DISCUSSION GUIDE FOR

Automated and Connected Vehicles, Pedestrians, and Bicyclists

**Pedestrian and Bicycle
Information Center**

Introduction

Pedestrians and bicyclists are a powerful indicator of the social and economic health and safety of a community. A high level of pedestrian and bicycle activity in a community is often associated with more robust economies and healthier, more socially-cohesive populations, while a lack of pedestrian and bicycle activity on roadways can be an indicator that personal security and safety needs are not being met or that destinations cannot be accessed on foot or by bike (PBIC, n.d.).

Presently, technology innovations are disrupting the status quo and reshaping the ways in which people travel. Auto manufacturers are offering new vehicle automation technologies in an effort to improve safety, ease the driving task, and appeal to car buyers. At the same time, nontraditional entities—such as technology firms like Google, Uber, and nuTonomy—are adopting new roles in the transportation arena, advancing shared mobility services and hastening the speed of automation technology development. As vehicle technologies become more automated, navigation around and interactions with pedestrians and bicyclists in complex travel environments will determine their success.

Public uptake of automated vehicles on a large scale basis will not happen until pedestrian and bicycle safety issues are addressed. Despite this fact, pedestrian and bicyclist safety and health issues are not at the forefront of automated vehicle discussions and research. For example, a January 2017 content analysis of 432 United States (U.S.) and international articles related to automated vehicle issues identified fewer than 20 that discussed pedestrian or bicycle topics, either briefly or in depth (Cavoli, 2017).

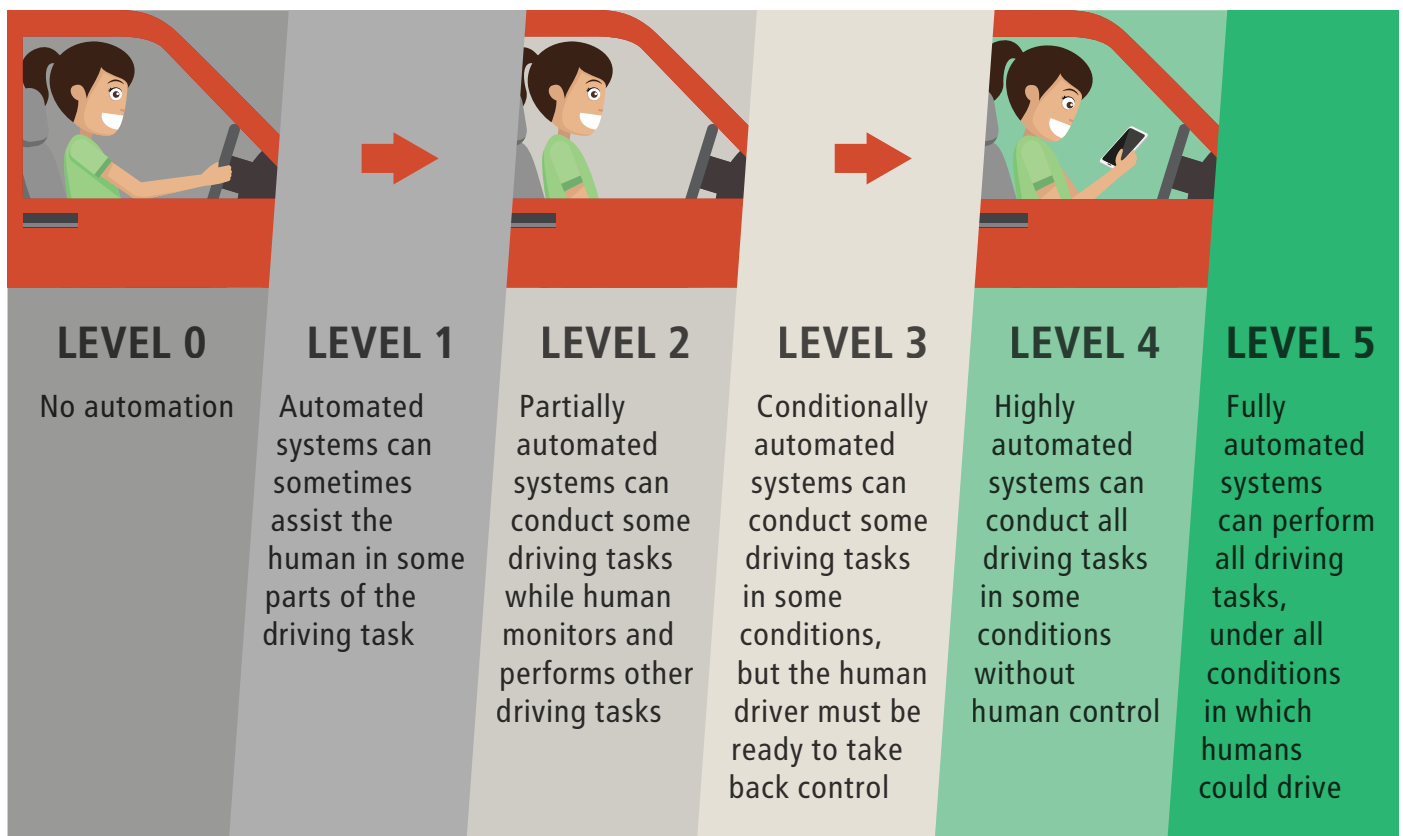This paper presents ten key challenge areas that need to be at the center of automated vehicle

LEVEL 0	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
No automation	Automated systems can sometimes assist the human in some parts of the driving task	Partially automated systems can conduct some driving tasks while human monitors and performs other driving tasks	Conditionally automated systems can conduct some driving tasks in some conditions, but the human driver must be ready to take back control	Highly automated systems can conduct all driving tasks in some conditions without human control	Fully automated systems can perform all driving tasks, under all conditions in which humans could drive

Figure 1. As levels of automation increase, the role of the driver shifts from one of active control of the vehicle, to monitoring, to limited or no involvement in the driving task.

Key Definitions and Terms

"Automation" can refer to the automated control of any number of functions within an automobile. The Society of Automotive Engineers International (SAE) has defined six levels of automation, illustrated in Figure 1. The National Highway Traffic Safety Administration (NHTSA) adopted these definitions in 2016.

In this paper, we use the term "automated driving systems" (ADS) to refer to vehicles with SAE Level 3 automation or higher. We use the term "automated vehicle technologies" (AV) when referring to automated vehicles in general. The following terms and technologies are referenced throughout this paper:

■ **Automated Driving Systems (ADS)** are vehicle functions that can be controlled by the vehicle itself for some period without driver input. A related term is **Highly-Automated Vehicles (HAVs)**, which refers to vehicles equipped with ADS; these terms correspond to SAE Automation Levels 3 – 5.

■ A **Human Machine Interface (HMI)** represents the physical and informational methods and technologies by which a person interacts with a machine. An example is a vehicle's settings interface, or the way in which automation modes are enabled by the driver.

■ The term **Autonomous Vehicles** does not have an industry-wide accepted definition, but typically refers to Level 4 or 5 vehicles that are capable of full self-driving without driver input, at least in some conditions.

■ **Connected Vehicles** use short-range wireless communication to share information about safety, the infrastructure, and other road users such as pedestrians and bicyclists (USDOT, n.d.-a). Automated and connected vehicles can exist separately, but together would be complimentary. CAV is a term often used to describe vehicles that are both connected and automated.

■ **Vehicle-to-Vehicle (V2V)** communication technology is a core component of connected vehicles, using radio signals to allow vehicles to communicate with each other over a short distance.

■ **Vehicle-to-Pedestrian (V2P)**, **Vehicle-to-Infrastructure (V2I)**, **Pedestrian-to-Infrastructure (P2I)**, and other similar acronyms (often condensed to **V2X** or **X2X**) designate wireless communications connecting vehicles, other road users, and the surrounding infrastructure, which also support connectivity-based safety and information systems.

■ **Deep Learning** is a type of **Machine Learning** technique, which is "the practice of using algorithms to parse data, learn from it, and then make a determination or prediction about something in the world" (Copeland, 2017). In this context, it is the way in which highly automated vehicle systems can be "trained" to recognize features of the roadway environment, including people.

