Automated Vehicle Safety Consortium™ Best Practice

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AVSC Best Practice for Interactions Between ADS-DVs and Vulnerable Road Users (VRUs)

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Rationale

It is important to establish common terminology and a baseline understanding of the challenges posed when automated driving system-dedicated vehicles (ADS-DVs) interact with VRUs so that those challenges can be addressed. This document on VRU interactions can facilitate communication among the industry and public, help calibrate expectations of all traffic participants, and improve broader acceptance of SAE level 4 and level 5 ADS-equipped vehicles.

Preface

The Automated Vehicle Safety Consortium™ (AVSC) is an industry program of SAE Industry Technologies Consortia (SAE ITC®) working to quickly publish best practices that will inform and lead to industry-wide standards advancing the safe deployment of automated driving systems (ADS). The members of this consortium have decades of accumulated experience focused on safe, reliable, and high-quality transportation. They are committed to applying those principles to SAE level 4 and level 5 automated vehicles so that communities, government entities, and the public can be confident that these vehicles will be deployed safely.

The Consortium recognizes the need to establish best practices for the safe operation of ADS-dedicated vehicles (ADS-DVs). These technology-neutral practices are key considerations for safely deploying ADS-DVs on public roads. Members of the AVSC intend to support the published principles and best practices in an effort to establish a suggested level for other industry participants to meet. These best practices will serve as a basis to enhance and expedite the formal industry standards development process through SAE International and other global standards development bodies. Effectively implementing these principles can help inform the development of sound and effective ADS regulations and safety assurance testing protocols that will engender public confidence in the efficacy of ADS-DVs.

Comment and open discussion on the topics are welcome in appropriate industry forums. As discussion unfolds, AVSC documents will be revised as significant information and/or new approaches come to light that would improve safety or public trust.

Introduction

According to the National Highway Traffic Safety Administration (NHTSA), 7,338 pedestrians and pedal cyclists were killed in 2019 and 140,000 more were injured in the U.S. [1]. Additionally, the number of pedestrians and pedal cyclists killed in crashes with motor vehicles in urban areas increased by 62% and 49%, respectively, since 2010 [1]. Globally, 26% of the 1.35 million road traffic deaths are pedestrians and cyclists [2]. Road workers are another vulnerable population on the roads. In 2019, there were 135 fatalities of workers in work zones in the U.S. as a result of vehicle crashes[1] [3]. These VRU interactions are important to consider during ADS development and deployment.

Numerous challenges and considerations face ADS developers, manufacturers, and fleet operators when designing and testing ADS-DVs for safer operation in the presence of VRUs. VRUs are diverse in their appearance, kinematics, and behavior. VRUs can be stationary or moving (e.g., police directing traffic or someone riding a kick scooter). VRUs may be in or near the roadway affecting traffic (e.g., a road worker or someone changing a tire). They may be moving with traffic, against it, or across it (e.g., a pedal cyclist, a jogger, or a wheelchair crossing at an intersection). VRUs may be following traffic code (e.g., crossing at a crosswalk) or choosing to violate it (e.g., crossing mid-block).

Automated driver assistance systems (ADAS) are becoming more common and offer great potential to improve VRU safety with vehicles currently on the road. The technology and test protocols used for ADAS (e.g., ALKS R157, EURO NCAP, CATARC) can be a foundation for ADS-DV testing, but Automated Driving Systems (ADS) involve the sustained operation of the dynamic driving task (DDT).

There is currently no consensus on all of the factors that should be considered during ADS interaction with VRUs, but broadly speaking, safety performance (in this case, safety during traffic interactions) is improved when all actors (in this case, VRU and ADS) share a general understanding of the world around them [4]. When interacting with other road users, including VRUs, ADS-DVs need to contribute positively to measures that support overall benefit (refer to AVSC00006202103). In instances where a VRU is following traffic code and behaving in a compliant fashion, this is straightforward; however, a majority of pedestrian fatalities occur at places other than intersections where VRUs failure to follow traffic code can increase the likelihood of a crash [5]. Therefore, it is important for ADS developers and manufacturers to consider VRUs that may not follow the traffic code.

1 According to workzonesafety.org, 135 of the 842 total fatalities were workers. Due to limitations in reporting, these deaths include all causes of worker fatalities in work zones.

