Ensuring Cooperative Driving Automation (CDA) and Vulnerable Road Users (VRUs) Safety Through Infrastructure

PUBLICATION NO. FHWA-HRT-22-085

SEPTEMBER 2022

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
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FOREWORD

Vulnerable road users (VRUs), including pedestrians, bicyclists, motorcyclists, and various micromobility users, account for a significant share of roadway fatalities. VRUs are at the most risk in urban areas, and, thus, urban areas are a focus area for implementing new transportation technologies. These new technologies include automated driving systems (ADS) and cooperative driving automation (CDA), which can potentially have positive or negative effects on VRU safety.

This literature review documents the potential impact of ADS-equipped vehicles and CDA technology on VRU safety and the potential role of infrastructure in facilitating safe interactions. This review discusses the factors that currently influence VRU collision rates, especially in high-risk urban areas. It also examines the capabilities and needs of ADS-equipped vehicles when interacting with VRUs and the additional positive and negative impacts that the deployment of CDA technologies are likely to have on VRU safety. Finally, the review includes a prioritized list of research gaps and safety risks that were identified by a panel of ADS and VRU experts who met to discuss the potential challenges associated with ADS-VRU interactions.

This report should be of interest to transportation engineers and researchers, State and local transportation agencies, and others who have an interest in VRU safety, ADS-equipped vehicles and CDA technologies, and the role of infrastructure in facilitating VRU safety.

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Recommended citation: *Federal Highway Administration, Ensuring Cooperative Driving Automation (CDA) and Vulnerable Road Users (VRUs) Safety Through Infrastructure* (Washington, DC: 2022) https://doi.org/10.21949/1521914.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HRT-22-085	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Ensuring Cooperative Driving Automation (CDA) and Vulnerable Road Users (VRUs) Safety Through Infrastructure		5. Report Date August 2022
		6. Performing Organization Code: HRSO-30
7. Author(s) Starla Weaver (ORCID: 0000-0002-9559-8337) Jose Calvo (ORCID: 0000-0001-8820-702X), Ananna Ahmed (ORCID: 0000-0002-5353-508X), Jesse Eisert (ORCID: 0000-0003-0116-5141)		8. Performing Organization Report No.
9. Performing Organization Name and Address Leidos, Inc 6300 Georgetown Pike McLean, VA 22101		10. Work Unit No.
		11. Contract or Grant No. 693JJ319D000012
12. Sponsoring Agency Name and Address Office of Safety and Operations Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Covered Final Report; May 2021–July 2022
		14. Sponsoring Agency Code ITS/JPO and HRSO-30
15. Supplementary Notes The contracting officer's representative was Brian Philips (ORCID 0000-0002-8426-0867).		

16. Abstract

Vulnerable road users (VRUs), including pedestrians, bicyclists, motorcyclists, and a variety of micromobility users, are at an increased risk for collisions, severe injuries, and fatalities relative to other road users, particularly in crowded urban environments. New transportation technologies could have both positive and negative effects on VRU safety. These new technologies include automated driving systems (ADS), which are capable of controlling vehicles with no or limited input from human drivers and cooperative driving automation (CDA), which send and receive cooperative and safety messages. The current literature review assesses the potential impact of ADS-equipped vehicles and CDA technology on VRU safety and the potential role of infrastructure in facilitating safe interactions. The review also includes a prioritized list of issues related to human factors and generated research needs, based on feedback from a panel of subject matter experts.

17. Key Words Vulnerable road users, automated driving systems, cooperative driving automation, infrastructure	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 32	22. Price N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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LIST OF ABBREVIATIONS

AADT	annual average daily traffic
ADS	automated driving systems
AV	autonomous vehicle
CDA	cooperative driving automation
eHMI	external human-machine interface
FHWA	Federal Highway Administration
GPS	Global Positioning System
LiDAR	light detecting and ranging
MUTCD	*Manual on Uniform Traffic Control Devices*
NHTSA	National Highway Traffic Safety Administration
OEMs	original equipment manufacturers
SME	subject matter expert
TCDs	traffic control devices
VRU	vulnerable road user
V2I	vehicle-to-infrastructure
V2P	vehicle-to-pedestrian
V2V	vehicle-to-vehicle
X2X	machine-to-machine

INTRODUCTION

Vulnerable road users (VRUs) account for a significant share of roadway fatalities. The term VRU refers to any road user who is not protected by the shield of a vehicle cab. This group includes pedestrians, bicyclists, motorcyclists, and a variety of micromobility users. In 2019, VRUs accounted for 34 percent (11,303) of all fatalities that occurred during a motor vehicle collision (National Center for Statistics and Analysis, 2020). Although VRU fatality rates have decreased from 2018 to 2019, VRUs are still tied with passenger car occupants for comprising the largest portion of fatalities from motor vehicle collisions and for making up a greater percentage of fatalities than the occupants of light trucks, large trucks, buses, and other vehicles.

VRUs are at particular risk in urban areas. Since 2015, shifts in population density have led to overall fatality rates in urban areas becoming more prevalent than fatality rates in rural areas, with more than 58 percent (19,595) of all fatal crashes occurring in urban areas in 2019 (National Highway Traffic Safety Administration (NHTSA), 2020). This shift has had a particularly negative effect on VRU safety. Fatalities of all types of VRUs have increased in urban areas since 2010, with motorcyclist fatality rates up 36 percent, pedalcyclists up 49 percent, and pedestrians up 62 percent in 2019 (NHTSA, 2020).

Urban environments are likely to be the target area for the implementation of new transportation technologies. Vehicles equipped with automated driving systems (ADS) or driving systems capable of controlling vehicles with no or limited input from human drivers are currently undergoing testing (SAE International On-Road Automated Vehicle Standards Committee, 2018). Likewise, cooperative driving automation (CDA), or components of the transportation system that are able to send and receive cooperative and safety messages, are in development (SAE International On-Road Automated Vehicle Standards Committee, 2020). Due to the presence of established infrastructure and larger potential customer bases, business models and market research suggest that many of the early adopters of ADS-equipped vehicles and CDA technology, such as rideshare and delivery companies, are likely to begin operations within urban environments (Legêne et al., 2020). The initial use of driving automation in crowded urban environments, where VRU traffic is also typically at its peak, indicates that interactions between ADS-equipped and CDA vehicles and VRUs will be common. Ensuring the safety of VRUs during these interactions might require the implementation of infrastructure solutions, countermeasures, and strategies.

The goal of this current literature review is to assess the potential impact of ADS-equipped vehicles and CDA technology on VRU safety and determine the potential role of infrastructure in facilitating safe interactions. First, this review discusses the factors that currently influence VRU collision rates, especially in high-risk urban areas. Next, the review examines the capabilities and needs of ADS-equipped vehicles when interacting with VRUs. This examination is followed by a discussion of the additional positive and negative impacts that the deployment of CDA technologies is likely to have on VRU safety. Finally, the review ends with a discussion of research gaps and safety risks that were identified by a panel of ADS and VRU experts, who met to discuss the potential challenges associated with ADS-VRU interactions.

VRU RISK FACTORS

Previous research has identified several major factors that increase VRU risks. These factors increase the VRUs' risk of collisions and the potential for severe injuries and fatalities. Major risk factors include vehicle speed, time of day, location of road crossings and surrounding infrastructure, and VRU characteristics and behaviors.

Speed

The speed of an oncoming vehicle is one of the known factors that increases VRUs' injury risk. Injury and fatality rates from a crash involving VRUs are highly influenced by the speed of the vehicle involved. It has been well established in the literature that the risk of serious injury and death increases as speed increases (Rosén et al., 2011; Tefft 2013; Gårder 2004). This increase is more pronounced at speeds greater than 37 mph. Tefft (2013) found that for pedestrians, the risk of severe injury or death increases exponentially as speed increases, particularly when a pedestrian encounters a vehicle traveling at a speed greater than 40 mph. In addition to increasing the risk of serious injury and death, high speeds increase the probability of crashes, because vehicles traveling at high speeds have less time to stop.