■ **Machine Vision** is the process of sensing and processing data recorded using light in the visible spectrum to extract information with the goal of, in this context, recognizing features of the built environment and other road users needed for travel decision-making. It is closely tied to the concept of machine learning, in that machine learning requires machine vision data in order to train the system.

discussions across all sectors and stakeholders, along with a glossary of key terms. It is intended to serve as a discussion guide and orientation piece for people entering the conversation from a wide variety of perspectives, including advocacy, public policy, research, injury prevention, and technology developers. Beyond these ten pedestrian and bicycle specific areas, there remain many other broad challenges affecting all road users (including bicyclists and pedestrians) that come with advancements in vehicle automation. Important concerns such as public perception, acceptance, and trust of automation; law enforcement and emergency response management; system reliability; liability and risk management; privacy; and cyber-security are beyond the scope of this paper, but readers are encouraged to explore the additional resources described at the end of this paper.

Safety and Mobility Considerations for Pedestrians and Bicyclists

New technology innovations and automations in driving tasks offer the potential to increase safety and mobility; however, high-profile crashes with partially and highly automated vehicles have already occurred, indicating that current sensing systems and driving strategies have much room for improvement (Lomas, 2017; Stewart, 2017). In particular, there are concerns about ADS detection of and interaction with pedestrians and bicyclists (Fairley, 2017; Barth, 2017; Levin, 2016). These cases point to the serious issue of unknown or unintended consequences of ADS.

Technological advances that are not planned carefully may produce difficult conditions for walking and bicycling, affecting the quality of life in neighborhoods, commercial districts, and other places where human street activity is essential. More importantly, hastily-implemented vehicle technology could result in pedestrian and bicycle injuries and fatalities. Even technologies that are carefully implemented are likely to have

unanticipated consequences that may affect pedestrians and bicyclists, as well as other road users. Thus, it is important for transportation professionals and the broader public to have ongoing conversations about both existing challenges and the problems that may arise in the future.

The "trolley problem"—in which an automated vehicle faces an unavoidable crash but is presented with a choice between killing a person (or group) outside the car or just the vehicle occupant—is a well-known moral dilemma that has generated a great deal of conversation, debate, and even spurred the development of a Massachusetts Institute of Technology (MIT) ethics testing ground, the Moral Machine. It represents a relatively extreme decision-making problem. Meanwhile, there are hundreds of other important—though perhaps less dire—technical, ethical, legal, and social hurdles that must be cleared in order to advance automated driving systems. The goal of the following section is to shed light on ten other "problems" that, like the trolley problem, merit further attention. These issues, which have the potential to affect pedestrians and bicyclists in particular as well as other road users, will ultimately need to be addressed through some combination of research, innovation, and policy-making. While many of these issues are inter-related and all are extremely nuanced, this paper offers a basic framework to approach these issues and consider policy and research needs moving forward.

Figure 2. A key challenge area for automated technologies lies in their ability to detect and predict the movement of pedestrians and bicyclists in a range of conditions.

#1: The Detection Problem

What it is: The perceptual and computational abilities of automated systems to detect, recognize, and anticipate the movements of other people in and near the roadway are limited (see sidebar). The performance of current technologies in detecting pedestrians and bicyclists is much lower in comparison to detecting other vehicles (Fairley, 2017). Conditions that present significant challenges to human drivers' ability to detect nonmotorized road users, such as low light or glare, adverse weather conditions, road curvature and other impediments to sight distances, present similar challenges for machine-based systems. Even under the best of conditions, machine vision systems are challenged by the detection of low-profile objects such as bicyclists.

Why it matters: Failure to detect, predict the behavior or trajectory, and appropriately react to another road user is an underlying factor in many types of crashes, from turning movement crashes to "multiple threat" crashes and others. A recent study noted that 25 to 60 percent of

pedestrian injury and fatal crashes occurred at intersections and 37 to 65 percent of bicycle injury and fatal crashes occurred at intersections, depending on the data source (Thomas, 2017). Arguably, driver failure to detect pedestrians and bicyclists and appropriately respond when turning left or right or going straight through an intersection is a common contributing factor to a crash. The advancement of turning assist features in Level 1 and 2 systems could reduce these types of crashes. However, the performance of the technologies available today is not well established, and without improved detection of pedestrians and bicyclists, even basic driver warning and assistance technologies, much less more sophisticated ADS, may not significantly enhance safety for vulnerable road users.

Policy implications: As some of the current detection systems rely on cues from the built environment (such as the striping of bike lanes to predict that a bicyclist may be near) (Levin, 2016), there is a need to consider policy and roadway design enhancements that can provide additional contextual warnings, improve detection of pedestrians and bicyclists,

and provide a larger safety margin. This will provide a service both for human drivers in the present as well as the more automated machine drivers of the future. Some of the most effective safety treatments, such as separated bike lanes, improvements in lighting, pedestrian crossing islands, and gateway treatments (FHWA, n.d.), will likely aid in making it easier to detect or predict the presence of pedestrians and bicycles.

Additionally, wireless beacons could theoretically aid in detection as well as connect to infrastructure (P2I) to affect signal timing and prioritization for pedestrians and bicyclists. However, consideration must be given to people who may not be carrying a device by choice or because they do not have the means to own a device (see #2: the V2X problem).

Current and needed research: Multiple approaches are currently under development to improve automated systems' ability to detect and identify pedestrians and bicyclists, which will enable better warning and avoidance technologies (see sidebar). These approaches include onboard systems such as camera-based machine vision systems (Harris, 2015; Hsu, 2016), radar (Siemens, n.d.), and advanced lidar (Ross, 2017; Navarro,

et at., 2016), as well as networked solutions including wireless V2P pedestrian identification beacons (USDOT, n.d.-b.; Volpe, 2017). A video analytics project, led by the Institute of Transportation Engineers (ITE), is currently underway to facilitate improved machine learning based on traffic camera footage. Future ADS applications could build upon the data and what is learned through this project. Additional research is needed to evaluate the pedestrian and bicycle detection capabilities of different ADS sensor systems under various conditions, including: low light, glare, adverse weather conditions, visually cluttered landscapes, crowded streets, amid horizontal and vertical curves, and obstacles such as parked cars. It will be important to evaluate the technology in terms of its ability to detect and predict people with diverse geometric shapes (including people in wheelchairs, different types of bicycles, etc.). Researchers also need to improve upon methods to infer pedestrian or bicycle travel behavior and directional intent. Studies to model or predict both crowd and individual behavior based on observable characteristics (such as body posture, travel speed, and direction) could be useful in ADS development.
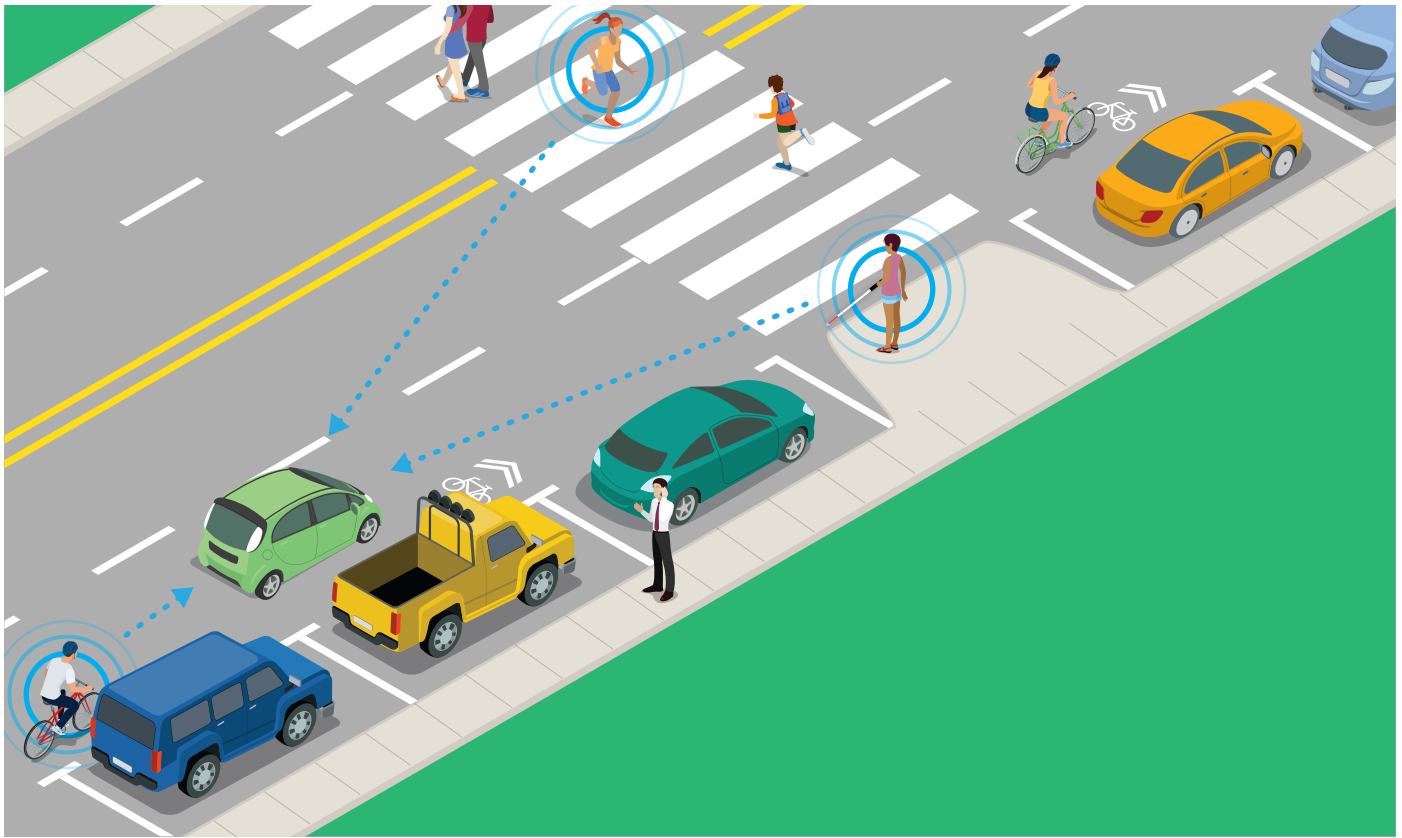
Figure 3. Vehicle to pedestrian or bicyclist technologies (V2X) could aid in detection of and communication with pedestrians and bicyclists, but an array of technology and equity issues must still be addressed.