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1. Scope

This Automated Vehicle Safety Consortium™ (AVSC) best practice provides considerations for ADS developers on interactions between SAE level 4 and level 5 fleet-managed ADS-DVs and VRUs. This document is developed from the perspective of an ADS-DV independent of any external digital/wireless communications (i.e., interacting with VRUs that are not connected through a digital communication device such as vehicle-to-pedestrian, vehicle-to-bike, or vehicle-to-infrastructure).

A definition for VRU and the challenges with ADS VRU interactions are described. This document does not prescribe actions of VRUs in the presence of ADS-DVs, but information about challenges presented to the ADS during VRU interactions is provided for readers which can help calibrate VRU expectations when in the vicinity of ADS-DVs.

Operational design domain (ODD), ADS-DV use case, and ADS technologies vary; because of this, the following are outside the scope of this document:

- Prescriptive ADS maneuvers in the presence of VRUs.
- ODD-specific test cases and pass/fail criteria.
- Test target (i.e., surrogate VRU) specifications.

Manufacturers should consult SAE J3116 and SAE J3157 for information pertinent to the design of test targets that may be useful to evaluating ADS.

This document focuses on ADS-DV and VRU interactions from the perspective of the ADS-DV. Impact testing is outside the scope of this document. Required tests relevant to vehicle design, class, and jurisdiction should apply[2].

2. References

2.1 Applicable Documents

The following publications were referenced during the development of this document. Where appropriate, documents are cited.

2.1.1 SAE Publications

Unless otherwise indicated, the latest issue of SAE publications apply. Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J2945/9	Vulnerable Road User Safety Message Minimum Performance Requirements
SAE J3016	Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles
SAE J3087	Automatic Emergency Braking (AEB) System Performance Testing
SAE J3088	Active Safety System Sensors
SAE J3116	Active Safety Pedestrian Test Mannequin Recommendation

[2] Examples of tests that may still apply regardless of ADS-DV interaction with VRUs may include tests for impact safety such as FMVSS Part 581—bumper standard for low speed damageability—and the Global Technical Regulation (GTR) 9 for pedestrian safety (under development), as well as collision avoidance tests such as IIHS P-AEB protocol (perpendicular adult (CPNA-25), perpendicular child (CPNC-50), parallel adult (CPLA-25)), NHTSA P-AEB draft tests, and the Euro NCAP pedestrian and bicycle safety protocol.

SAE J3131	Definitions for Terms Related to Automated Driving Systems Reference Architecture
SAE J3134	Automated Driving System (ADS) Marker Lamp
SAE J3157	Active Safety Bicyclist Test Targets Recommendation
SAE J3194	Taxonomy and Classification of Powered Micromobility Vehicles
SAE J3216	Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles
AVSC00002202004	AVSC Best Practice for Describing an Operational Design Domain: Conceptual Framework and Lexicon
AVSC00004202009	AVSC Best Practice for Data Collection for Automated Driving System-Dedicated Vehicles (ADS-DVs) to Support Event Analysis
AVSC00006202103	AVSC Best Practice for Metrics and Methods for Assessing Safety Performance of Automated Driving Systems (ADS)
AVSC00008202111	AVSC Best Practice for Evaluation of Behavioral Competencies for Automated Driving System Dedicated Vehicles (ADS-DVs)

2.1.2 Other Documents

[1] National Center for Statistics and Analysis, “Overview of motor vehicle crashes in 2019,” National Highway Traffic Safety Administration, Washington, D.C., 2020.

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3. Definitions

3.1 Automated Driving System (ADS) (SAE J3016)

The hardware and software that are collectively capable of performing the entire DDT on a sustained basis, regardless of whether it is limited to a specific operational design domain (ODD); this term is used specifically to describe a level 3, 4, or 5 driving automation system.

NOTE: In contrast to ADS, the generic term “driving automation system” refers to any level 1 to 5 system or feature that performs part or all of the DDT on a sustained basis. Given the similarity between the generic term—“driving automation system”—and the level 3 to 5-specific term—“automated driving system”—the latter term should be capitalized when spelled out and reduced to its abbreviation (ADS) as much as possible, while the former term should not be.

3.2 ADS-Dedicated Vehicle (ADS-DV) (SAE J3016)

A vehicle designed to be operated exclusively by a level 4 or level 5 ADS for all trips within its given ODD limitations (if any).

