

The tool's evaluations of CV features will potentially apply to equipment, DSRC transmission, and messages. The tool will determine whether planned RSUs are in the right locations. Consideration will be given to ensuring that line-of-sight transmission paths are not blocked and that information can be received by vehicles before it will be needed. In addition to evaluating geometry, the tool will evaluate the software that generates V2I messages to ensure they adhere to standards and are consistent with best practices in supporting traffic. The tool will check TIMs and MAP messages for compliance with highway design plans. More specific features are likely to come from early stakeholder meetings.

Levels of road readiness for AVs are being considered the infrastructure counterpart to SAE's vehicle-automation Levels. This aid will assess those Levels in existing roads using as-built drawings for proposed construction and reconstruction projects.

Many diverse stakeholders need to be consulted at several stages. The FHWA geometric-design staff, representatives of users at State transportation departments and private engineering firms, early transportation department CV-technology adopters, vehicle manufacturers, equipment suppliers, and domain experts in the relevant fields (e.g., DSRC transmission and machine vision) are all crucial to the project's success. Preferably, there would be more than one organization representing each viewpoint. Some meetings must gather all stakeholders in the same room.

Objective

This initiative will result in a new software tool so that highway designers can evaluate a design's ability to support CVs and AVs. The first phase will advance the work to a software requirements document.

Potential Benefits

This initiative will be a significant step in moving highway support of CVs and AVs from pilot studies to operation.

Relationships to the Existing Body of Knowledge

NCHRP has a pending project to develop a uniform classification system to help agencies assess the degree of readiness of their roadways to accommodate CVs and AVs.(172) Johnson, in a report for the Royal Automobile Club Foundation for Motoring Ltd. discussed a number of ways to prepare roads for AVs.(173) Part of the recommended work will involve incorporating the findings of these and similar studies in the tool.

Tasks

The preparatory phase will comprise two tasks.

Task 1. Establish a List of Desired Features

- Enlist stakeholders representing the necessary disciplines and perspectives.
- Develop a list of design attributes that the aid will evaluate.
- Identify technical criteria for evaluating a design according to each of the attributes.
- Sketch possible user interfaces for the module.

Task 2. Prepare to Write the Tool

- Draft a concept of operations.
- Draft a software requirements document and interface documents.

Follow-On and Implementation Activities

The software tool will be developed in a subsequent phase. At first, the tool can be tested against an existing CV deployment at a pilot site. The next step is to demonstrate it in a construction or reconstruction project, or at least in a new RSU deployment effort. As the practice of CVs and AVs matures, the software tool can eventually become a new module for the IHSDM.

INITIATIVE 9. TIGHTER MARKING AND SIGN REQUIREMENTS IN THE MUTCD

Background

The MUTCD includes standards, guidance, and options for pavement markings and signs. However, the MUTCD can never fully anticipate all geometries and alignments. There are instances in which the MUTCD is open to subjective interpretation by traffic engineers, resulting in inconsistent applications of pavement markings and signs. These inconsistencies can confuse an AV's machine vision. This initiative will gather cases from AV manufacturers about longitudinal pavement markings and sign images that were ambiguous or impossible to interpret. It will also gather information from State and local transportation-department cases in which the MUTCD did not apply directly and gave inadequate instruction.(4)

Human factors, machine vision principles, MAP message standards, and highway engineering practicalities can be applied to developing new wording that resolves potential issues. The result can lead to a revision to the MUTCD, which would provide supplemental guidance for unconventional geometries or perhaps change requirements.(4)

The initial project will make recommendations on which situations to include in the MUTCD and which require research to find the best solution. Some variations will inevitably be left for the AV manufacturers to navigate.(4)

Objective

Tighter standardization will lead to consistent application of longitudinal marking and signs within and across States. Developing longitudinal-pavement-marking requirements that are more broadly applicable will lead to consistent, reliable, and higher quality markings and signs, all of which perform the way they are intended. This is beneficial both to human drivers and AV machine-vision systems, increasing the probability of the markings being recognized and correctly interpreted and at the same time supporting safe navigation.