#2: The V2X Problem

What it is: Connected technology such as vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), and other V2X technologies represent the potential for safety improvements utilizing short-range communication to inform roadway users and the infrastructure itself about the presence and status of road users such as pedestrians. V2X technology, however, suffers from multiple problems that currently limit its use in improving detection of and communication with pedestrians and bicyclists. These issues include poor location accuracy (especially in urban canyons), inability to forecast maneuver intentions, serious challenges in minimizing false positives and false negatives, privacy issues, and issues surrounding driver/vehicle expectations when confronted with people not carrying an active beacon due to cost, choice, or system failure. Two key challenges will be in (1)

designing systems that can be beneficial even if the connected technology is not ubiquitous; and (2) avoiding systems that create new blind spots and unintended consequences (e.g., by presuming that all road users are connected or by prioritizing connected signals over direct perception).

Why it matters: Multiple threat situations, where a driver passes another vehicle that is blocking his or her view of a crossing pedestrian, often lead to serious pedestrian crashes. Many other crash types result when sight distances are limited or pedestrians or bicyclists are obscured from view by objects such as trees, utility poles, or parked vehicles. Given the limitations of current detection technologies (see #1: The Detection Problem), connected technologies (using cell phones or perhaps built into or mounted on bicycles) could improve driver or vehicle detection of pedestrians or bicyclists in important situations, irrespective of the level of automation. V2P beacons could

also play a significant role in improving safety for particularly vulnerable pedestrians, including people who may act unpredictably (such as children and people with mental illness) as well as people who need additional crossing time at signalized intersections (such as children, seniors, and people with disabilities). Wireless beacons could theoretically connect to infrastructure (P2I) to affect signal timing and prioritization for pedestrians and bicyclists. This technology could help compensate for the narrow detection profile of bicyclists, as well as provide warning when a bicyclist is approaching an intersection and may not be able to stop in time.

Policy implications: All people have a right to travel on public streets safely, so ultimately ADS and connected systems must find a way to detect and respond to all road users, not just those carrying devices. Consideration must be given to people who may not be carrying a device by choice or because they do not have the means to own a device. For example, children may be less likely to have smartphone-based V2P systems to warn of their presence, resulting in a case where V2X technology alone will not likely produce safety benefits for child pedestrians. It is also critical that equity considerations factor into the discussion, such that differential safety benefits will not accrue for pedestrians and bicyclists with the means to afford advanced wireless communication systems relative to those who cannot.

Current and needed research: The Intelligent Transportation Systems Joint Program Office (ITS JPO), the Federal Highway Administration (FHWA), and NHTSA has been conducting V2P research and investigating a range of applications. For V2X applications, there is a need to better understand the limitations of their application (such as cost, limited accuracy of positioning information, no ability to predict intentions, privacy concerns, trust, expectation, use, reliability, and over-reliance) as well as their potential benefits (such as improved detection or crash prevention). There is also a need to evaluate the availability and practicality of V2X technologies for all types of pedestrians and bicyclists to ensure that the benefits of these technologies are equitably distributed (i.e., to people of all ages, incomes, educational levels, physical abilities, etc.).
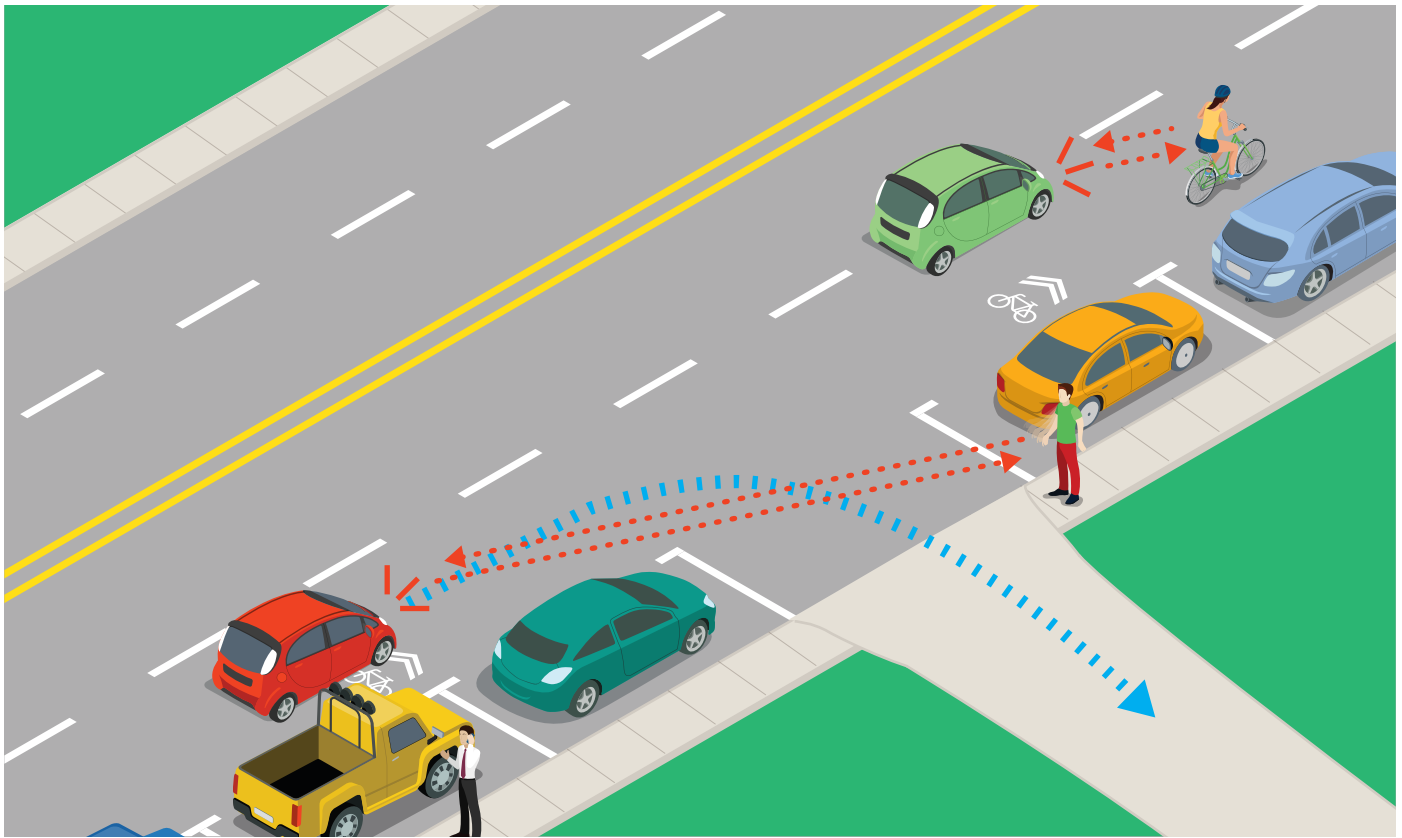
#3: The Communication Problem