3.3 [Object] Classification

A process that establishes a match between confirmed entities and entity class prototypes stored in the system’s knowledge database [6].

NOTE: Object classification is used to refine assumptions about the future state/location of a detected and perceived object. Assumptions are factored into ADS planning.

3.4 Dynamic Driving Task (DDT) (SAE J3016)

All of the real-time operational and tactical functions required to operate a vehicle in on-road traffic, excluding the strategic functions such as trip scheduling and selection of destinations and waypoints, and including, without limitation, the following subtasks[3]:

- Lateral vehicle motion control via steering (operational).
- Longitudinal vehicle motion control via acceleration and deceleration (operational).
- Monitoring the driving environment via object and event detection, recognition, classification, and response preparation (operational and tactical).
- Object and event response execution (operational and tactical).
- Maneuver planning (tactical).

[3] Subtasks 3 and 4 are collectively referred to as OEDR.

- Enhancing conspicuity via lighting, sounding the horn, signaling, gesturing, etc. (tactical).

3.5 [ADS-DV] Fleet Operator

An entity that manages a fleet of ADS-DVs and/or the services provided by said fleet.

NOTE: Fleet operator excludes non-commercially deployed, privately owned vehicles.

3.6 Object and Event Detection and Response (OEDR) (SAE J3016)

The subtasks of the dynamic driving task (DDT) that include monitoring the driving environment (detecting, recognizing, and classifying objects and events and preparing to respond as needed) and executing an appropriate response to such objects and events (i.e., as needed to complete the DDT and/or DDT fallback).

3.7 Monitor the Driving Environment (SAE J3016)

The activities and/or automated routines that accomplish real-time roadway environmental object and event detection, recognition, classification, and response preparation (excluding actual response), as needed to operate a vehicle.

3.8 Predictable Vehicle Motion Control (AVSC00006202103)

Predictable vehicle motion control means predictable behavior by the ADS-DV from the standpoint of other [human] road users. Predictable behavior by an ADS-DV reduces risk (e.g., a decrease in rear-end crashes).

4. What is a VRU?

AVSC members believe that the common characteristic that defines VRUs is that they are at a higher risk of being injured or killed if involved in crashes with motorized vehicles than occupants secured and protected within vehicles that have greater mass and higher velocity. While it is reasonable to expect VRUs in any ODD, the types of VRUs, behaviors, and subsequent responses from an ADS may vary depending on the ODD. Defining what constitutes a VRU helps clarify discussions around safety performance and interactions between ADS-DVs and other road users.

4.1 Defining the VRU

The term “vulnerable road user” has been used by many organizations to refer to many different types of road users based on their relative likelihood of injury in a crash with a motor vehicle [7]. Most organizations agree that pedestrians and pedal cyclists are VRUs, but beyond those types of road users, there is disagreement across various stakeholder groups as to what constitutes a VRU. Table 1 highlights some of the confusion that can result by focusing on labels.

TABLE 1 Types of road users identified as VRUs by various organizations

VRUs	SAE J2945/9[4]	NHTSA[5]	EU[6]	WHO[7]	ISO[8]	IEEE[9]	BSI[10]	NSC[11]	SSC[12]
Pedestrians	x	x	x	x	x	x	x	x	x
Pedal cyclist/ bicyclist	x	x	x	x	x	x	x	x	
Motorcyclist	x	x	x	x	x	x		x	x
Road workers	x							x	
Disabled pedestrians/ wheelchair users	x	x			x		x	x	x
Powered micro-mobility vehicles[13]		x	x				x	x	
Horse riders							x		
Young/elderly drivers			x						
Animals		x							

The AVSC defines a VRU as “any human road user not occupying a vehicle.” While individual ADS developers may have exceptions, VRUs meet three criteria:

- They are at a higher risk of being injured as a result of a crash than those inside a vehicle who are offered protection from the vehicle and its passive safety systems.
- The range of kinematic parameters governing their motion may be significantly different from on-road vehicles.
- The regulations that govern their interactions with other road users are distinct from on-road vehicles.

Horse riders, listed Table 1, are worth special attention because according to the AVSC definition, animals are not considered VRUs. Horse riders, however, are considered VRUs because a human is riding or walking the animal. Animals without human riders or companions are considered dynamic objects that should be avoided to minimize risk to vehicle passengers, other human road users, and the animals themselves.