Potential Benefits

This work is part of the larger effort to reduce the number of instances in which an AV is unable to determine its proper path. This effort will expand the operating domain of AVs and reduce the number of RwD crashes resulting from misinterpreted markings.

Relationships to the Existing Body of Knowledge

Several studies have confirmed that the main challenge of AVs is longitudinal pavement markings that are inconsistently applied and inadequately maintained. For example, a finding from the 3,400 miles of automated driving covered by an experimental AV revealed that lane marking inconsistency between States posed significant problems.(76) Two recent studies examined how the width, color, and retroreflectivity of pavement markings affect their suitability for machine vision under dry and wet conditions.(66,161) A current research project is assessing how elements of physical highway infrastructure and traffic control devices in particular can be designed, enhanced, and applied to meet the needs of both the human driver and the machine driver.(174) The European Road Assessment Programme and Huggins et al. discussed the effect of inconsistent lane markings and road signs on safe AV navigation.(175,176) In the absence of adequate applied markings, some researchers, Lattke et al. among them, have shown that a vehicle can track another longitudinal feature parallel to the lane.(35) AV manufacturers have said that a V2I message that locates the lane with respect to recognizable fixed objects would prove useful.

Tasks

This initiative would involve three tasks.

Task 1. Identify Inconsistent Longitudinal-Pavement-Marking and Road-Sign Applications

- Discuss what situations give rise to these inconsistencies.
- Document the reasons and rationales for these inconsistencies.
- Assemble a list of the extra, State-created markings and signs. For example, some States use varieties of black and white stripes to enhance contrast on light-colored concrete.
- Compile a list of features subject to misinterpretation by AVs as pavement markings (such as sealing lines and ghost stripes—latent visible features after a stripe has been removed).

Task 2. Develop Guidelines That Close the Gap Between the MUTCD Standards and State Practices

- Provide solutions to the problematic situations that give rise to inconsistent pavement marking and sign applications.
- Identify how to update the MUTCD so that it considers AVs.(4)

Task 3. Identify Secondary Sources of Information

- Identify sources of redundant information that can be useful in situations in which pavement markings and signs designed strictly according to the MUTCD's rules fail to convey full geometry information.(4)

Follow-On and Implementation Activities

The first year's effort should be able to identify many inconsistencies in pavement marking and recommend trial solutions to a few of them. Some ambiguities may be resolved by consensus. Selecting the best contrasting pavement marking, among other issues, will require a research program carefully designed to estimate crash modification factors and select the best approach.

INITIATIVE 10. SYNTHESIS OF MACHINE-READABLE SIGN TECHNOLOGY

Background

Road signs instruct drivers how to navigate easily, drive safely, and observe laws. Some existing machine-vision systems are able to identify and interpret signs and can display the signs on the instrument panel. However, signs can be obscured by traffic, weather, or vegetation, or they can be damaged. Information on road signs can be communicated to vehicles electronically. Available technologies include the TIM communicated to CVs, an RFID tag affixed to a sign or other object, and cellular messaging. Each technology has its own relative advantages in terms of deployment, maintenance cost, ability to reach many vehicles, ease of changing the message, susceptibility to loss, and other factors. Information from these supplemental sources can be displayed on the instrument panel to the human driver or made available to AVs' decisionmaking algorithms.

Machine-readable sign technology must be assessed so that highway designers and vehicle manufacturers can select an approach that meets their joint needs.

Objective

The objective is to list available products and mature technologies that can communicate information from road signs to CVs and AVs.

Potential Benefits

A redundant source of road-sign information will benefit all drivers. Human drivers with vehicles that have displays will not be subject to obscured or missing signs. AVs will perform more reliably in their operating domain when road-sign information is delivered directly in machine-readable form. This synthesis will aid in the cooperation of highway operators and vehicle manufacturers to establish a common approach.