What it is: Communicating intentions between road users occur in a variety of ways, from facial expressions to head movements to hand gestures. In an ADS future, this culturally-based, human-centric communication will gradually be supplemented and eventually replaced by a human-machine interface (HMI) that may be more or less transparent and intuitive. Consider, for example, a case where a driver wishing to turn across a sidewalk to enter a driveway or parking lot encounters a pedestrian whose trajectory is likely to intersect the vehicle's. In this case, the pedestrian likely has legal right-of-way, but to ensure her safe travel she is likely to confirm that she has been seen by the driver. Their communication would involve a complex and culturally-guided series of interactions, including

facial expressions (e.g., smiles, raised eyebrows, etc.), and gestures (e.g., a horizontal wave meaning "go ahead" or a vertical wave meaning "thanks"). Many communication cues used today could be absent or presented differently in ADS. This shifts the communication from interpersonal to human-machine, with humans on both sides of the interaction being affected. In the future, pedestrians and other road users will have to figure out when a vehicle is being controlled by ADS, how to establish trust that they have been detected, and how to communicate regarding expected behaviors, and when to proceed. This may be particularly challenging for people with disabilities, especially vision-related disabilities. Automated vehicles may also require significant "training" or programming in order to understand human communications and predict behaviors (such as knowing how to interpret a hand gesture when a bicyclist signals intent to turn or stop, or how to interpret from body language when

a pedestrian standing on the side of the road is trying to cross the street versus simply waiting on a bus).

Why it matters: Interactions between AVs and bicyclists and pedestrians (and all other road users) need to be transparent, socially acceptable, and efficient. Consistent communication standards are needed to ensure both acceptance and safety, particularly across cultures where right-of-way laws and norms may vary considerably (see #4: The Right-of-Way Problem). ADS vehicles will need to communicate intent with symbols, text, and/or sounds, and take into account the needs of people with hearing or vision impairments. These symbols can't be inconsistent with the Manual on Uniform Traffic Control Devices (MUTCD), which regulates roadway signs, signals, and pavement markings. For example, it would not be acceptable to have round, green stop signs mounted on the front of AVs to indicate the need to stop. Further, communications must be consistent across all ADS vehicle types to prevent confusion and risk.

Policy implications: Communication issues are likely to be made more challenging by mixed fleets with many different HMIs and styles of operation. Data and "blueprint" sharing may be necessary (though not likely to occur voluntarily) to ensure that communication systems are consistently integrated and tested across all makes and models of vehicles, and understood by vehicle users and pedestrians and bicyclists alike.

Current and needed research: There is ongoing U.S. Department of Transportation (USDOT) research surrounding automated vehicle communication of intent with shared road users. Additional research is needed to explore how people desire to communicate and will actually communicate with AVs, and how this will affect their behaviors and interactions in the future. It is also critical that cross-cultural factors be considered, as rules, customs, social norms, languages, and traffic laws will vary not only between countries but within diverse countries such as the United States. It is an open question how a car developed and tested by a manufacturer in one country will be regionalized for behavior and communication styles that make sense to pedestrians and bicyclists in specific markets, let alone regions where the vehicle may travel over its lifespan. Additionally, while numerous studies have sought to understand what the driving public wants out of future vehicles, there is currently a lack of research on the needs, desires, and comfort level of pedestrians and bicyclists in relation to traveling around and communicating with AVs. See #5: Passing Problem for one recent survey of a bicycle advocacy group's membership.

Figure 5. There are many unanswered questions with respect to how ADS will adhere to varying laws requiring yielding right-of-way to pedestrians, and the ripple effects that ADS interactions will have on human driver and pedestrian expectations and behaviors.

#4: The Right-Of-Way Problem

What it is: This issue is closely related to #3: The Communication Problem. Social customs and communications that govern giving right-of-way to pedestrians vary from place to place. State and local laws also vary with respect to who has the right-of-way in crosswalks in different settings, and even in the definition of a crosswalk (e.g., marked versus unmarked crossing) and where the pedestrian must be with respect to it (e.g., with a foot in the crosswalk or approaching it). Driver failure to give right-of-way to pedestrians at legal crossings is a leading cause of pedestrian crashes (Schneider & Sanders, 2015). Currently, it is not well established how AVs will yield right-of-way to pedestrians or what other communication challenges, behavioral adaptations (from other

pedestrians or human drivers), or other unintended consequences will arise as more of these AV-pedestrian interactions take place. For example, if an ADS is designed to always stop for pedestrians, there is the potential for pedestrian behavioral adaptation (e.g., "gaming" the limitations of the system) or over-trust of the technology, which could increase the risk of conflicts and crashes in mixed fleets (i.e., when ADS vehicles yield at crosswalks and human drivers often do not). It is also possible that zones with high levels of pedestrian activity and many pedestrian crossings will make automated vehicle movement inefficient and impractical.

Why it matters: Theoretically, having more ADS on the roadway that routinely yield to pedestrians may lead human-driven vehicles to follow suit, further establishing yielding to pedestrians as a social norm in more places and leading to

safety benefits. Combined with advancements in connectivity, it is conceivable that pedestrians may be able to cross at locations and/or times that are more flexible and convenient than going to the nearest marked crosswalk and waiting for a signal, thus enhancing mobility as well. These scenarios raise implications for how transportation agencies can approach multimodal traffic management in order to facilitate safe and efficient interactions between all road users and support social and economic vitality in a variety of development contexts.

Policy implications: Automobiles, regardless of the level of automation, should give right-of-way to pedestrians at legal crosswalks as current laws require. If right-of-way laws differ across jurisdictions in which an AV operates, then additional challenges may arise. Even when a pedestrian doesn't have the legal right-of-way, vehicles should make every effort to avoid a crash with a pedestrian. Regulation of the industry to create standardized "rules" can also create consistency, which is vital for interaction with other road users and may have ripple effects on liability in the event of a crash. Having a variety of vehicle yielding behaviors across traffic situations could cause significant confusion or risk in a mixed-vehicle fleet if a proportion of vehicles are controlled by fixed programming from a manufacturer while the rest of the driving population is guided by social norms that may conflict with formal regulations. Either ADS programming will need to have some amount of built in learning and flexibility, or localized social norms will have to undergo some period of adjustment to a more common set of standards, or both.