Due to the impact of speed on both crash risk and crash severity, several infrastructure countermeasures have been used to attempt to reduce speed in areas where VRUs are at risk. Lowering speed limits in areas with high volumes of pedestrian traffic can reduce vehicle speeds (Hu & Cicchino, 2020). In addition, installing roundabouts and multiway stop signs reduce drivers' speed (Retting et al., 2003). Traffic-calming measures—including narrowing a road lane, adjusting the curvature of roadways, and adding pedestrian islands and speed humps—also slow down traffic, although research on whether the slower speeds generated by traffic-calming measures translate to increased pedestrian safety is mixed (Retting et al., 2003).

Visibility

Visibility plays a major role in pedestrian safety. Most pedestrian fatalities (76 percent) occur after nightfall (NHTSA, 2019). Drivers at night have reduced sight distance in comparison to their daytime sight, and both pedestrians and drivers are more likely to be drowsy or impaired when traveling at night (Toran Pour et al., 2017). Dark roads are one of the leading causes of VRU deaths because drivers on dark roads are not able to see VRUs, and VRUs often overestimate their visibility (Wang & Cicchino, 2020). Infrastructure that increases pedestrian visibility can improve road safety. This improvement can be achieved by increasing the number of roadway lightings near pedestrian crossings or by installing lights within crosswalks (Miller et al., 2004). During both nighttime and daytime hours, cars parked along the edge of roadways can prevent drivers from seeing pedestrians who intend to cross the road. Eliminating roadside parking or creating diagonal parking can also help increase pedestrian visibility (Retting et al., 2003).

Location and Infrastructure

Another factor that increases the risk of collisions involving pedestrians is the location at which such crashes occur and the infrastructure at the crash location. Traffic control devices (TCDs) are known to reduce the crash risk for VRUs (Gårder, 2004). Infrastructure can be used to separate pedestrians from traffic, either temporally or spatially. Temporal separation can be achieved by implementing measures that prevent pedestrians and drivers from attempting to cross an intersection at the same time. For example, exclusive traffic signal phasing can be used to allow a time during which only pedestrians are able to cross the road. Exclusive traffic signal phasing leads to significant reductions in traffic crashes involving pedestrians. Pedestrians can also be temporally separated from drivers by long yellow lights that allow traffic to clear the intersection before pedestrians begin crossing. Pedestrian crossings that automatically detect and adjust their timings when a pedestrian is present on the roadway achieve the same result. Spatial separation of pedestrians from drivers can be achieved by overpasses and underpasses, provided that pedestrians consider such passageways to be safe and convenient. Sidewalks can keep pedestrians away from the edges of a road, whereas refuge islands and curb extensions can make crossing the road easier by segmenting large crossings into multiple, more manageable segments (Retting et al., 2003).

Road types also influence pedestrian crash risk. Wide roads, such as arterial roads and major collectors, have been shown to have higher crash rates than two-lane roads, even after accounting for differences in pedestrian volume (Gårder, 2004). Arterial roads are considered high-capacity urban roads, with speeds and traffic flow just below freeways or motorways on the road classification hierarchy. Pedestrians, specifically, are at the highest risk of being involved in crashes on roadways that are in areas that have high traffic volume, are highly populated, and have employment density as well as areas with large concentrations of commercial or retail and multifamily residential land uses (Loukaitou-Sideris et al., 2007). Built environment and traffic density also make some roads more dangerous than other roads for pedestrians. A study by Zhao and Chen (2016) investigated data extracted from the Transportation Police Bureau in Zhengzhou and Xi'an, China, and found several variables related to roadway type that were linked to bicyclists' crash frequency. These variables included the number of left-turn lanes, number of through lanes, left turn annual average daily traffic (AADT), and annual average ratio or major direction AADT to minor direction AADT. As each of these variables increased, the crash frequency increased as well. The availability of midblock crosswalks was associated with a reduction in crash frequency. In addition, greater corner radius and greater shoulder width are associated with a higher number of pedestrian crashes (Fitzpatrick et al., 2016).

Most collisions involving pedestrians occur at major intersections (Rothman et al., 2012). Such collisions likely occur because most pedestrians cross the road at major intersections. Furthermore, major intersections typically contain large volumes of vehicle traffic moving at relatively fast speeds. Thus, both pedestrian exposure and crash rates may be overrepresented, in particular, for intersections. Midblock crossings, especially those at unsignalized crossings and those at crossings with no markings, are the riskiest in terms of injury and death rates, especially for children (Rothman et al., 2012).

In addition to the structure of the roadway and location of the crossing, the existence of markings and infrastructure that support safe crossings for pedestrians also contribute to the risk of crashes involving VRUs. Crosswalk markings are associated with slower speeds, both with and without a pedestrian present (Knoblauch & Raymond, 2000; Schneider et al., 2004). Crosswalk markings can increase the conspicuity of pedestrians and channel pedestrians who are crossing from multiple midblock locations to a single, designated path. However, the effect that crosswalk markings alone have on pedestrian safety is unclear. Some reports indicate that these crossings enhance safety (Knoblauch et al., 1988), whereas other researchers report that the markings are associated with an increased crash risk, particularly when the crossings are implemented with no other interventions on multilane roads (Herms, 1972; Koepsell et al., 2002; Zegeer et al., 2001). One possible reason for the increase in pedestrian crash risk on marked crosswalks could be a bias in the proportion of pedestrians crossing at those locations. Research shows that pedestrians typically prefer crossing at intersections with crosswalk markings (approximately 70 percent of pedestrians cross at marked intersections) (Zegeer et al., 2001). If crosswalk markings are added as a treatment to roadways that already have a high rate of pedestrian crashes, then the markings may actually encourage pedestrians to continue crossing at those high-risk locations. Thus, when installed at high-risk locations, markings are best used in combination with other interventions, such as curb extensions, a raised median, a crosswalk island, or pedestrian signals (Zegeer et al., 2001).

Meir, Parmet, and Oron-Gilad (2013) provide another potential explanation for the mixed results with regard to the effectiveness of crosswalk markings at midblock locations: They found that under conditions of uncertainty, such as when pedestrians' field of view was restricted by parked cars or road curvature, the presence of a marked crossing increased the tendency for pedestrians to enter the roadway. The effect was especially exaggerated among children. Marked crossings might increase the confidence of pedestrians, such that they are more likely to attempt potentially risky road crossings. The results suggest that unsignalized midblock crosswalk markings should not be used on roadways where pedestrians' view of oncoming cars is restricted or in locations where children make frequent, unattended crossings.

VRU Characteristics and Behavior

The frequency of pedestrian crashes and fatalities varies as a function of age, with children and older adults being most at risk of severe injury or death (NHTSA, 2019). Because of their size, children tend to be less visible to drivers. Children also have underdeveloped perceptual motor coordination (Chihak et al., 2010), and they are less able to identify hazardous situations or judge roadways as dangerous than adults (Meir, Parmet, & Oron-Gilad, 2013; Meir, Oron-Gilad, & Parmet, 2015). As a result, children are more likely to quickly enter potentially dangerous roadways.

Older adults are also at an increased risk of being in a road-crossing accident (Rothman et al., 2012). Age-related reductions in perceptual, motor, and cognitive abilities can place older adults at greater risk when they are attempting to cross a road. For example, as adults age, their useful field of view, or the area over which they can acquire information in a brief glance, narrows such that they may be less able to see oncoming traffic (Bromberg et al., 2012). Aging can also be associated with reductions in mobility that reduce walking speed (Lobjois et al., 2013). When faced with simple one-way road crossings, older adults are often able to compensate for reduced perceptual and motor functions by choosing larger gap sizes, such that their road-crossing ability is not impaired (Lobjos et al., 2003). However, when faced with multilane crossings, older adults tend to be less successful at adequately attending to and basing crossing decisions on traffic in the far lane than younger adults. This tendency puts older adults at a greater risk for injury or death when crossing multilane roadways (Dommes et al., 2014). When involved in a collision, older adults, whose health statuses and bodies tend to be more fragile than younger adults, are at a much greater risk of severe injury or death (Hakamies-Blomqvist et al., 2004).