Relationships to the Existing Body of Knowledge

An NCHRP project nearing completion studies the requirements for pavement markings so that AVs can use them.(172) This project will be a similar effort for signs. A topic being considered for NCHRP will examine the physical highway's future infrastructure—specifically traffic control devices—with respect to AVs.(177)

The MUTCD has standards for human-readable signs.(4) SAE J2735 has standards for contents of CV messages, which might contain some conventional road-sign information.(178) Although writing them is beyond the scope of this initial effort, standards for machine-readable signs will eventually be necessary.

Tasks

This initiative would involve two tasks.

Task 1. Literature and Product Review

- Identify products marketed to communicate road-sign information to vehicles.
- Identify other potentially applicable products and technologies.

Task 2. Assessment

- Develop a list of criteria for evaluating the technologies that encompasses the needs of all stakeholders.
- Rate the products and potential products.
- Recommend continued evaluation of the products.
- Outline the standard needs of machine-readable sign technology.

Follow-On and Implementation Activities

This task requires a balance of conflicting needs. As conventional signs have been standardized for decades, machine-readable signs must be sufficiently standardized so that vehicles can interpret them as they travel across jurisdictions. On the other hand, overly restrictive decisions could stifle innovation. A necessary step in the future will be to convene stakeholders from State transportation departments and other highway operating agencies, vehicle manufacturers, and technology vendors, to develop a path forward that provides both flexibility for technology enhancements and certainty to vehicle manufacturers.

INITIATIVE 11. IDENTIFICATION OF HIGH-RISK LOCATIONS USING CV DATA

Background

Crash-prone locations have traditionally been identified by the high incidence of crashes over a period of years. BSMs are broadcast by vehicles equipped with CV devices. BSMs contain a vehicle's location, speed, brake-application status, and other information. A series of BSMs from a single vehicle can be analyzed to indicate when a driver needed to make sudden maneuvers or when a driver nearly lost control. These incidents can be used as surrogates for crashes in general and RwD crashes in particular.

Records of near-crash incidents can call State transportation departments' attention to unexpectedly sharp curves, instances of low friction, poor visibility, and other needs. Transportation agencies can use the data to quickly identify locations needing corrective action, unlike current methods, which require waiting for numerous crashes to occur. These crash precursors can prove more valuable in selecting appropriate remediation because, unlike mere crash counts, they suggest the crash's cause.

A State transportation department can scan information from aggregated BSMs for indications of RwD-crash precursors. The time, location, and nature of precursors are recorded. When the density of precursors reaches a certain threshold, officials are alerted to the possibility that a location is susceptible to a certain kind of RwD. Officials examine the data, collect further information as necessary, and implement countermeasures. For example, if many dynamic stability-control activations are recorded on rainy days, the inadequate drainage or deterioration of the HFST may be discovered, and the transportation department may decide to groove the pavement. Many hard-braking events might indicate inadequate warning of a curve.

In a practical deployment, BSMs would be analyzed by an RSU because summary data are easier to send to the back office than a large volume of raw BSMs. At the research stage, individual BSMs may be necessary.

Objective

The objective is to develop a means to identify locations or conditions that are susceptible to RwDs, using information from vehicles' BSMs.

Potential Benefits

The initial phase will indicate which contents of the BSM or combinations of contents are related to RwDs. Subsequent phases will include pilot deployments to confirm the relationship between algorithms and departures in prospective studies while refining the algorithms.

When fully implemented, State transportation departments will be able to identify locations with unusually large numbers of precursors to RwDs. They will be able to use the detailed information to select suitable countermeasures.

Relationships to the Existing Body of Knowledge

Smith et al. tested candidate algorithms with existing data.[(65)] Most of the crashes they analyzed were forward collisions, including some RwDs. Algorithms specific to RwDs need to be developed and tested.

A recent GAO report on CV benefits reported an effort in Japan, in which 160 locations of sudden braking were identified using data from vehicles.[(151)] Officials investigated the cause, and remedial steps (such as trimming trees to improve visibility) decreased injury crashes by 20 percent.