Current and needed research: Due to the rapid pace of technology development under proprietary conditions, there is currently little information that is publicly available on how auto manufacturers and software developers are creating the algorithms used to govern ADS vehicle behavior, and what safety implications these may have. According to nuTonomy's Chief Operating Officer Doug Parker, "Essentially, we establish a hierarchy of rules and break the least important," he said (Bhuiyan, 2016). It will be important for the pedestrian, bicycle, and safety community to have a voice in determining the values that drive the "hierarchy" of AV navigational rule-making, in particular the rules used to govern when AVs give right-of-way to other road users. Research is needed to independently test how ADS maneuver and give right-of-way to pedestrians and bicyclists and whether changes to state or local statute may be needed to enhance safety and consistency during these interactions.
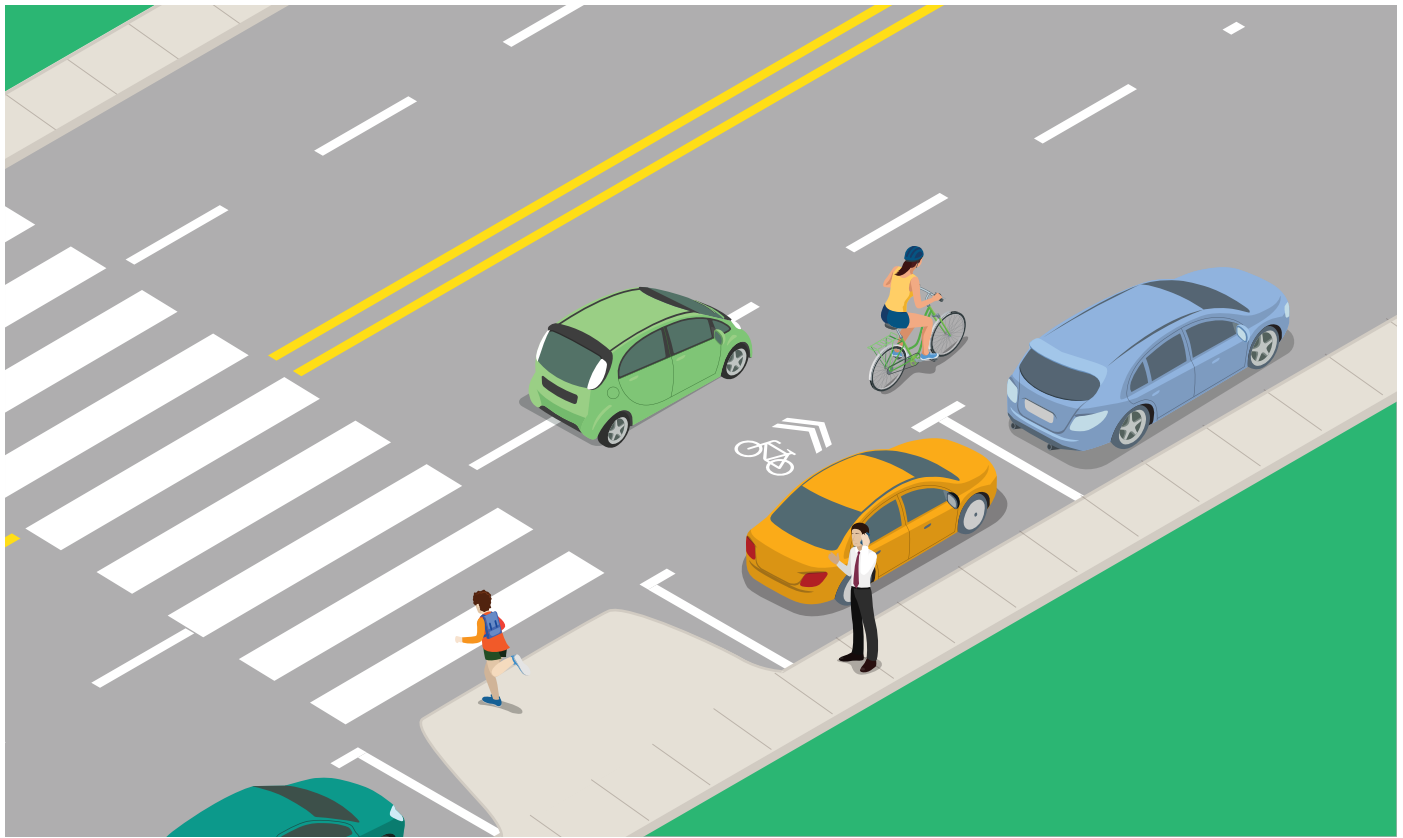
Figure 6. The ways in which ADS are programmed to pass slower-moving cyclists, within the confines of existing traffic laws, will be an important issue to address.

#5: The Passing Problem

What it is: Recent studies have shown that more than one-third of bicyclist fatalities involve improper overtaking maneuvers by the driver (Schneider & Stefanich, 2016; McLeod & Murphy, 2014). Drivers passing bicyclists too closely is a common and unpleasant experience for many riders, which has been shown to reduce interest in bicycling (Sanders, 2015). There is currently significant variation among state laws with respect to the minimum passing distance required around bicyclists. Little to no research exists to show what passing distance is most safe or comfortable for the bicyclist at different travel speeds, or how these laws have been enforced or affect actual passing distances. In addition to variations in passing laws, there is even more variation in the presence and quality of existing on-road bicycle infrastructure (e.g., wide shoulders, bike lanes, and shared lane facilities), which determines the level of separation between bicyclists and motor vehicles.

Why it matters: ADS will need to be equipped with advanced detection, prediction, and avoidance maneuvers to safely navigate around bicyclists, whose behaviors may include weaving between vehicles, legally riding in the middle of a travel lane at a slower speed than other traffic, and even cases where a bicyclist has crashed. Additionally, ADS will need to have a set of control instructions to enable them to operate in a way that is predictable and comfortable for bicyclists. This could lead to more consistent, interpretable interactions among ADS and cyclists and allow for more confidence among riders. It could potentially lead to greater enthusiasm for riding as "close calls" are reduced or eliminated and the safety benefits of automation become more widely known in the cycling community.

In a recent study, bicycle advocacy group Bike Pittsburgh surveyed its members regarding their experiences in sharing the road with Uber's fleet of self-driving vehicles being tested in the city. They found that "people did feel much more comfortable riding next to autonomous vehicles than they did next to human vehicles," in part because of the lack of road rage and the predictably conservative movements of the test vehicles (Krauss, 2017).

Policy implications: In a traffic environment with advanced automation, a safe bicycle passing and/or following distance could be standardized (either by industry leaders or state and federal regulators). Without such standardization, ADS designers will have to determine how to deal with the variety of local laws within a distribution region (e.g., states within a country; municipalities within a state) and how to adapt vehicles when ordinance boundaries are crossed with minimal impact on passenger and bicyclist comfort. This is the topic of ongoing research sponsored by the Transportation Research Board National Cooperative Highway Research Program [NCHRP Project number 20-102(07)] that will provide guidance and resources to state departments of transportation (DOTs) and divisions of motor vehicles (DMVs) on regulation and legislation for ADS (NCHRP, n.d.). Yet, this specific research project is not exploring bicycle passing laws.

Current and needed research: Currently, there is little evidence to show how ADS are being programmed to operate around bicyclists. According to a recent article, "Waymo's cars are programmed to pass bikes in accordance to state laws, usually with three feet of clearance" (Krauss, 2017). Uber recently acknowledged its problem with automated vehicles encroaching on bike lanes (Levin, 2016), and a recent video of an ADS test in London showed it closely passing a bicyclist, concerning many that the detection system failed or was slow to recognize the bicyclist, or that it was not programmed to provide enough of a margin for error when passing (Barth, 2017). As machine vision and bicycle detection technologies are still in their infancy, some systems are still relying on detection of bicycle lane markings (rather than road users) to predict the presence of a bicyclist (Levin, 2016), highlighting the research needed in this area before these systems are ready for real-world testing.

#6: The Speed Problem

What it is: There is a nonlinear relationship between vehicular speeds and pedestrian and bicyclist injury severity—the risk of death when struck at 24 miles per hour is 10 percent, but the risk of death when struck at 48 miles per hour is 75 percent (Tefft, 2013). Systems that govern traffic speed or provide enhanced feedback to drivers could reduce speeding-related crashes and the resulting injury severity.

Currently, roads have set speed limits that represent the maximum speed that drivers may legally drive, but drivers typically navigate within a range of speeds depending on their personal preferences, environmental and roadway conditions, needs and comfort level for given situations. A key question moving forward is whether ADS will have the ability to be instructed to travel at speeds other than the speed limit to allow for personal preference while maintaining safety.

Why it matters: A recent National Transportation Safety Board (NTSB) study found vehicle speed to be related to an increased likelihood of a vehicle-vehicle crash and also higher driver or passenger injury in the event of a crash (NTSB, 2017). The study issued 19 safety recommendations that could be implemented by various agencies to reduce speed-related crashes and injuries. Similar studies have found a strong relationship between vehicular speeds and pedestrian and bicyclist injury severity. Therefore, the opportunity to regulate AV speed could have significant safety benefits for pedestrians and bicyclists.