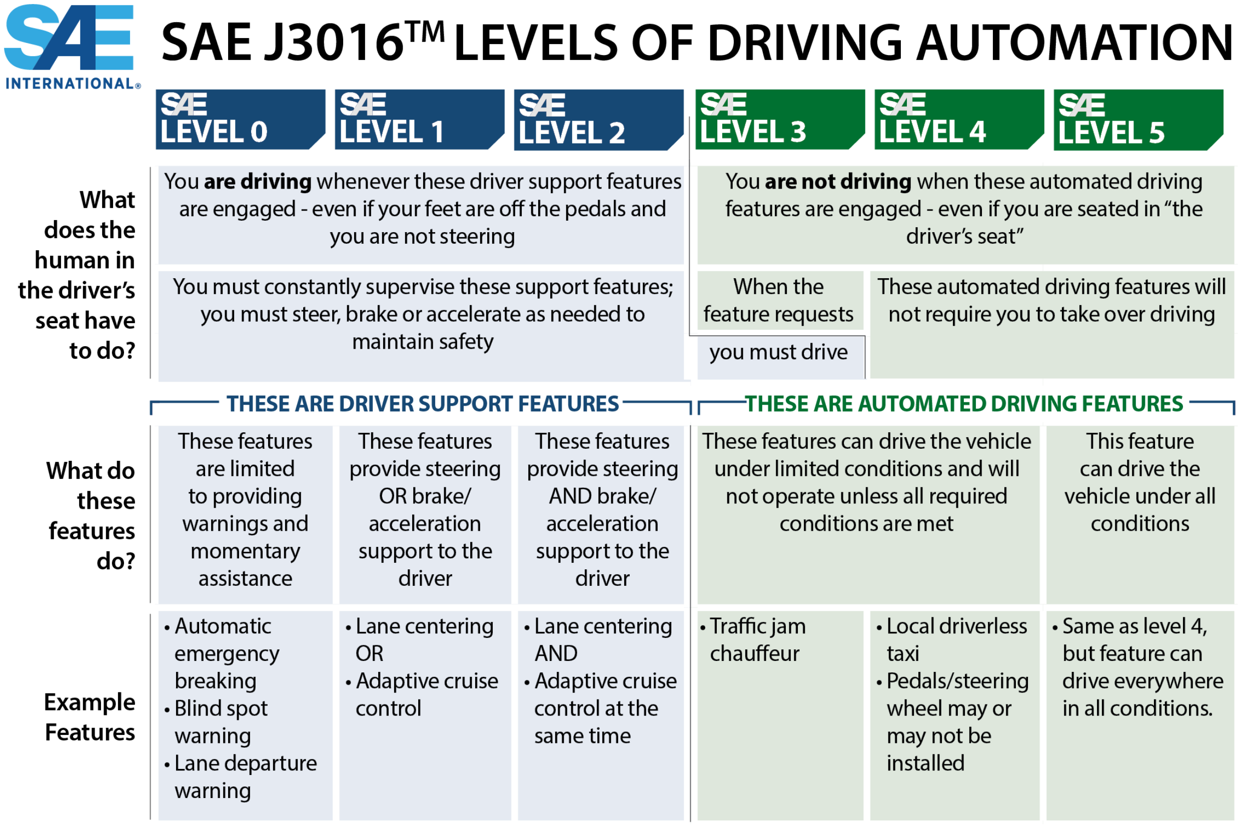
Gender also influences VRU risk. Research suggests that males tend to engage in more risk-taking activities than females. This increased risk-taking has interesting implications on road-crossing abilities that vary by age. Specifically, assessments of children's road-crossing ability demonstrate that male children tend to display more mature road-crossing behavior, or behavior that is more similar to that seen among adults, than their female counterparts (Shen et al., 2015). However, by the time males reach adolescence, this reduced fear and increased risk-taking behavior becomes a liability. For example, Schwebel et al. (2009) found that 19-year-old males spent less time attending to traffic before entering a virtual roadway than their female counterparts, and as a result, young men are more likely to be involved in a collision than women of a similar age. Among adults overall, male pedestrian fatality rates are more than double the rates for females (NHTSA, 2019).

VRU behavior is also concerning when assessing the risk to VRUs. Research shows that pedestrian distractions, especially distractions attributable to the use of handheld devices such as smartphones, create an increased risk for VRUs (Fitzpatrick et al., 2016). In addition to looking at or using cellphones, behaviors such as listening to music with headphones and talking with other VRUs are also distracting. On average, just under 50 percent of pedestrians at cross intersections engage in distracting behaviors, of which cellphone use makes up about 10 percent of those behaviors (Fitzpatrick et al., 2016). This distracted behavior is concerning because some drivers might be expecting some type of communication with a pedestrian based on their previous experiences when cellphone use was not as ubiquitous. Previous research indicates that pedestrians often (in roughly 90 percent of cases) attempt to communicate with drivers of oncoming vehicles to let the drivers know of their intention to cross (Rasouli et al., 2017). Rasouli et al. (2017) found that looking in the direction of an approaching vehicle was the most prominent form of communication and that for roughly 15 percent of the time, other gestures such as head nodding or hand waving were used. Given this finding, the high rate of distraction among pedestrians is concerning. If drivers have become reliant on these forms of communication, then pedestrian distraction could be a risk factor for VRUs' interaction with conventional drivers. However, pedestrian-driver interaction is likely to be less of an issue as technology advances and ADS become more prevalent, provided ADS are not anticipating VRU communication.

ADS

The development of driver support features and vehicle automation capabilities has the potential to change the way that VRUs and vehicles interact. The following section defines ADS capabilities, examines five features that ADS-equipped vehicles might need to interact safely with VRUs, and outlines the potential role infrastructure can play in facilitating that interaction.

SAE International On-Road Automate Vehicle Standing Committee (2018) specifies six levels of driving automation, based on the roles and responsibilities of the driver and the automated system (see figure 1).



SAE J3016™ LEVELS OF DRIVING AUTOMATION

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	You **are driving** whenever these driver support features are engaged - even if your feet are off the pedals and you are not steering			You **are not driving** when these automated driving features are engaged - even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests you must drive	These automated driving features will not require you to take over driving	
	THESE ARE DRIVER SUPPORT FEATURES			THESE ARE AUTOMATED DRIVING FEATURES		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering OR brake/ acceleration support to the driver	These features provide steering AND brake/ acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• Automatic emergency breaking • Blind spot warning • Lane departure warning	• Lane centering OR • Adaptive cruise control	• Lane centering AND • Adaptive cruise control at the same time	• Traffic jam chauffeur	• Local driverless taxi • Pedals/steering wheel may or may not be installed	• Same as level 4, but feature can drive everywhere in all conditions.

Figure 1. Levels of Automation (SAE International On-Road Automated Vehicle Standards Committee, 2018).

Level 0, which is the lowest level, represents the conventional vehicle. A Level 0 vehicle may be equipped with advanced safety features that warn the driver about potential safety threats or implement momentary safety maneuvers (e.g., emergency braking, electronic stability control), but the driving task is not automated.

When operating at Levels 1 and 2, the driver temporarily receives assistance from driver support systems that provide either lateral or longitudinal control (Level 1) or both lateral and longitudinal control functions (Level 2). The system is described as an assistive rather than an automated system because the driving task remains the responsibility of the driver.