An NCHRP project currently under consideration will examine how agencies manage the data expected from CV applications, which can support transportation operations.[(179)] The results of that project will support the analysis of CV data for many purposes, including the one recommended here.

Tasks

The first phase will be to refine the concept of operations in preparation for a pilot study:

- *Identify precursors to RwD crashes.* Consider references in the literature review in chapter 2 and consult other sources.

- *Relate the precursors to BSM contents.* Develop candidate algorithms for detecting precursors that are related to a location's crash risk. Different algorithms will likely be necessary for different precursors. An integrated algorithm may be needed to relate to overall RwD risk.

- *Test and refine the algorithms.* Data may be available from previous naturalistic driving studies. Alternatively, data can be generated by a Monte Carlo simulation of vehicles navigating roadway segments while various combinations of roadway, weather, and driver deficiencies are modeled. Estimate the sensitivity of the algorithms for identifying high-risk locations and conditions.

- *Outline a pilot study.* Design a prospective study to collect BSMs from vehicles in naturalistic driving. Collecting BSMs before and after an event may be desirable. The study will have enough vehicles and duration so the algorithms can be quantitatively evaluated. The outline will include criteria for selecting locations and expected results.

Follow-On and Implementation Activities

Planning will be followed by a pilot study in which BSMs are collected to test algorithms. The study would be more efficient if joined with an existing CV effort (such as those being planned in Tampa, FL; New York, NY; Wyoming; and Columbus, OH). The pilot study will further refine the algorithms and write lessons learned to aid in establishing a system at a State transportation department. The duration of the pilot study will be decided in the first phase; at least a year is likely necessary.

The ultimate users of the system will be State transportation departments responsible for identifying and mitigating hazards on their highways. Researchers developing the algorithms and implementing the systems will need to consult with State transportation department representatives at milestones during this project to ensure that the product will be consistent with their deployment of V2I equipment and that the data are presented in a useful form. Closer coordination with State transportation departments will be needed when remediation actions are considered.

EXISTING AND SMALLER EFFORTS

This section describes other activities for the RwD Team to monitor as they proceed or encourage development in the future.

Road Weather Information to AVs

Slippery surfaces contribute to RwDs. Localized road weather information from CVs is made available to State transportation departments to support treatment decisions and manage traffic flow.[99,180,181] Road users presently employ this information only to support travel decisions. As manufacturers make more use of localized weather information for travel decisions or for controlling vehicles, State transportation departments will have a role in supplying the information. Among the sources of road weather information are RWISs' sensors reading pavement temperature and humidity, State transportation department vehicles (usually snowplows), and V2I messages from CVs. AV manufacturers may want different combinations of snow cover, surface temperature, relative humidity, estimated friction, or a temporary speed limit.

Standards and Business Model for Maintaining and Delivering Roadway Geometry

V2I standards have two messages for delivering geometric information—MAP and TIM. Elaborate 3D maps are commercially available. Inherent map shortcomings are that they need to be updated continuously, and a conventional GPS signal is inadequate for lane-level navigation. A policy question is whether a State transportation department has a responsibility to provide a minimal level of detail. A technology question is about the best reference, which is a fixed roadside object the vehicles can sense (such as a bridge abutment, a benchmark placed in the pavement, or a station to broadcast a correction signal). AV navigation would benefit from collecting, maintaining, updating, and communicating roadway attribute information (maps) seamlessly and in a uniform manner.

Farrell et al. observed that distribution of such feature maps is still in its infancy. To date, such distribution has not been implemented and tested over large regions (i.e., States, countries). Various CV testbeds, on increasing scales, have been implemented.[182] As these demonstrations have progressed, recommended changes (e.g., large-sized messages to allow accurate descriptions of large intersections, and additional features) to SAE J2735 have been one of the demonstration outcomes.[178]

Given the need for the maps to be updateable, interesting questions arise:

- How will the need for local map updates be detected or communicated to the map manager?
- How will local map updates be integrated into the map database efficiently while maintaining spatial continuity?
- How can data integrity be assured if map updates are obtained from different sources?