The AVSC’s three criteria for defining VRUs provides a means to frame discussions involving ADS-DV and VRU interactions related to safety performance, risk management protocols, and test evaluation. Classification of actors as VRUs will vary from developer to developer and may be influenced by the use case and ODD in which an ADS-DV is deployed.

VRUs are pedestrians, pedal cyclists, and other human road users that meet the criteria of being unprotected, moving differently than road vehicles, and are subject to different traffic rules than road vehicles. This focus emphasizes a pre-crash perspective of VRUs and is important for ADS-DV interactions with VRUs and improving societal metrics (e.g., crashes). This perspective also provides consideration for behavior and OEDR, combining them with the more traditional post-crash perspective of VRUs based primarily on the likelihood of serious injury resulting from a crash.

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[11] National Safety Council (NSC) Position/Policy Statement: Vulnerable Road Users [30].
[12] Singapore Standards Council (SSC) TR 68 : Part 1 [28].
[13] There are a wide range of small, powered mobility devices specifically named in the references. They are consolidated here because they meet the criteria defined in SAE J3194. The organizations referenced may have specific exceptions and not consider some specific micromobility vehicles as VRUs.

4.2 ADS-DV Interaction Challenges with VRUs

Numerous challenges and considerations face ADS developers, manufacturers, and fleet operators when designing and testing ADS-DVs for safer operation in the presence of VRUs. An important element of automated driving is object and event detection and response (OEDR). OEDR is defined in SAE J3016/ISO 22736 as consisting of monitoring of the driving environment in real-time and preparing an appropriate vehicle response to the objects and events that are present. OEDR is a fundamental element of executing the DDT and some external variables may change multiple times in under a second. For example, VRUs might pose detection, classification, and response challenges that can impact the path plan of the ADS. VRUs may be difficult to detect at a sufficient distance because of their physical properties, may be difficult to predict their future state, and the consequences of detection or prediction errors may be more severe.

One challenging example of VRU interactions for an ADS is infrastructure and signage where interactions with VRUs may be more likely to vary from location to location (or ODD to ODD). Additionally, some geographies may utilize various types of beacons which, when activated, can transfer right of way from a vehicle to a VRU—e.g., pedestrian hybrid beacons (PHBs) or rectangular rapid flashing beacons (RRFBs). In some cases, VRUs may be unfamiliar with beacons or other traffic control devices, resulting in unexpected behavior or behavior inconsistent with most VRU behavior in the area[14]. Some challenges ADS developers face when testing interactions with VRUs are listed in Tables 2 and 3.

[14] As an example, tourists may not be familiar with local traffic control devices, especially if they are new or newly developed as traffic control device technologies continue to evolve.

TABLE 2 Some challenges and examples associated with detecting and classifying VRUs

Challenges to Monitoring the Driving Environment for VRU Detection and Classification	Examples*
Detection (variability in shape, texture, color, material, obscuration, etc.)	• VRU physical properties: ▪ Shapes can be large, small, tall, short, vary in skin color, number of appendages, or type of locomotion. ▪ Shape outlines can vary or be obscured if the pedestrian is carrying something such as grocery bags, an umbrella, books, an infant, etc. ▪ Clothing type varies by season and location. Color and texture vary and can also blend in with the environment. ▪ Orientation or pose can vary such as between a walking pedestrian and a person with assisted mobility or the differences between a traditional pedal cyclist and recumbent cyclist. • Environmental properties: ▪ Weather and lighting factors can challenge VRU detection, especially when combined with other detection challenges (e.g., pedestrians crossing in shadows or unlit areas). • Location-related properties: ▪ VRUs might appear anywhere including domains or areas where they are legally forbidden or unlikely to be (e.g., pedal cyclist on freeway). ▪ VRUs may be obscured by the roadway geometries such as vertical or horizontal curvature or by static or dynamic obstacles such as parked vehicles, signs, other pedestrians, etc.
Classification	• Individual dynamics may vary from group dynamics (e.g., an individual pedestrian or a crowd of pedestrians). • VRUs can emerge from other objects such as a pedestrian emerging from a parked vehicle. • The presence or movement of human limbs can vary (e.g., walking a pedal cycle, standing on a powered scooter or skateboard, moving on crutches, carrying a package, operating a wheelchair, pushing strollers, or otherwise unable to swing one's arms).[15]
* Examples are provided to clarify challenges to ADS testing. The list is not all-inclusive. Additional items may be added based on context.	