When operating at Level 3 or higher, the vehicle is controlled by the ADS, which is able to perform all vehicle operations within a specified operational design domain. Unlike at lower levels, where the driver is responsible for monitoring the system, ADS-equipped vehicles might not require a driver at all. At Level 3, the driver may engage in nondriving tasks and is not obligated to attend to the roadway while the ADS controls the vehicle, provided the driver is ready to take over control of the vehicle when requested. At Level 4, there is no condition in which the user would be required to take control of the vehicle. If a vehicle equipped with a Level 4 system reaches the limits of its designated operating domain, the ADS is responsible for achieving a minimal risk condition (e.g., pulling off to a shoulder) without any driver assistance. At Level 5, which is the final level of automation, the ADS does not have a specified operational design domain. Instead, this system should be capable of functioning in all conditions in which a human driver would be capable of driving. The current review focuses on ADS or vehicles operating at Level 3 or higher.

The transition from driver support systems to ADS-equipped vehicles represents a fundamental change in the role of both the vehicle and the driver. Much of the research in this area has been focused on how the introduction of ADS can provide increased safety and convenience to the vehicle user. However, the transition also has important implications for VRUs, especially in urban environments, where interactions between ADS and VRUs are likely to be most frequent. Ensuring that ADS and VRUs are able to interact in a safe manner is a potentially difficult task. Utriainen and Pöllänen (2021) proposed five features that ADS-equipped vehicles require to interact safely with cyclists: (1) the ability to recognize bicycles, (2) the capacity to exhibit yielding behavior based on local laws, (3) the ability to communicate intent to cyclists, (4) the ability to correctly predict the cyclists' intent, and (5) the capability to engage in safe driving patterns. When applied to VRUs more generally, the list creates a helpful framework for understanding the potential benefits and challenges associated with ADS-VRU interactions and highlights the potential role that infrastructure may have in helping promote VRU safety.

Recognize VRUs

The first step to successful ADS-VRU interaction is the necessity for ADS to successfully detect and classify VRUs. This task can be challenging for several reasons. The first reason is VRU size. VRUs tend to be considerably smaller than the passenger vehicles that surround them on the roadways. Even the largest VRUs—such as users of motorcycles, scooters, or bicycles—will have rather small profiles, especially when traveling in the same or opposite direction as another vehicle (as opposed to traveling across traffic). In fact, most collisions between passenger vehicles and both bicycles and motorcycles occur when those VRUs are traveling parallel to a vehicle (Barnett et al., 2020; de Craen et al., 2014). VRUs must be detected regardless of the background environment, which might be cluttered with buildings, signs, vegetation, and other road furniture, especially in urban areas.

Once detected, VRUs must be classified and distinguished from other nonmoving objects in the environment. The task of VRU classification is complicated by the wide range of VRU shapes. The profiles of bicycles, scooters, strollers, and wheelchairs are all different, but they are all equally important to detect. Likewise, the characteristic gait pattern of healthy adults will not be present among pedestrians who are using a mobility assistance device, such as a cane or walker, or among pedestrians who are carrying heavy packages. The reflectivity of any specific VRU can also vary, based on the clothing they are wearing or the time of day. Overcoming these potential challenges has proven difficult, especially during early attempts at VRU detection (Turner et al., 2007). More recent work indicates that technologies' ability to correctly detect VRUs is improving but has yet to be perfected (Tafidis et al., 2019).

ADS-equipped vehicles use different types of sensors—including a camera, light detecting and ranging (LiDAR), radar, Global Positioning System (GPS), and sonar—to obtain information about the surrounding environment. Different sensors vary in their effectiveness at detecting

VRUs. Combs et al. (2019) examined the potential for ADS-equipped vehicles that use different types of sensors to reduce the rates of pedestrian fatalities. The authors virtually reconstructed 5,000 crashes that occurred with a reported pedestrian fatality by using sensor technologies that are expected to be available in ADS-equipped vehicles to determine how many of these crashes could have been avoided by ADS using each detecting technology. For the purposes of this study, the authors assumed that accurate pedestrian detection would be the only potential barrier preventing an ADS-equipped vehicle from being involved in a collision. Five potential combinations of sensors were tested: camera; LiDAR; radar; a combination of camera and LiDAR; and a combination of camera, LiDAR, and radar. Dramatic differences in each technology's ability to prevent the recreated fatal crashes were found, ranging from less than 30 percent with cameras alone to more than 90 percent with the combination of camera, LiDAR, and radar. Combinations of technologies proved more successful than an individual technology, but even the combination of all sensors was not sufficient to prevent all reported crashes.

Advances in sensor detection and classification technology are likely to aid in VRU detection in the future. However, until those advances become a reality, changes in infrastructure may be able to help bridge the gap. Much like human eyes, autonomous vehicle (AV) sensors are susceptible to deficits during adverse weather and in poor lighting conditions (Ye et al., 2021). Therefore, the installation of adequate lighting in areas with high VRU traffic could benefit both ADS-equipped vehicles and conventional drivers (Olszewski et al., 2015). Because VRU detection and classification requires differentiating VRUs from the background environment, limiting the amount of clutter, including signing, near the roadway could also improve detection.

Yield Based on Local Laws

To function safely in their interactions with VRUs, ADS should behave in a manner that complies with all transportation policies and laws, especially laws related to yielding to, and stopping for, VRUs. However, this task might be more difficult than it appears. In the United States, yielding laws for pedestrians and bicyclists vary by State. ADS that intend to operate in different areas of the country may need to change their operation based on their current location. An obvious example of these differences among States can be seen in bicycle passing laws. All States specify that vehicles that are passing bicyclists must do so at a safe distance; however, the specific distance that is considered safe varies by State, from 2 ft in North Carolina to 6 ft for roads with a posted speed limit higher than 35 mph in South Dakota (Barnett et al., 2020). Human drivers show a willingness to break other traffic laws to comply with passing laws and avoid crowding a detected bicyclist. In an examination of more than 1,500 bicycle passing maneuvers, Chapman and Noyce (2012) found that human drivers safely crossed a solid centerline more than 53 percent of the time when passing a bicyclist on roads that did not contain bike lanes. When encountering two seemingly incompatible laws, human drivers are usually able to weigh the potential importance of each law and act in a way that helps ensure the safety of VRUs.

How ADS-equipped vehicles will react under circumstances in which State laws may be in conflict has yet to be determined. However, original equipment manufacturers (OEMs) who retain liability for ADS behaviors are unlikely to program ADS-equipped vehicles to violate any traffic laws. Although this exclusion of traffic law violations in the ADS programming is likely to benefit VRU safety in most instances, it could be problematic in situations where laws may be in conflict, such as when the width of a lane is not sufficient to allow an ADS-equipped vehicle to comply with bicycle passing laws without leaving its lane. The addition of bike lanes or physical separation between cyclists and vehicles, which could prevent this conflicting situation, has already been proposed as a *Manual on Uniform Traffic Control Devices* (*MUTCD*) recommendation for ADS accommodation (Federal Highway Administration (FHWA), 2020).

Bicycle laws vary by State regarding how vehicles should behave around bicyclists and how bicyclists can behave when interacting with vehicles (Barnett et al., 2020). For example, Delaware law specifies that cyclists can respond to stop signs as though they were yield signs, whereas in Idaho, cyclists can respond to red lights as though they were stop signs. Moreover, five States indicate that cyclists can pass through red lights after a reasonable amount of time. To navigate safely, ADS will need to be aware of these potential differences and change their predictions of bicyclists' behaviors in different locations. However, expecting VRUs to always operate according to State laws might not be reasonable. Many VRUs are likely to be unaware of State-specific laws, especially VRUs who are traveling between States. Actual yielding behavior among VRUs has been found to be only nominally linked to formal yielding rules and policies (Sakshaug et al., 2010).