As with many previous initiatives, the distinction between AV navigation and RwD avoidance may be blurry, but FHWA and its State partners clearly have an interest in working with industry to answer these questions. Data for mapping is a part of an anticipated NCHRP project.[177]

Standard for Pavement-Marking Removal

Standards address the texture, color, retroreflectivity, and other features of pavement markings. However, there is no standard for longitudinal-marking removal or treatment after scraping. It is important to ensure that unneeded markings and their residues are completely removed when adjustments to lane use or assignment are made. Often, particularly in work zones, ghost stripes, or an appearance of the former stripes, are still visible after markings are ground off. Ghost stripes can lead to confusion for drivers and the machine vision of AVs. Therefore, research on treatments needed during or after lane-marking removal to suppress ghost stripes is imperative.

Recovery Guidance for Errant Vehicles

A more futuristic project would be to guide errant vehicles back to their lanes or, at least, away from roadside hazards. At least one step has been taken toward that goal.[35] Avoiding rollovers on slopes and avoiding unexpected roadside features (such as recently disabled vehicles and their occupants) are among many considerations.

RwD-Safety Risk Index for Road Segments

A comprehensive RwD-safety risk index would quantify the exposure, probability, and consequence of expected RwD crashes as a function of location. The index could be based on presence or absence of guardrails, shoulder widths, presence or absence of utility poles, manholes, ditches, and other roadway hazards. The objective is to develop a technique to support RwD safety analyses by examining the features of road segment and scoring their corresponding risk indices. The risk index would be communicated to vehicles by incorporating it with the navigation systems or transmitting it via V2I communication. The index can be used to adjust the threshold for issuing a warning to road users (e.g., drivers may receive high-intensity warnings when approaching a road segment with a relatively high RwD-safety risk index—assuming a high safety index represents a high probability and severity of RwD crashes).

Reconsidered Geometric Design for AVs

Shladover and Gettman developed a broad plan of CV and AV research for AASHTO.(169) Two of their recommendations on RwDs should be noted in this report. Their recommendation 2.4, that State transportation departments and vehicle manufacturers cooperate on technical DSRC standards, was referenced in initiative 6 on communication between vehicle manufacturers and transportation agencies. Their recommendation 2.7, to reconsider roadway geometric design concepts for AV operations, is to address the transformative effect AVs will eventually have on infrastructure. Any such changes need to make full use of knowledge about RwD-avoidance principles.

New IHSDM Module for CV and AV Technology

When CV and AV technologies have matured to the stage that infrastructure standards for supporting them are settled, references to them will appear in the *Highway Safety Manual*, and a dedicated module for the IHSDM can be considered.(112)

CHAPTER 5. CONCLUSIONS

The literature review and the Web meetings heightened understanding of CV and AV technology to prevent and mitigate RwD crashes. The gaps between current and desired capabilities became clear. The RwD Team can consider promoting the items in the research implementation plan to fill those gaps and enhance its mission.

LITERATURE REVIEW

The literature search produced an abundance of information on how CV and AV technology can be used to improve RwD safety and the development needs of these technologies. The results of the literature search concerning the effectiveness of the emerging technologies for counteracting RwD crashes can be summarized as follows:

- *CVs.* Vehicle connectivity (V2V and V2I technologies) can be useful for many applications that directly reduce RwD crashes and their severities. CV technology is being successfully demonstrated in research projects. Some applications of CV technology are speed management, lane-level localization of vehicles, curve warnings, spot weather warnings, and lane drop warnings. CVs can be effective for counteracting RwD crashes by providing critical safety messages regarding downstream weather, road friction, road alignment, and other infrastructure-related information. Another innovative use of such technology is for identification of hot spots without waiting for significant numbers of crashes to occur.