ADS detection of VRUs must be robust to account for the various types of VRUs. Different sensor modalities have different strengths and weaknesses [8].

Detecting and classifying VRUs are not the only challenges. In conjunction with detection and classification, the ADS also predicts behavior and formulates an appropriate response. Table 3 provides a few examples.

[15] Sometimes objects in the environment are thought as boxes moving through space. The term "kinematics" is commonly used to refer to the motion of these bounding boxes. Here we use the term "kinesthetics" to refer to the motion or movement within the box that may be used to help classify objects/VRUs and improve predictions about intended behavior.

TABLE 3 Some challenges and examples associated with predicting behavior and formulating an appropriate response to VRUs

Challenges to Predicting Behavior and Formulating an Appropriate Response	Examples*
VRU behaviors may be context dependent [9]	• Children may behave in a more unpredictable manner than adult pedestrians. • Movement patterns may change during or after rain or other weather events. • Behaviors may change due to the presence or absence of other road users and the volume of traffic. • VRU types may behave differently based on other events (e.g., concert or sporting event). • Distracted VRUs may have different behaviors or be more likely to disobey traffic rules (e.g., cyclist or pedestrian using a mobile electronic device). • Behaviors may change due to the presence or absence of traffic control devices or infrastructure such as pedestrian islands at crossings or dedicated pedal cycle lanes (e.g. PHBs and RRFBs).
Interacting with VRUs includes a greater amount of ambiguity[16] compared to other road users	• The kinematics of certain VRUs (especially pedestrians and powered scooters) allow them to change direction very quickly. • Humans can change their intended trajectory or destination with no external indications as to their intent leading to sudden changes in direction. • VRU trajectories may intersect with ADS paths but their intention to stop or acknowledge (and yield to) the ADS-DV right of way may be difficult to discern. • Humans use myriad methods to communicate with one another to resolve ambiguous scenarios (e.g., hand signals, eye contact).
VRU behavior may vary in different ODDs	• Compliance with traffic code may vary among VRU types, in certain geographic areas, at certain times of day, or under some conditions. • The same type of VRU may behave differently from one location to another (e.g., New York to Boston; urban to rural; freeway to collector road). • The same type of VRU may behave differently depending on the time of day (e.g., morning rush versus dinnertime versus weekend).
* Examples are provided to clarify challenges to ADS testing. The list is not all-inclusive. Additional items identified may be added based on context.	

An ADS must consider classification and prediction errors. VRU behavior can be influenced by factors that are knowable to an ADS, such as weather, environmental conditions, the presence of construction, and traffic control devices. VRU behavior can also be influenced by unknowable factors that are internal to the VRU and cannot be perceived externally. In addition, VRUs can change heading more rapidly than vehicles. For example, a pedestrian may change direction in the middle of a crosswalk and move back to the sidewalk. Object classification can improve prediction by narrowing the set of an object's likely behaviors in a scenario, but like other object classes, prediction errors can arise from unknowable factors influencing VRU decisions. VRUs may also behave unpredictably if they are unfamiliar with local rules. For example, tourists in an unfamiliar area or pedestrians interacting with new types of traffic control devices may increase uncertainty. **Developers should design and test their ADS end to end system level performance to ensure safe execution of the dynamic driving task in the presence of reasonably expected variations of VRUs in differing conditions (such as shape, color, texture, density, lighting variation, and environmental conditions).**

[16] VRUs ultimately have volition over their behavior. Human (i.e., VRU) behavior is a product of environmental factors, the behaviors of other agents, and a complex interaction between individual beliefs, knowledge, and social influences [17].

An ADS must detect objects that may impact the tactical and operational driving tasks. Human drivers are taught to avoid interfering with the smooth flow of traffic [10]. **ADS Developers should design the ADS to follow traffic code.** In this way, VRUs are not expected to make special considerations in the presence of an ADS-DV. If an ADS detects an object, but the object is not or cannot be classified, an ADS can still plan a trajectory to reduce the probability of a conflict. For example, when an ADS encounters an unclassified object, it may plan more conservative maneuvers (such as increasing lateral or longitudinal separation) to protect an unknown object that might be a VRU.