Policy implications: As suggested by the National Association of City Transportation Officials (NACTO) policy statement on AV, it may be desirable to maintain current speed limits in cities to allow for safe roadway travel by pedestrians given human capabilities (both pedestrian and vehicle operator), unpredictability, and vulnerability. In some cases, with advancements in technology it may be beneficial to reduce speed limits to improve pedestrian and bicyclist
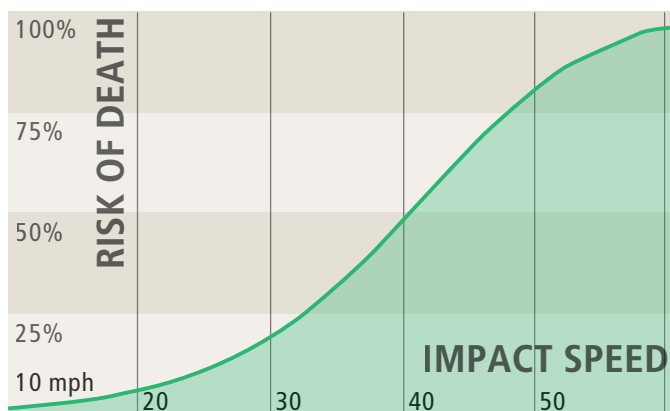

Figure 7. ADS speed governance around pedestrians and bicyclists has strong implications for injury severity in the event of a crash. Data shown are based on Tefft study referenced in text.

safety and comfort, especially if optimized vehicle routing and intersection coordination can keep overall travel times similar while improving safety for pedestrians and bicyclists. NACTO's policy statement proposes a maximum 25 mph speed limit within cities.

Current and needed research: There is currently little research focusing specifically on this problem for pedestrians and bicyclists. Research is needed to evaluate the types of crashes that AVs are more or less likely to encounter with pedestrians relative to existing driver-controlled vehicles, and ways in which speed modification in these circumstances may improve nonmotorized road user safety. For example, it may be advantageous to dynamically moderate speed in areas where pedestrians or bicyclists are more likely to appear; this is currently done in school zones, but a more discrete and dynamic approach could be taken using advanced machine sensors and communication.

#7: The Pickup/ Dropoff Problem

What it is: Vehicles attempting to enter or exit parking spaces often must maneuver around bicyclists and pedestrians (many of whom are also getting into or out of nearby vehicles). Sight lines may be limited by parking lot columns, other vehicles, or vehicle mirror design. Many drivers, particularly seniors, face mobility challenges that restrict head turning movements and the ability to fully scan their environments when entering/ exiting parking spaces. Hence, in some localities more than a quarter of pedestrian crashes occur in parking lots and/or involve backing vehicles (Sandt et al., 2014). Also, for on-street parallel parking configurations, dooring by drivers entering/exiting vehicles may be an issue if the bike facility orients bike riders into a position that is within the door zone. The prevalence of dooring crashes varies by community but can represent anywhere from three to 20 percent of all bicycle crashes, and can result in fatalities ("Dooring," n.d.).

Why it matters: Automated vehicle technologies offer both safety opportunities and challenges with respect to parking related issues. Even without ADS, Level 1 and Level 2 automated vehicle technologies— such as vehicle exit assist—could considerably reduce the likelihood of a dooring crash as the reliability and usage of these features grows. Back up sensors and parking assist features could also reduce parking related crashes. However, the popularity of shared mobility services has given rise to an increase in pickup/dropoff and short-term parking movements in traffic, which may increase the frequency of conflicts and crashes involving pedestrians and bicyclists near those areas. This may be exacerbated by the introduction of more ADS vehicle fleets in the coming years. Addressing safety issues that arise with pickup/dropoff will be of particular importance for children or people with disabilities who are using ADS as their first mode of independent transportation, but who represent especially vulnerable pedestrians before they enter and after they exit a vehicle.
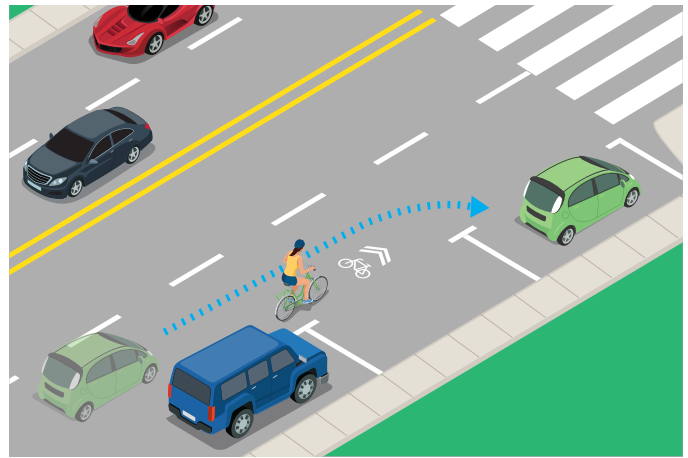

Figure 8. Navigating in/out of parking spaces or dropoff zones presents specific challenges for ADS interaction with pedestrians and bicyclists.

Policy implications: Agencies such as the Los Angeles Department of Transportation have already begun to carefully think through the interaction that occurs when people move from vehicle to other modes of travel, and are working on a strategy to plan and create mobility hubs throughout the community. This concept may be useful as ADS are integrated into the multimodal travel environment. As connected, automated, and shared vehicle systems continue to develop, curbside management practices and even traditional parking lot design will ultimately demand new thinking.

Current and needed research: FHWA's Achieving Multimodal Networks: Applying Design Flexibility & Reducing Conflicts brings together information and guidance when considering key conflict points for multimodal travel, such as the locations related to parking and transition between transit, driving, and walking/biking. Additional research is needed to provide best practices in curbside management, parking design, and passenger pickup/dropoff zone design that accommodates nonmotorized road users as well as ADS.
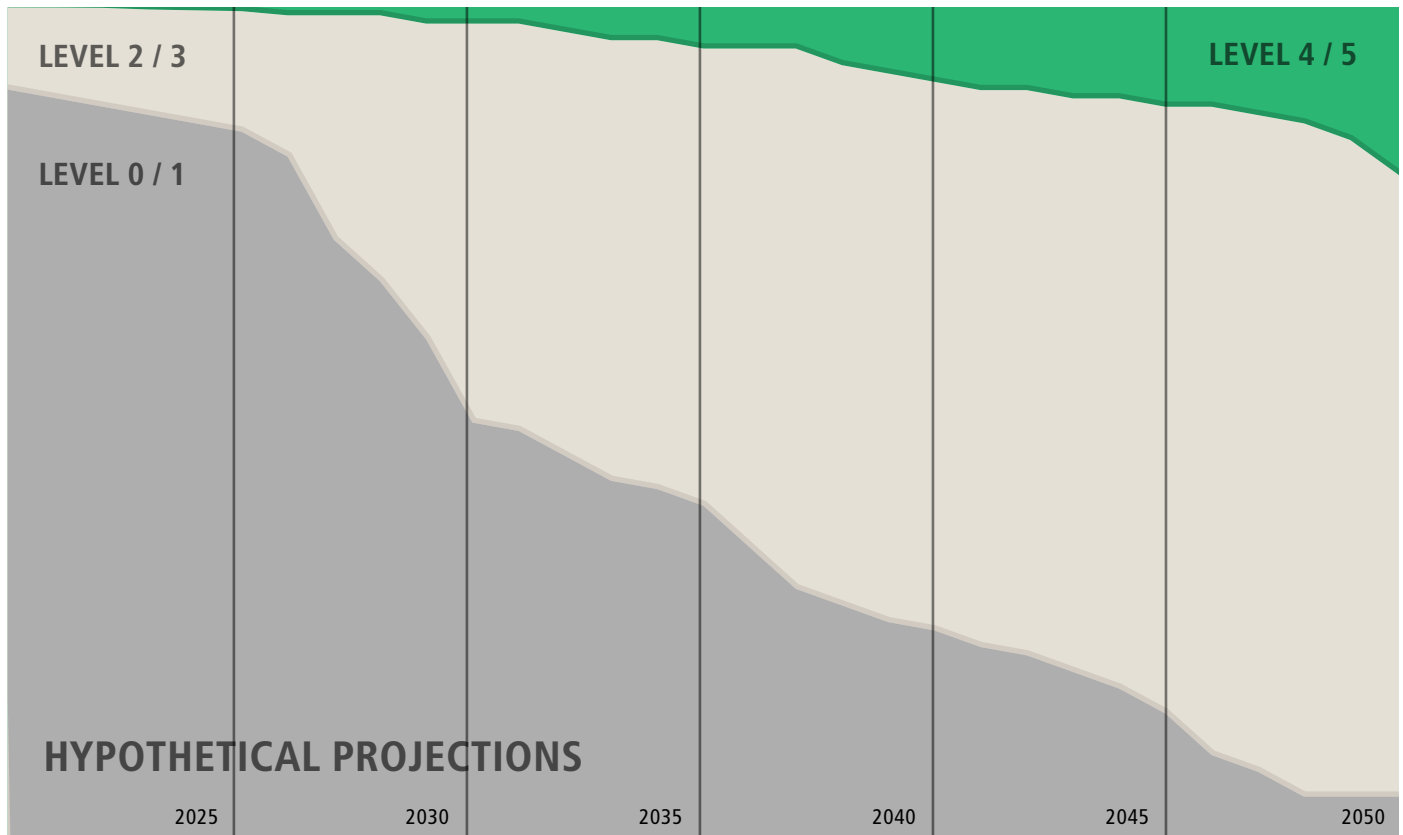
Figure 9. Hypothetical projections of the total U.S. vehicle fleet composition with respect to level of automation, indicating that lower levels of automated vehicles will represent a large portion of the vehicle fleet for a long period of time. Data are hypothetical as there is currently no industry consensus or reliable estimate for specific levels of automation over time.