- *Vehicle automation.* The effectiveness of driver-assistance systems (such as LDW and low-level vehicle-automation systems like LKA systems) has been found to be less than initially predicted. Due to excessive false warnings, drivers tend to deactivate the systems. Low-level driver-assistance systems and low-level vehicle-automation systems typically rely primarily on machine vision, and their performance is limited by lighting and weather conditions. Many current LKA systems also fail to adapt to individual drivers' habits. Considering that driver errors are contributing factors to a significant proportion of crashes, vehicles with high levels of driving automation are a promising technology for improving road safety by eliminating driver error. AVs are challenged by inconsistencies in existing infrastructure. In addition, existing road signs and lane markings were not developed for automated use. These shortcomings present opportunities for modification of the existing infrastructure. High-resolution, 3D, digital maps of roadways and nearby features are promising technologies that can help AVs recognize their lanes and efficiently navigate in roads where lane markings are faded or covered with snow. Smart infrastructure attempts to reengineer the existing roadways by adding a digital component. Smart lane markings and smart roadway lights dynamically improve visibility of lanes and roadways during nighttime driving and adverse weather conditions.

GAP ANALYSIS

A total of 27 participants from diverse stakeholder perspectives attended 3 Web meetings. Participants included technology developers, research and development organizations, vehicle manufacturers, State and local transportation department and transportation official representatives.

The findings from the needs assessment include the following:

- The biggest challenge AV technologies face is a lack of standardization. Lane-marking patterns differ between States and within States. Curves in different States with identical geometry can have advisory speeds more than 10 miles per hour different. V2I message contents are in the development stage.

- The needs of CV and AV technologies differ, though there are some common needs. As AVs mature, they will require information available through CVs or other sources.

- Redundancy of information is always beneficial. Sensors on a vehicle cannot acquire all the information necessary in every circumstance. Information about the static components of the infrastructure (e.g., signage and roadside inventory) can be used in combination with information obtained from AV sensors and messages from V2V and V2I applications.

- Technical issues need to be addressed for V2I applications to be effective in rural areas. Power for RSUs is a question, and an economic way of deploying RSUs with sufficient density for seamless communication coverage is needed.

- V2I connectivity requires that transportation departments install RSUs and develop applications on vehicles to use the information. This is the "chicken and egg" metaphor in which it is unclear whether transportation departments should first install RSUs or manufacturers should first develop and perfect their V2I applications.

- Collaboration and frequent communication between infrastructure officials and developers of CV and AV technologies is necessary for a common understanding of the challenges and capabilities.

These findings were consistent with the findings of the literature review. Together, they provided a strong foundation to develop a comprehensive list of initiatives for the research implementation plan. Initiatives were outlined to address the RwD components of each gap.

RESEARCH IMPLEMENTATION PLAN

This report identifies some steps that FHWA can take to prepare for a future when CVs and AVs are more common. Through these initiatives, FHWA's partners at State transportation departments can prepare themselves and the infrastructure that they operate to realize the safety benefits CVs and AVs offer. The report recommends technology advancements so the infrastructure can better support CV and AV operations. It recommends outreach activities, so the staff at State and local transportation departments understand their role in deploying and maintaining their assets that support CVs and AVs. The projects cover topics, ranging from outreach and education to State and local transportation departments' staffs to technical issues concerning the capabilities of CV and AV technologies for reducing the frequency and severity of RwD crashes.

FHWA and the RwD Team's continued contribution to the broad programs sponsored by other Government agencies, academia, and industry will improve the likelihood of achieving successful implementation of CV and AV capabilities. Taken together, these efforts will improve the infrastructure's transition from the current norm of human drivers with conventional traffic control devices to a future where CVs and AVs are common.

CV and AV are emerging technologies, and their applications will not be perfected instantly. Rather, they will require continual research and development. For these technologies to have a beneficial effect, they will require communication-standard implementations and some infrastructure-component modifications. The benefits of CV and AV applications will not be specific to RwD crashes only; benefits will always overlap with other safety concerns (e.g., rear-end and lane-change crashes), mobility, environment, and others. Table 1 shows the research activities and their focus areas.