However, in many cases, overly conservative behaviors can cause confusion and frustration in other road users. To avoid this, if a detected object can be classified with sufficient confidence and the ADS can make reasonable assumptions about the object's class and environment, it may refine its behavior to improve mobility. For example, a detected object may be classified as a pedal cyclist legally riding in a shared lane. Using that classification, the ADS might apply the appropriate traffic code safety margins and account for other contextual elements such as the environment and other road users to determine the next course of action. The motion planning considerations may result in the ADS maintaining speed and passing the cyclist or remaining behind the cyclist. With a detected object now confidently classified, an ADS can plan a refined set of maneuvers. These maneuvers factor in assumptions about the VRU class and the context (applicable traffic code, environment, other road user, etc.) of the situation and determine how the risk will be managed. **Robust motion planning should consider both compliant and reasonably foreseeable non-compliant behaviors by VRUs.**

5. Building a Behavioral Competency Evaluation—Responding to VRUs

Performance-based tests that currently evaluate advanced driver assistance system (ADAS) technologies can provide a foundation for some interactions between VRUs and ADS-DVs, but ADS-DV interactions with VRUs are more complex than ADAS interactions. Where ADAS tests evaluate reactions as a single maneuver, ADS performs the DDT on a sustained basis so may need to string together multiple maneuvers into context-dependent behaviors while completing trips[17].

ADS-DV interactions with VRUs may be described in DDT-relevant terms using the behavioral competency framework described in AVSC00008202111. AVSC member companies utilize this framework to develop applicable metrics, relevant acceptance criteria, and metric thresholds for VRU testing. In the sections that follow, a simple example for "responding to VRUs" is illustrated using the framework.

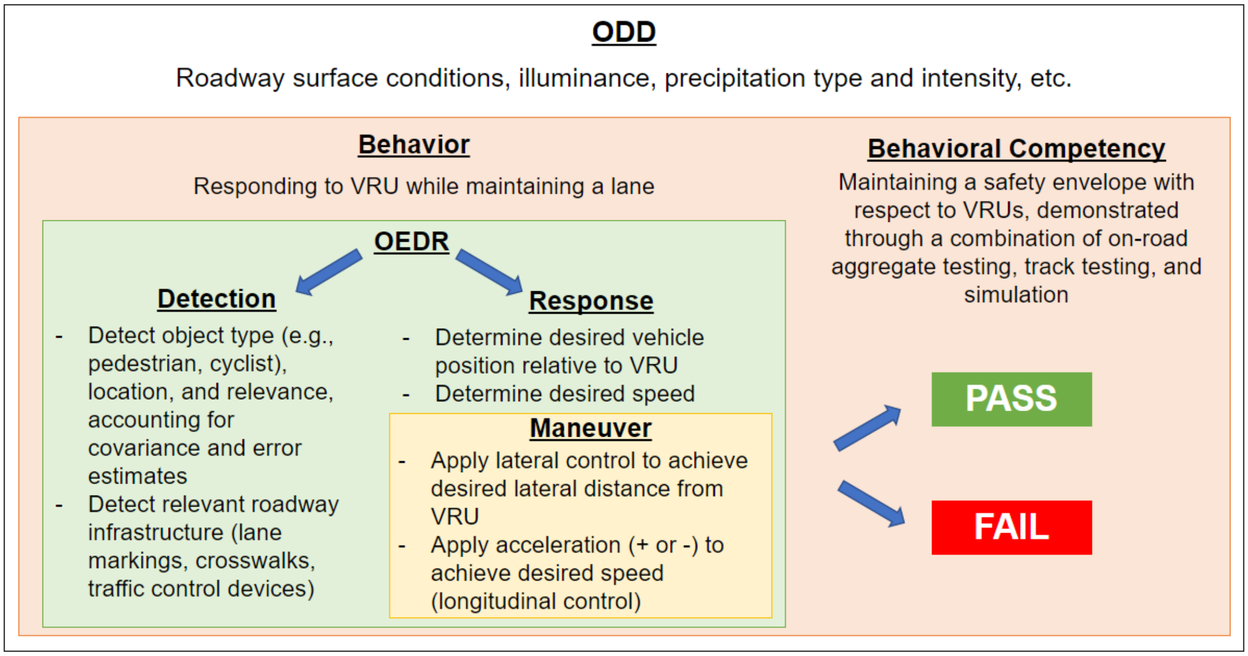
Scenarios provide context for ADS behavioral competencies which are constructed using terms that describe ODD conditions, OEDR, and maneuvers. The descriptions are built using narrative text and graphics to clarify situations and expected outcomes. The behavioral competency is evaluated using pass fail criteria such as safety envelope metrics against thresholds established by the manufacturer (refer to AVSC00006202103).