Determining the circumstances and extent to which ADS should yield to VRUs poses an important dilemma. If ADS-equipped vehicles always follow traffic yielding laws, then this predictability could help to enforce those laws in a manner that positively influences VRU behavior in the long term (Utriainen & Pöllänen, 2021). But this practice would make VRUs who currently fail to yield as required by law more susceptible to crashes in the short term. Given VRUs' susceptibility to death and serious injury during a crash, even a short-term increase in crash rates would be extremely detrimental to transportation safety. Alternatively, if ADS-equipped vehicles take a more conservative approach by always yielding to VRUs, the traffic network flow would slow down, especially in high pedestrian areas. Subsequently, VRUs would likely learn to expect ADS-equipped vehicles to always yield, and, as a result, VRUs might engage in more risky behavior. However, because OEMs are likely to determine actual yielding functions, there is the potential for variability in the way that different ADS-equipped vehicles respond to pedestrians.

With repeated interaction, VRUs are likely to learn to anticipate the yielding behavior of ADS-equipped vehicles in different situations. Until that conditioned learning is achieved, infrastructure could help inform VRUs about yielding laws and encourage correct yielding behavior. For example, signs and crossing signals could be used to specify situations that define when VRUs do and do not have priority. Alternatively, ADS-equipped vehicles could help VRUs reduce their potential uncertainty about yielding behaviors in different situations by directly communicating intent.

Communicate Intent

One method that VRUs use when trying to determine whether the driver of a conventional vehicle will yield is to attempt to interact with the driver. VRUs use eye contact and hand gestures to communicate their intent and determine whether they should attempt to cross a road (Fitzpatrick et al., 2016). VRUs cannot engage in this method of communication with ADS-equipped vehicles, given that there is no driver with whom to communicate with. A large number of studies have attempted to examine the need for ADS-equipped vehicles to communicate intent to VRUs and the methods that could be used to produce such communication (Alvarez et al., 2019; Chang et al., 2018; Colley & Rukzio, 2020; Fridman et al., 2017; Hensch et al., 2019; Lundgren et al., 2017; Löcken et al., 2019; Mahadevan et al., 2018; Mirnig et al., 2018).

Most studies whose purpose was to assess the value of ADS-VRU communication have used some type of an external human-machine interface (eHMI). EHMIs are designed to either communicate the intent of the ADS to the VRU or to instruct the VRU on when and how to act. Various eHMI types have been proposed and tested, ranging from relatively simple lightbars to text-based messages to animated communication images (Friedman et al., 2017). The effectiveness of these methods has varied. Simple eHMIs tend to be more effective than complex communication systems (Löcken et al., 2019), but even simple, novel eHMIs might be difficult for VRUs to understand. For example, when Hensch et al. (2019) attempted to use a lightbar affixed to a vehicle to communicate with pedestrians, most pedestrians noticed the eHMI on top of the vehicle but did not believe that they were being addressed by the light signal. Only approximately one-fourth of the participants in the study assumed that the lights represented a warning message to road users. eHMIs that use text messages have the benefit of not requiring VRUs to learn a new communication system (Chang et al., 2018; de Clercq et al., 2019). However, young children and adults with vision deficits may have difficulty with such messages. As a result, multimodal messaging is sometimes recommended (Mahadevan et al., 2018).

The effectiveness of eHMIs has been somewhat mixed. This variation in effectiveness might be because VRUs overestimate how much they attempt to interact with vehicles. For example, surveyed bicyclists identified “accurate detection” as their primary need when interacting with ADS-equipped vehicles, and they expressed a desire for ADS-equipped vehicles to communicate detection explicitly (Hegna et al., 2021). However, when Alvarez et al. (2019) tested pedestrians’ reactions to an ADS-equipped vehicle that was designed to explicitly communicate detection, the eHMI did not affect the pedestrians’ intention to cross the road. Similarly, Clercq et al. (2019) found that eHMI was effective at making pedestrians feel safe but only during instances when the eHMI indicated that it would yield to the pedestrian and not when the eHMI indicated that it did not intend to yield. It seems that when pedestrians identify a vehicle as ADS-equipped, they most likely expect that vehicle to yield, and, therefore, the pedestrians are less willing to comply with eHMI messages that indicate that they should yield to the vehicle.

An alternative to eHMIs is to have ADS-equipped vehicles convey their intent to yield in a manner similar to that used by conventional vehicles. When judging whether to cross in front of a vehicle, pedestrians often use vehicle speed as a cue to determine whether they have been detected by the driver (Ackermann, Chemnitz & Beggiato, 2018; Varhelyi, 1998). When VRUs who had been involved in a crash were asked why they chose to cross the road in front of the vehicle that collided with them, one of the most common responses was that they saw the car decelerate and assumed the driver intended to yield to them, but the slowdown was actually a result of other traffic elements (Habibovic & Davidsson, 2012). Pedestrians express a desire to have ADS-equipped vehicles indicate when they are turning and stopping in a manner similar to the way that such information is gained from conventional vehicles (Merat et al., 2018) and seem to be in favor of familiar communication tools that are already used by drivers, such as flashing lights and honking horns (Löcken et al., 2019). If ADS-equipped vehicles convey their intent through behaviors already employed by drivers, then the learning curve that would be required to interact with ADS-equipped vehicles would be lessened and traveling within mixed fleets would become more predictable for VRUs.

If ADS-equipped vehicles are able to successfully communicate their intent to VRUs in a way that ensures VRU understanding and safety, then the presence of ADS could eventually remove the need for infrastructure intended to convey information about yielding and right-of-way. However, current research indicates that successful ADS-VRU communication may still be a long way off. Furthermore, ADS-equipped vehicles and conventional vehicles are expected to operate in a mixed fleet with VRUs for many years after ADS' implementation. As a result, infrastructure that facilitates safe VRU-vehicle interactions is likely to be necessary for decades to come.

Predict VRU Intent

Ensuring ADS have the ability to correctly predict VRU intent is even more difficult than ensuring ADS can communicate intent successfully. Compared with vehicles, VRU movements are far less restricted and can change at any moment. Even in the most seemingly simple VRU-ADS interaction, road crossing, there are several factors that determine a VRU's willingness to make a crossing (Balk et al., 2014). Once a pedestrian initiates a crossing, the speed, path, and even segments in which the crossing will be accomplished will vary, depending on the pedestrian's capabilities and the infrastructure of the crossing. As a result, accurately predicting how a VRU will behave in a given situation is likely to be challenging (Vissers et al., 2016).

Despite the inherent difficulty of the tasks, many AV developers are attempting to generate systems that are capable of predicting VRU intent (Ohn-Bar & Trivedi, 2016; Kumaar Jayaraman et al., 2020). One potentially promising method for achieving this goal is through neural networks and machine learning. Machine learning could enable ADS to combine information about body and head positions with key infrastructure elements to model and predict pedestrian crossing behavior (Kooij et al., 2014). Initial attempts to use machine learning have demonstrated that machine learning approaches substantially improve the classification of both pedestrian and bicyclist states better than nonmachine learning methods (Goldhammer et al., 2020). One of the main barriers to these prediction models is the absence of extensive databases of VRU behavior that are needed to train these models (Ohn-Bar & Trivedi, 2016). However, with the continued improvement of pedestrian detection systems, the generation of such databases and the capabilities of the subsequent prediction models are likely to improve.

The presence of specific infrastructure elements in an environment are capable of either limiting or facilitating VRU behaviors. As a result, the presence of infrastructure in an environment with high VRU traffic is likely to make the behaviors of those pedestrians more predictable. For example, Balk et al. (2014) found that environmental elements, such as visible countdown pedestrian signal, and median size, were used to form a model of pedestrian road-crossing behavior that correctly predicted 90 percent of the crossings in an urban area.