As shown in table 1, the recommended initiatives cover diverse topics concerning RwD crashes and CV- and AV-technology development. Overall, the initiatives cover technical issues concerning CVs and AVs, communication standards development, State and local transportation agency engagement and outreach, support to be provided by infrastructure officials, adjustments to be made to traffic engineering manuals (such as the MUTCD), and economic benefit–cost analyses of the emerging technologies.(4)

Table 1. Range of approaches the initiatives cover.

Initiative	Specific to RwD	Infrastructure	Includes CV	Includes AV	A New Initiative	Technology	Standards	Outreach
1. Effectiveness of current driver assistance	X	-	-	-	-	X	-	-
2. Characterization of lane-keeping practices	X	X	X	-	-	X	-	-
3. Simulations to estimate the benefits of CV countermeasures for RwDs	X	-	X	-	-	X	-	-
4. Curve-warning challenge	X	X	X	X	X	X	-	X
5. Extensions to the CSW application	X	X	X	X	X	X	X	-
6. Input from State and local transportation departments and other stakeholders	-	X	X	X	-	-	X	X
7. V2I technology–awareness training for State agencies	X	X	X	X	X	-	-	X
8. Software aid to design for accommodating CVs and AVs	-	X	X	X	X	X	-	-
9. Tighter marking and sign requirements in the MUTCD(4)	X	X	-	X	-	-	X	X
10. Synthesis of machine-readable sign technology	-	X	-	X	X	X	-	X
11. Identification of high-risk locations using CV data	X	X	X	-	X	X	-	-
A. Road weather information to AVs	X	X	X	X	X	X	X	-
B. Business model for roadway geometry	-	X	X	X	-	-	X	-
C. Standard for pavement-marking removal	-	X	-	X	-	-	X	-
D. Recovery guidance for errant vehicles	X	X	-	X	X	X	-	-
E. RwD safety index for road segments	X	X	X	X	X	X	-	-
F. Reconsidered geometric design for AVs	-	X	-	X	X	-	X	-
G. New IHSDM module for CV and AV	-	X	X	X	X	X	X	X

X = the initiative in the row has the attribute named at the top of the column.
-Not applicable.

APPENDIX. WEB MEETING PARTICIPANTS

Three Web meetings were held to assess the needs of CV and AV technologies. The objective of the Web meetings was to assess the gaps between the states of CV and AV technologies suitable for counteracting RwD crashes and their successful deployment. Identifying the gaps will lead to the need for FHWA actions and steps to develop the research implementation plan. Table 2 lists the number of participants from the various types of organizations.

Table 2. Meeting participants represented diverse perspectives.

Affiliation	Number of Participants
State or local transportation department	10
Independent research organization	7
Industry	6
University	4
Total participants	**27**

The Web meetings were held on March 14, 22, and 29, 2017, from 1 to 3 p.m. eastern time.

WEB MEETING 1

Most of the participants came from State and local transportation departments. The readiness of the infrastructure and planning agencies to embrace CV and AV technologies was discussed. Topics included evaluating the awareness of agencies on CV and AV technologies, assessing what agencies are envisioning, and discussing how they intend to incorporate CVs and AVs in their transportation planning activities.

WEB MEETING 2

Most of the participants were leading researchers and developers from academia and industry. The objective of this meeting was to assess the suitability of these technologies for counteracting RwD crashes, to discuss their challenges and opportunities, and to examine how infrastructure officials can support them.

WEB MEETING 3

A mix of stakeholders attended the final meeting. This meeting focused on encouraging consultation among the researchers and developers of CV and AV technologies, State and local transportation departments, and infrastructure officials so that they could share experiences, raise awareness of their roles, and outline studies that create a common understanding of how the design, operations, and maintenance of the infrastructure may be modified to better accommodate CVs and AVs.

Discussion questions designed to stimulate conversation among the participants were prepared before each Web meeting. A staff member from FHWA welcomed the participants at the beginning of each meeting. The discussions in all three meetings continued smoothly with the moderator intervening only occasionally.

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