#8: The Driver Handoff Problem

What it is: While vehicles with Levels 1 and 2 automation are becoming available on U.S. roadways, as of this writing there only a small number of Level 4 (capable) vehicles being tested in restricted areas and under controlled conditions and continuous supervision of safety drivers, which means that they are actually operated at Level 2. According to the experts consulted at the time of this writing, for the next thirty years, drivers, bicyclists, and pedestrians are likely to encounter a largely mixed fleet with many vehicles at lower levels of automation that still require significant oversight, monitoring, and input by drivers. Given the current limits in detection and prediction (see #1: The Detection Problem), Level 3 systems will need to make distinct decisions: when

should the vehicle execute behaviors itself or hand control back to the driver? There is a particular concern regarding how automated vehicles will communicate to the driver that they are not able to safely perform the necessary tasks, especially in a mixed traffic environment. It is likely that there will be a need for, at a minimum, many seconds for the driver to re-engage, and the vehicle must be capable of transitioning to a minimal risk condition if the driver does not re-engage.

Why it matters: This is an especially critical issue in the realm of pedestrian and bicyclist safety. The time required for a safe handoff to drivers may be more than the time available to react to a dangerous situation. Drivers confronted with an unexpected pedestrian or bicyclist in the road may be tasked with taking back control at a precarious moment and simply will not be ready to quickly execute an essential braking or swerving maneuver.

Policy implications: Some manufacturers, including Ford, have announced that they are bypassing intermediate levels of automation in favor of working directly toward Level 4, or automation that does not require human monitoring and intervention (Naughton, 2017; Ford Motor Company, n.d.). In the absence of voluntary industry action and/or statewide or federal regulation or guidance to ensure safe and consistent behaviors, there may be opportunities for local policy regulations to restrict (e.g., at night, on shared streets, in pedestrian districts, school zones, etc.) where and when ADS can operate in order to protect pedestrians and bicyclists. Some organizations, including NACTO, have called for restrictions on vehicles with less than Level 4 ADS to operate on any roadways where pedestrians and bicyclists are allowed. School zones, in particular, may be unsuitable places for Level 2-3 automated feature operation, due to the proximity of many child pedestrians and bicyclists who are both extremely physically vulnerable as well as more unpredictable than the average road user. It is likely that school zones will require special regulations and vehicle control, and it is imperative that machine-vision/lidar/radar systems be optimized to function with high levels of accuracy in these circumstances. Beyond these areas (since children and vulnerable road users are not restricted to traveling in school zones), there may be other areas or situations where vehicles with mid-level automation may be restricted in operation to manual-only mode. These may include other situations where a high degree of unpredictability is expected, such as around street festivals, group running or cycling events, residential areas, or any nonfreeway environment where a shared-use space exists with a volume of pedestrians or bicyclists that may overload limited sensing capabilities.

Current and needed research: While this has been a major topic of interest beyond this paper, still more research is needed into vehicle-driver communication and technology/interface design to better understand when a handover must be made to the driver, and how to safely and quickly reengage the driver at the proper time (Dogan et al., 2017; Walch et al., 2017; Feldhütter et al., 2017; Clark & Feng, 2016; Körber et al., 2016). Research is also needed to determine which contexts, particularly those where vulnerable road users are present, might be unsuitable for the levels of automation (e.g., Level 2-3) that require high levels of human driver monitoring and situational awareness.

#9: The Mode Shift Problem

What it is: Several questions and models have emerged concerning how ADS will impact travel behaviors, mode choices, and ultimately land use patterns and policies and city and roadway design. For example, will the pricing and comfort of ADS support a private-ownership model, and will this lead to substantial increases in vehicle miles traveled and accelerate sprawl, as some research has indicated (Anderson & Larco, 2017)? Will a shared mobility model take hold, such that ADS could eliminate the need for excess vehicles and associated travel lanes and parking? Would this open the door for more human-centered designs, or could it also contribute to increases in miles traveled, more barriers for walking and bicycling, and an even greater public health crisis due to sedentary lifestyles?

Why it matters: Until Level 4 automation accounts for a significant percentage of the vehicle fleet, it will be difficult to answer questions about how ADS are likely to impact future transportation models (including pedestrian and bicycle demand models) and street designs. Perhaps, in the distant future, ADS and V2X technologies will be so advanced and pervasive that there will not be a need for crosswalks or traffic signals or lane markings as we know them today. Perhaps there will be comprehensive networks of well-designed separated facilities, shared mobility hubs, and AV drop off zones all integrated into communities. While many questions and scenarios will not be answered or realized for years to come, there is no need to wait for AVs to emerge to set forth the policies and design guidance needed to prioritize safety, comfort, mobility, and equity for pedestrians and bicyclists now and in the future.
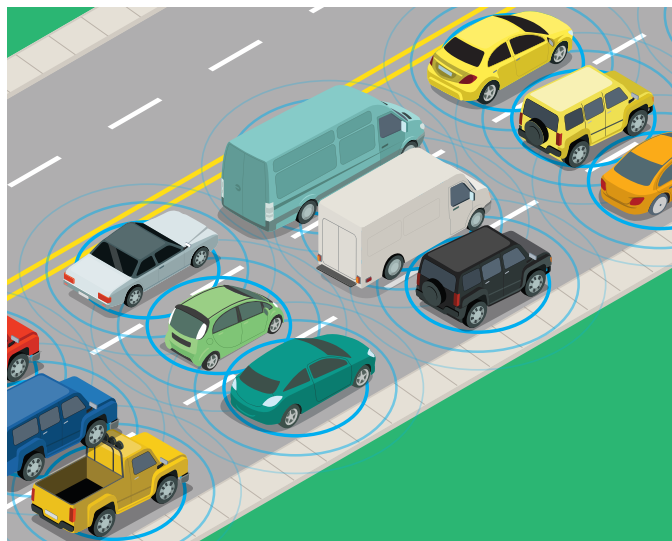

Figure 10. There is much speculation about whether ADS might lead to increases in vehicle miles traveled and how this will impact other road users and transform city and roadway design.

Policy implications: Many organizations have published policy statements or calls to action to address key issues or provide guidance on interactions between automated vehicles and nonmotorized roadway users. For a thoughtful discussion of automated vehicles, travel behaviors, and built environment policy needs, see the series of policy briefs developed by UC Davis's Institute of Transportation Studies.

Current and needed research: Research is needed to quantify travel demand and mode changes that result from the introduction of more automated vehicles, and how pedestrian and bicycle modes might be positively or negatively impacted from the perspectives of safety, mobility, and access, among other considerations.

#10: The Data Problem

What it is: Across the spectrum of AV development, access to and sharing of data has been extremely limited. This is often attributed to the proprietary nature of the technology development and to privacy concerns, as well as to data management issues.

Why it matters: As ADS are road tested, they generate terabytes of data in a very short time, which may open new possibilities for better studying pedestrian and bicycle safety issues. Access to data streams (such as GPS, radar, Lidar, and video systems) and big data analysis tools may provide important insights into behaviors that can contribute to or perhaps avoid crashes, as well as help document the number of pedestrians and bicyclists encountered by AVs (which could complement local counting efforts and aid in estimating exposure). In particular, if a crash occurs between an AV and a pedestrian or bicyclist, it will be important to have systems in place to record or report that event (e.g., by the vehicle itself as well as by police and local, state, and Federal governments) and to extract both pre- and post-crash data that can be used to investigate the nature of the crash. Data sharing across industry leaders may also expedite safety by helping to identify "edge" or "corner" cases—events or situations that occur only at an extreme operating parameter or outside of normal operating conditions—that can be used to train automated vehicles using machine learning to know how to safely respond, even when it hasn't come up against such a scenario before.