Safe Driving Patterns

One of the main risks to VRUs comes from unsafe drivers. According to a seminal study by Singh (2015), 94 percent of vehicle crashes can be attributed to human error. Dangerous driving practices, such as speeding and reckless or aggressive driving, put VRUs at risk. Drivers who are impaired, drowsy, or distracted can be just as dangerous. For example, drivers' failure to see or check for pedestrian traffic is a common source of collisions (Habibovic et al., 2013; Werneke & Vollrath, 2012). In a detailed analysis of 60 collisions with pedestrians and bicyclists, Habibovic & Davidsson (2012) found that the most common contributing factor to crashes recorded in the dataset was the failure of the driver to notice a pedestrian or bicyclist, which accounted for 80 percent of the crashes. Although some of these crashes might have been attributable to circumstances that even a good driver or ADS would have had difficulty avoiding (e.g., weather-related perceptual limitations), most are believed to be due to driver error, including driver impairment, fatigue, and distraction. If the majority of crashes originate with human drivers, then eliminating human drivers should have the potential to vastly reduce crashes and improve the safety of VRUs. Thus, an ADS' ability to navigate the roadway using safe driving patterns is one of the greatest potential benefits of this technology.

Thus far, ADS have not met the goal of continuous safe driving patterns. Data from reports of crashes that involve ADS-equipped vehicles from the California Department of Motor Vehicles indicate that pedestrians are still at risk (Ye et al., 2021). This continuing risk is not unexpected, given that ADS-equipped vehicles on the roadway are still under development. Modeling data that make predictions about safety and traffic flow once ADS are ready to be deployed paint a more optimistic picture of ADS-VRU interactions. Tafidis et al. (2019) used microscopic traffic flow simulation software, combined with a surrogate safety assessment model, to predict how bicyclists and ADS-equipped vehicles would interact within a city with a high degree of cyclist traffic and a 100-percent ADS market penetration. Significant reductions in both the quantity and severity of conflicts between cars and bikes were found. Moreover, these safety advantages were accompanied by improved traffic throughput for cyclists. The results point toward the advantages that ADS-equipped vehicles can have for VRUs.

Although the responsibility for ADS-equipped vehicles to achieve safe driving patterns lies with the manufacturers of the systems, appropriate infrastructure can speed the ability of ADS to achieve this goal. The *MUTCD* notice of proposed amendments includes several recommendations for facilitating ADS' driving abilities (FHWA, 2020). ADS that use machine vision will benefit from signing that is standardized, is parallel to the road to which it applies, and, when using LEDs, uses high refresh rates. Since ADS' lane-keeping ability tends to rely on lane markings, ADS-equipped vehicles can benefit from lane line widths that are consistent in size and color. Other recommendations include that lane markings should be added along entrance ramps and exit ramps; along tapers, where an auxiliary lane is added; and throughout temporary traffic control zones, such as detours or work zones.

The five safety features that ADS-equipped vehicles need, which are outlined under the heading ADS in this review, provide a path toward improved interactions between VRUs and ADS-equipped vehicles. Are these features sufficient to ensure VRU safety? After identifying these features, Utriainen and Pöllänen (2021) assessed fatal bicycle crashes that occurred in Finland between 2014 and 2016 to determine whether the proposed characteristics could have prevented those crashes. For most of the crashes, the successful implementation of these five features would have prevented the fatality. However, a minority of crashes involved situations in which a visual obstacle would have prevented an ADS from detecting the cyclist, and the time to collision after the cyclist was detected would not have been sufficient to allow the vehicle to come to a stop in time to prevent the collision. Preventing such crashes would require an extremely cautious ADS, such as an ADS that slowed down each time it neared an object that had the potential to obscure the view of a cyclist. Such as system would hinder traffic flow to an unreasonable extent. Thus, even when ADS technology is at its peak, some circumstances in which the technology would not be capable of preventing a collision with a VRU are expected (Seiniger et al., 2013).

In cases where ADS-VRU safety cannot be achieved by ADS alone, infrastructure may be able to bridge the gap and help ensure VRU safety. Installation of adequate lighting and reductions in sign clutter in areas with high VRU traffic could help both ADS-equipped vehicles and conventional drivers recognize VRUs. Bike lanes and physical separation between vehicles and bicycle paths could help ADS-equipped vehicles comply with local laws. Treatments, such as signs and crossing signals that specify when VRUs do and do not have priority, could encourage both VRUs and ADS-equipped vehicles to yield, based on local laws. Although the ability of ADS-equipped vehicles to successfully communicate their intent directly to VRUs might limit the need for future infrastructure treatments, at present, the presence of infrastructure elements in the environment could help to make VRUs' movements more predictable for both ADS-equipped and conventional vehicles. Moreover, consistent signing and lane markings are likely to facilitate ADS-equipped vehicles' ability to achieve safe driving patterns. One additional capability that has the potential to improve ADS safety is cooperative communication.

CDA

Literature on the capabilities of ADS when interacting with VRUs indicates areas where ADS can improve VRU safety, but there are limits on the technology, which could put VRUs at risk. The addition of cooperative communication or CDA technology could help to mitigate those risks. Vehicles equipped with CDA are capable of transmitting and receiving safety and navigation information (Yang et al., 2017). CDA vehicles are able to connect and communicate with other CDA vehicles through vehicle-to-vehicle (V2V) communication, and with infrastructure and VRUs, through vehicle-to-infrastructure (V2I) and vehicle-to-pedestrian (V2P) communication. CDA communication between unspecified devices that are not within vehicles is referred to as machine-to-machine (X2X) communication.

V2V communication occurs when a CDA vehicle directly transmits information to and receives information from other nearby CDA vehicles. One type of information that can be shared is a basic safety message, which includes the current status of a vehicle, the location of the vehicle, and the other objects the vehicle is able to detect within its immediate vicinity (Nallamothu et al., 2019). During conventional driving, detection of other objects on the roadway tends to be limited to line of sight. Drivers become aware of other road users only when they directly hear or see them. ADS-equipped vehicles can use different types of sensor technologies to detect other objects on the roadway. Some sensors have capacities that exceed those of human senses in certain conditions (Lin et al., 2019). However, as noted in the previous paragraph, the technology still needs to be developed further, and to some extent, the technology is still limited when a road user is occluded by another object (Tafidis et al., 2019). In both cases, the driver or system is likely to be surprised by a VRU that is outside their line of sight, such as when a VRU behind a parked vehicle becomes visible or emerges from fog or snow. A vehicle equipped with CDA technology that detects a VRU could transmit the information about the location of that VRU to other CDA vehicles in its vicinity by offering a warning to nearby vehicles before a vehicle's sensors would be capable of detecting the VRU on its own (Wolterink et al., 2010). Furthermore, this message transmission is not limited to other line-of-sight vehicles because vehicles with CDA technology are able to transmit information around curves and through obstacles (Yang, 2017).

In addition to communicating directly with other vehicles, CDA vehicles have the potential to receive and transmit information to roadside infrastructure through V2I communication. Communication infrastructure that is constructed at key locations could receive safety information from connected vehicles and geocast relevant information to other connected vehicles, thereby increasing the range of messages transmitted by vehicles (Wolterink et al., 2010). Infrastructure could also transmit information about the upcoming roadway or traffic directly from local traffic management centers or smart intersections. V2P communication also offers the potential for CDA vehicles to communicate directly with VRUs, if those VRUs have access to CDA technology.

As previously noted, pedestrian detection remains a challenge for ADS-equipped vehicles. Fatalities can often occur during conditions in which adverse weather and poor lighting might reduce sensor detection abilities (Habibovic & Davidsson, 2012). There are also fatal crashes in situations in which the area between the vehicle and the pedestrian is obstructed by other vehicles, vegetation, or buildings (Utriainen & Pöllänen, 2021). CDA communication offers the potential to make CDA vehicles aware of the presence of a VRU in these situations from either infrastructure that detects the presence of the VRU and conveys that information to the vehicle or from signals sent directly from a VRU that carries a CDA-capable device. Even as AV sensors become more adept at accurately detecting humans, VRU safety could benefit from the redundancy coming from a combination of perceptual and cooperative technologies (Merdrignac et al., 2017).