Policy implications: NACTO and some member cities have described AV data sharing needs and principles and raised awareness of issues that will need to be addressed, such as privacy issues, data ownership, and big data management. In particular, NACTO calls for the establishment of a standardized data report to be submitted through a third party platform with detailed information on disengagements and collisions, and the locational data before and after the incident. Crash data and

Figure 11. The figurative "black box" of ADS data contains a wealth of information on how ADS interact with other road users and can aid in understanding and developing safer systems, but managing and sharing big data remain challenging.

conflict avoidance or disengagement incidents around bicyclists and pedestrians in particular may be important measures of ADS performance.

Current and needed research: Several USDOT-designated AV proving grounds are tasked with testing out AV technologies and providing critical insights into optimal big data usage. The USDOT's Enterprise Data initiative is also researching mechanisms for hosting, managing, and using big data for improved safety and mobility for all travel modes and is in early discussions with large data management and technology organizations to explore the integration of open data approaches. Further research is needed to understand the challenges and opportunities to enhance data sharing.

Moving Forward

As vehicle automations and technology innovations continue to evolve and influence the ways people travel, it will be important to take advantage of opportunities to make pedestrian and bicycle travel safer while mitigating potential negative impacts on walking and bicycling. Billions of dollars have already been invested in automated vehicle research and development, a trend expected to continue as automotive and technology industries compete for leadership and profitability in this domain. If the pedestrian and bicycle research and safety community engages in a broad spectrum dialogue about issues for nonmotorized road users, this will provide a meaningful opportunity to leverage investment in AV in a way that will ultimately lead to greater safety and mobility benefits for all road users.

It will be important to identify the venues in which decision-making about automated and connected technologies and testing is taking place and to ensure that key issues affecting vulnerable road users are being raised and addressed. In addition to the specific issues described in this paper, there is a more general concern with system testing and verification. Discussion is warranted to examine the need for standardized testing protocols that can be used by all auto manufacturers and independent parties before new technologies are brought to market to test and ensure the safety of the ADS around nonmotorized road users in a variety of conditions. NACTO and others have called for a common standard for operations and for basic performance and safety benchmarks. With further research and discussion, NACTO's list of minimum safety assessment items could be further enhanced to specify pedestrian and bicycle related testing needs.

Currently, there are many venues in which AV issues are being discussed, evaluated, and addressed:

Transportation Research Board (TRB) and other research venues/conferences: Discussion of pedestrian and bicycle issues as they relate to AVs should not be limited to the TRB Pedestrian and Bicycle Committees, sessions, and research, but integrated throughout all areas. Important studies and guidance—expected to influence future policy making and implementation—must include pedestrian or bicycle specific topics within their scope. This may require more interaction between traditionally siloed groups and more representation of pedestrian and bicycle interests on NCHRP panels, conference scientific committees, etc. The Automated Vehicle Symposium, an annual conference co-sponsored by TRB and the Association for Unmanned Vehicle Systems International (AUSVI), will be an important venue to continue discussing pedestrian and bicycle challenges related to AVs.

Proving grounds and AV manufacturer test beds: In January 2017, the USDOT designated 10 "proving ground pilot sites to encourage testing and information sharing around automated vehicle technologies." Outside of government sponsored research, many private firms are funding research and development of AV technologies in a growing number of locations. These include Google/Alphabet/Waymo, Intel/MobilEye/BMW, NVIDIA/Mercedes/Audi, Uber/Otto, nuTonomy, and others. Currently, there is little formal research being published from these pilot tests about ADS interactions with pedestrians and bicyclists. How these groups account for pedestrian and bicycle safety needs, incorporate transportation safety research, and engage pedestrian and bicycle stakeholders will have a significant impact on the safety and equity of the resulting products and innovations. In regions where ADS are being tested, there are considerable opportunities for collaboration between researchers, industry leaders, and local advocacy groups. For example, Carnegie Mellon University research staff have engaged with Uber and local groups such as Bike Pittsburgh to conduct research on AVs and incorporate the perspectives of pedestrians and bicyclists. The pedestrian and bicycle advocacy community will play a critical role in monitoring public sentiment and illuminating areas of AV/pedestrian and bicycle interaction that need improvement. At the same time, more transparency between private firms testing AV technology and the public would be beneficial for the short- and long-term acceptance of these technologies.

City, Regional, State, and Federal governments: All of these entities are involved in generating guidance, regulations, policies, and statutes related to AVS. As states in the U.S. have traditionally been responsible for driver licensing and testing, this authority is expected to extend to the testing and approval of ADS. As such, many states have been implementing a variety of guidelines and regulations for testing and implementing automated vehicles within their boundaries, and engaging stakeholders throughout the process. Cities, metropolitan planning organizations (MPOs), and State DOTs also have an interest in incorporating AV assumptions into long-range transportation planning. See the sidebar for more federal, state, and local resources.

Member organizations: Several groups are leaders in the transportation field and looked to by their members and other organizations to provide a voice in transportation policy. These include organizations such as SAE, American Association of Motor Vehicle Administrators (AAMVA), the National Conference of State Legislators (NCSL), the Association of MPOs (AMPO), American Association of State Highway and Transportation Officials (AASHTO), NACTO, and the Institute for Transportation Engineers (ITE), among others. All are engaged in the issues surrounding AV and have sub-groups that actively monitor AV issues and lead related initiatives. For example, AAMVA, which represents the U.S. and Canadian officials who administer and enforce motor vehicle laws, formed an Autonomous Vehicle Working Group and is working to develop additional guidance for the regulation of highly automated vehicles. Others, such as AMPO and AASHTO, have hosted conference events and developed AV research roadmaps, respectively. These groups will continue the conversation around automated vehicles and provide opportunities to engage with the pedestrian and bicycle advocacy and research community. See the next page for additional resources.

Enhanced engagement and conversation across research, industry, and practitioner sectors and the public can support the creation of more robust goals for how AVs can safely interact with other road users, performance measures, and research that can foster the necessary technological advancements. Ultimately, there remain significant technical and social issues as well as regulatory considerations that need to be addressed before the safety potential of AVs can be fully realized for pedestrians and bicyclists. The questions this paper raises are an invitation for the broader community to engage on the issues and consider the necessary research, data, policies, and regulations that will be needed to guide new technologies for public good. The more that vulnerable road users are considered, the more likely the transportation innovations of the future will be able to improve safety, mobility, health, and equity for all.

Acknowledgements

For more information

Beyond this paper focusing on pedestrian and bicycle issues, a much broader conversation has been happening about automated vehicles and the systems they will impact. Following is a list of organizations, events, and resources where interested readers can go to continue to learn and engage on a wider variety of AV topics:

- **Pedestrian and Bicycle Information Center (PBIC):** A hub of news, research, and resources centered on pedestrian, bicycle, and automated and connected technology issues.

- **National Highway Transportation Safety Administration:** Information on NHTSA policy, updates on technology and innovation, and answers to frequently asked questions.

- **Intelligent Transportation Systems (ITS) Joint Program Office:** Information on the USDOT's initiatives involving ITS, including a subpage on automated vehicle research.

- **Transportation Research Board (TRB):** The TRB Pedestrian Committee's subcommittee on Pedestrians, Bicyclists, and Autonomous Vehicles meets regularly to discuss and advance research around AVs. The TRB Vehicle-Highway Automation Committee examines a broader range of AV issues.

- **Automated Vehicles Symposium:** A TRB co-sponsored conference held annually brings together industry, government, and academia from around the world to address technology, operations, and policy issues.

- **National Association of City Transportation Officials:** This organization released a policy statement on automated vehicles and is expected to provide further guidance to member communities as they advance AV-related policies and regulations.

- **National Conference of State Legislatures (NCSL):** This organization tracks state-level enacted legislation related to automated vehicles.

- **Association of MPOs AV Working Group:** This working group serves as a focal point for MPOs to engage with USDOT on connected and automated vehicle programs, policies, and issues. This page contains more information on the working group and a detailed list of resources and meeting presentations.

- **Eno Center for Transportation:** This organization regularly covers AV-related policy news and is a go-to resource for policy makers.

- **National Operations Center of Excellence:** This organization includes a searchable database of information on automated and connected vehicles and intelligent transportation system technologies.

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