The potential for CDA technology to benefit VRUs through direct V2P and X2X communication has led to several proposals on how to equip VRUs with CDA technology, including smart attachments to bicycles, smartphone apps, and GPS sensors designed to communicate with infrastructure that then communicate with vehicles (Ordell et al., 2017). Information exchange can occur in several ways. Pedestrian detection systems integrated into the infrastructure at intersections and unsignalized midblock crossings could be used to then inform oncoming drivers and CDA vehicles about pedestrians who might be obscured by a cluttered roadway.

Communication from infrastructure to personal smart devices could help pedestrians better understand when they do or do not have crossing priority. For example, Khosravi et al. (2019) highlighted the potential for smartphone applications that use X2X technology to benefit pedestrians with visual impairments. The application used CDA technology to read signal phase and timing information to determine when it was safe for pedestrians to cross a signalized intersection, and then the application used audio and haptic alerts to convey that information to pedestrians. V2P communication could also be used by bicyclists and pedestrians to receive alerts or warnings when they are in close proximity to other road users, including buses and other motorized vehicles and bicycles (Hincapié-Ramos & Irani, 2013). Providing VRUs with information about potential points of conflict could enable them to alter their behaviors in a way that improves safety. For example, an alert about a vehicle approaching from around a curve could prevent a pedestrian from starting to cross an intersection, an audio alert could help a pedestrian with visual impartments detect the presence of vehicles from a greater distance, or an alert about a motorist approaching from behind could prompt a bicyclist to move closer to the curve.

CDA technologies also offer the possibility for directly communicating with VRUs who may be distracted. For example, visual notifications displayed on a CDA-capable mobile device could communicate with pedestrians who are looking down at their phones. Rahimian et al. (2016) found that pedestrian notification systems displayed to a texting participant were able to prevent the increase in collisions and risky crossings that typically occur when a participant is texting. However, participants who used the notification system also spent less time looking at traffic than participants in either the control (no texting) group or the texting without notifications group, suggesting that participants provided with a notification system may reduce the amount of attention they pay to the road when crossing. This reduction of attention has also been seen among drivers using collision avoidance systems (Dotzauer et al., 2015). Furthermore, once a user has learned to rely on such systems, reductions in attention have been found to transfer to situations in which the alert system is no longer in use. Discovering ways to ameliorate potentially dangerous effects of X2X systems on attention is likely to be an important goal of future research.

Another challenge associated with X2X communication is providing VRUs with access to CDA technology. Bicyclists in Norway and the Netherlands showed some support for the potential benefits of a bike-mounted eHMI that could communicate with ADS. However, potential users were averse to cost and theft risks of on-bike eHMIs. Moreover, VRUs were hesitant about personally bearing the burden of safety, preferring to leave the responsibility to ADS (Hegna et al., 2021). Similarly, bicyclists in the United States expressed a willingness to purchase connectivity equipment if doing so would increase their safety, but that willingness varied, depending on how willing they were to purchase other biking equipment and the estimated price of the technology (Patil, 2016). If connectivity and other safety devices are only adopted by bicyclists that can afford them, then the safety of low-income riders, who may be in most need of nonvehicle transportation options, could be compromised.

Equity concerns are important when considering the feasibility of CDA technology for improving pedestrian safety. Because both a transmitter and receiver are required for the transfer of CDA information, the technology is predicted to be most effective at high levels of market penetration (Yang & Fisher, 2021). The rate of market penetration is likely to lag behind in low-income socioeconomic areas, where the cost of the technology may be prohibitive. Depending on how the technology is implemented, CDA technology may also be less accessible to persons with physical or cognitive disabilities.

Overall, the potential benefits of CDA are promising. However, very little testing or implementation of this technology has been done, and the actual extent of CDA benefits will not truly be realized until more real-world testing is available (Kockelman & Li, 2016). The limited testing that has been done, however, suggests that current iterations of CDA technology have the most benefit when used under their specific operational domain and conditions (Yang & Fisher, 2021). Furthermore, some research has shown that the safety benefits of CDA technologies will only be fully realized at a 100-percent market penetration (Tafidis et al., 2019).

Nevertheless, CDA technologies have many benefits. The primary benefit is the potential to reduce injuries and fatalities through crash severity and crash rate reduction (Anaya et al., 2014; Mahadevan et al., 2019). In addition, there are substantial cost reductions associated with the reduction in crash rates and crash severity. CDA technologies could potentially reduce costs associated with crashes by as much as $126 billion per year, with the greatest potential savings being associated with forward collisions in tandem with cooperative adaptive cruise control, which is estimated to save $22 billion per year (Kockelman & Li, 2016). Furthermore, the benefits of CDA can extend to improving the safety of the vehicle operators as well as pedestrians and other VRUs on the roadways. Primarily, the benefit to VRUs from CDA technologies in comparison to ADS in general is that CDA can gain information from the environment beyond that available to ADS sensors and use that information to help avoid potentially dangerous ADS-VRU interactions (Anaya et al., 2014).

EXPERT OPINIONS

In December 2021 and March 2022, the FHWA Human Factors Team brought together a panel of VRU, driving automation, and CDA experts to discuss the potential benefits and challenges associated with VRU-ADS interactions. Five subject matter experts (SMEs) from industry, government, nonprofit, and academia backgrounds participated.

The first panel meeting began with all members introducing themselves and identifying what they believed were the most critical safety issues related to ADS-equipped vehicles and VRUs. To facilitate the discussion, the Human Factors Team then presented brief background information on ADS and CDA technologies and on the potential interaction with VRUs, once this technology is implemented within urban areas. The team also commented on the potential role of infrastructure in increasing VRU safety. Next, the team posed three questions to help facilitate and guide the panel discussion:

1. What current problems between vehicles and VRUs do you think ADS-equipped vehicles and CDA technology have the potential to solve?
2. What new problems could the introduction of ADS-equipped vehicles and CDA technology bring for VRUs?
3. What changes in infrastructure, including built infrastructure and TCDs, could help to mitigate problematic interactions between ADS-equipped vehicles and VRUs?

Based on a discussion of these questions, the team generated a list of research gaps, which the panel members ranked based on the importance of prioritizing research on the specific topics. A final panel meeting enabled the Human Factors Team to gain consensus on the prioritized list of research topics and to identify additional research gaps that might be a concern for ADS-VRU safety.

The overarching concerns of SMEs regarding the safety of VRUs in the context of the emerging use of ADS-equipped vehicles and CDA vehicles ranged from unrealistic VRU expectations to inefficient VRU detection. The following issues were identified by the SMEs as potential safety-critical issues:

- Mismatched expectations. There is a gap between how VRUs would expect ADS-equipped vehicles and CDA vehicles to interact with them and how this fleet of vehicles may actually be designed to interact. Expectation mismatch was identified as a cause of misunderstanding that might result in an inappropriate reaction by both sides.

- Certain demographic groups. Older adults and people with mobility-related disabilities might need more time to cross a road than a typical pedestrian. The reaction of ADS-equipped vehicles and CDA vehicles in such situations was deemed unclear, hence causing concern for safety professionals.

- Rapid accommodation expectations. The ADS industry is expecting rapid accommodation of built infrastructure and TCDs. A swift moving demand on traffic and safety standards can cause insufficient investigation on the safety aspects of these changes in infrastructure.

- Detection sensors dependence. ADS-equipped vehicles are heavily dependent on detection sensors to identify conflict points and VRUs. Detecting VRUs, especially in crowded urban environments, is challenging for existing sensor technology that is reported in the literature or is being tested by different transportation agencies. The robustness of the detection systems used by ADS OEMs may be a concern because details of their effectiveness have not been disclosed by the OEMs.

- VRU variations. VRUs across different ages, different needs, and different accessibility requirements need different accommodation by ADS-equipped vehicles. Cultural practices and differences in State laws lead to differences in how VRUs behave in different locations. ADS-equipped vehicles, which are likely to travel between different locations, will need to behave safely when interacting with VRUs despite these regional differences.

- ADS-equipped vehicle prioritization. Current literature suggests a bias toward the introduction of and prioritization of the needs of ADS-equipped vehicles over the potential needs of other road users. Therefore, before initiating infrastructural expansions to accommodate ADS-equipped vehicles, there should be research to measure the feasibility of these changes and the safety benefits of such accommodations across all road user types, including the potential effect on conventional drivers and VRUs.

- Solutions organization. Dividing proposed topics into problems and solutions can provide a roadmap for how different agencies and authorities can approach meeting the identified research needs.

Advanced vehicle technology offers several safety and operational benefits. By removing driver distraction, reckless driving, driving under the influence, and other risky behaviors, the overall transportation network can become safer. Moreover, reduced congestion resulting from this technology would contribute to operational efficiency. Yet, many questions remain unanswered and warrant further investigation. Whether ADS and CDAs will be capable of responding to these concerns remains an open safety challenge.

PRIORITIZED LIST OF RESEARCH NEEDS

The following list of research needs was generated and prioritized based on reviewed literature and SME ratings and discussions. The list consists of several potential concerns that are likely to result from ADS-VRU interaction as well as some potential solutions that could help mitigate these concerns.

Areas of Concern

ADS-equipped vehicles and CDA technology offer several potential benefits to the transportation system beyond that which can be achieved with conventional vehicles. However, there are also a number of potential concerns related to how these vehicles will interact with VRUs. The field would benefit from additional research on these concerns and the potential role of infrastructure in mitigating these concerns.

Equity Issues Related to Access to Automated and Cooperative Technology

Persons with certain types of disabilities have limited mobility in the current transportation system. ADS and CDA technologies have the potential to be especially useful to this group, provided the implementation of the technology includes appropriate accommodations. Research examining the usability of ADS and CDA technology for persons with physical and cognitive disabilities could help to identify needed accommodations and help facilitate more equitable technology implementation.

VRU Detection Limitations and the Potential for Infrastructure to Support VRU Detection

Research indicates that there are limits to VRU detection abilities that may put VRUs at risk (Utriainen & Pöllänen, 2021). Can appropriate infrastructure use CDA technology to supplement VRU detection in a way that increases VRU safety?

Determining and Evaluating New Conflict Points Between VRUs and ADS-Equipped Vehicles

ADS-equipped vehicles are likely to be used by rideshare and delivery service companies. The locations where such vehicles pick up and drop off passengers and goods have the potential to be new points of conflict between ADS-equipped vehicles and VRUs. Many roadways, especially in crowded urban environments, do not have locations designed to accommodate pedestrian pickups and dropoffs. As a result, pedestrians engaging in these activities are likely to be in conflict with both ADS-equipped vehicles and traditional traffic. Furthermore, without sufficient infrastructure, ADS-equipped vehicles may resort to blocking bike lanes. Research is needed to determine new locations where VRU-ADS conflict points may occur and what, if any, infrastructure can be used to mitigate conflict and increase VRU safety.

Variability in VRU Capabilities Based on Factors Such as Age and Mobility Capabilities

Older VRUs are often the most vulnerable to injury and fatalities (NHTSA, 2020). When implementing crash countermeasures, it is often the most vulnerable VRUs that must be accommodated. ADS-equipped vehicles that make predictions about VRU intent based on typical pedestrians may leave older pedestrians and pedestrians with limited mobility at risk. Research that assesses VRU behavior will need to include a wide variety of VRUs if it is to be effective in improving safety.

Evaluation of the Impact of Bias in VRU Safety

Research on the interaction between ADS and VRUs often includes an assumption that transportation agencies will make changes to infrastructure and shared spaces that prioritize the needs of ADS-equipped vehicles. However, transportation agencies may not have the means or desire to make such changes. Research is needed to measure the potential safety benefits of creating infrastructure that accommodates the needs of ADS-equipped vehicles and the feasibility of implementing such changes across a variety of roadway types, particularly roadways with high levels of VRU traffic.

Issues Related to VRUs Interacting Within Mixed Fleets

ADS-equipped, CDA-capable, and conventional vehicles are expected to all occupy the roadway together within a mixed-fleet environment. Therefore, VRUs may be unaware of the type of vehicle they are interacting with at any given moment. How vehicle-VRU interactions may change in mixed-fleet environments is an area with a great deal of potential research.

VRU Gap Acceptance for Automated Vehicles

VRU safety during road crossings is dependent on pedestrians selecting safe gaps between vehicles. Research suggests that gap selection can be influenced by vehicle type and size (Klatt et al., 2016). Current research suggests that many pedestrians overestimate the detecting capabilities of ADS-equipped vehicles (Horrey et al., 2021). Will that overestimation translate to riskier crossing decisions when interacting with ADS-equipped vehicles, and can countermeasures be implemented that reduce risky crossing behaviors?

The Government's Role in Ensuring Appropriate Levels of ADS Technology

The introduction of new driving technology onto the Nation's roadways raises questions about who will be responsible for ensuring the technology being developed has undergone adequate safety testing before being deployed. In the United States, requirements for testing and crash reporting are being issued at the State level, with some States, such as California, issuing strict guidelines for ADS testing and other States providing little to no guidance to OEMs (Ye et al., 2021). The potential roles that government organizations such as FHWA, NHTSA, and other transportation agencies will play in generating standards for ADS deployment and collision reporting have yet to be determined. Research that examines the effectiveness of different State policies could be used to guide decisionmaking at a national level.

Potential Solutions

The concerns outlined in the previous section have the potential to be mitigated by advancements in technology and the implementation of infrastructure countermeasures. Some additional potential solutions that warrant further investigation are outlined in this section.

Rules, Standards, and Regulations for VRU and ADS Interaction

The introduction of ADS-equipped vehicles into spaces currently occupied by VRUs, in particular, for those spaces related to curbside interactions between VRUs and ADS-equipped vehicles, is likely to generate conflicts and questions of right-of-way that go beyond what has previously been legislated. New rules, standards, and regulations could provide VRUs and ADS manufacturers with guidelines to help navigate this new space and mitigate conflict. Specifically, there may be a need for new rules for right-of-way and passing when ADS-vehicles interact with VRUs, curb management policies and regulations, and standards for pickup and dropoff zone design.

X2X Communication and the Potential Benefits and Challenges Associated With Shared CDA Data

Cooperative (X2X) communication offers many potential benefits for VRUs, and many open research questions, particularly as X2X communication relates to infrastructure. Questions range from the type of information that should be conveyed to the timing and manner of the conveyed information, to the recipient for whom the information will be most beneficial.

Educating and Managing VRUs' Expectations Regarding ADS Capabilities

Research suggests that VRUs may be prone to overestimate the capabilities of ADS-equipped vehicles (Horrey et al., 2021). Furthermore, in the absence of a dangerous conflict, trust in vehicle automation appears to increase with increased exposure (Penmetsa et al., 2019). Educating VRUs about ADS capabilities could be one way to help manage VRU expectations and trust in a way that encourages safe ADS-VRU interactions.

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Recommended citation: Federal Highway Administration,
Ensuring Cooperative Driving Automation (CDA) and Vulnerable Road Users (VRUs) Safety Through Infrastructure (Washington, DC: 2022) https://doi.org/10.21949/1521914.

HRSO-30/09-22(WEB)E