[17] For a complete description of a "trip," refer to SAE J3016.

5.1 Formulating and Evaluating a Behavioral Competency

AVSC00008202111 recommends a common lexicon and illustrates the relationship between a behavior and behavioral competency.

FIGURE 1 Relationship between behaviors, OEDR, and maneuvers



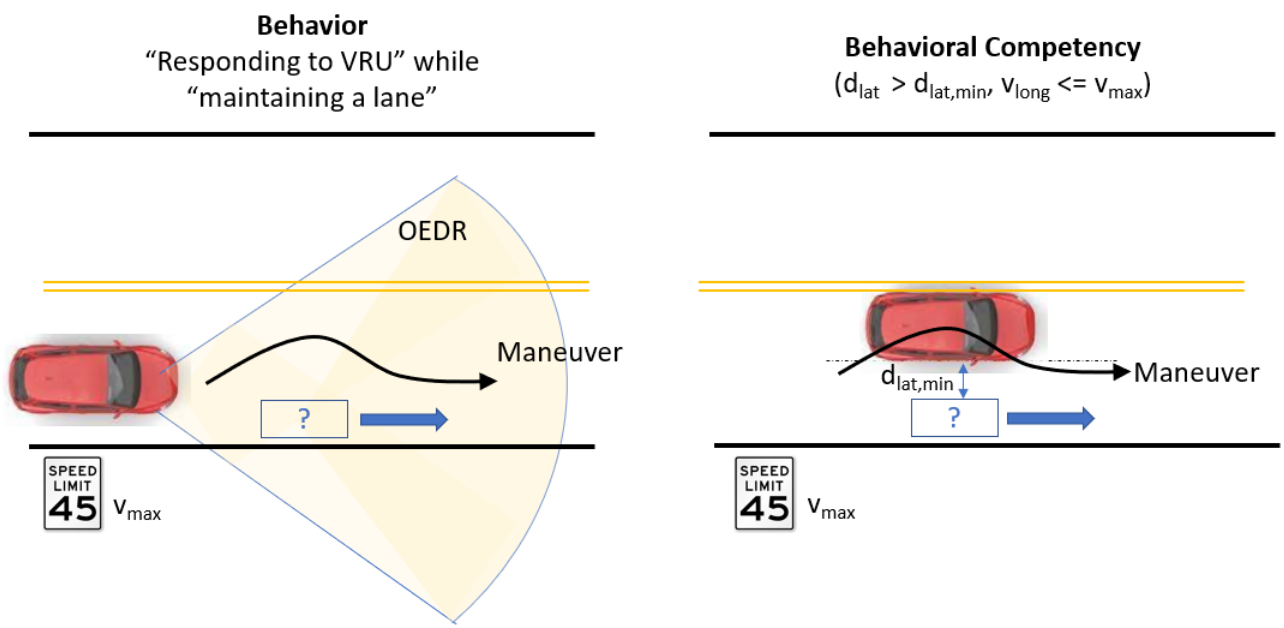
Context distinguishes a behavioral competency from a simple maneuver (see Figure 1). The ADS may interact with a VRU while it is performing many different aspects of DDT, especially roadway infrastructure-related competencies such as navigating lanes and intersections.

An example VRU interaction while maintaining a lane is shown in Figure 2. Table 4 can help developers capture additional context that can be used in a testable scenario by including roadway infrastructure and dynamic conditions that include challenges unique to VRUs. The check boxes represent potential scenario context, and the check marks indicate what is specific for this example. Additional scenario considerations are described in Rao et al. (2021) [11].

In Figure 2, an ADS detects an object while traveling along a two-lane roadway with bi-directional traffic. The expected behavior of the ADS is to continue in its lane without exceeding thresholds for safety metrics. Passing is not an option in this scenario. The roadway geometries are known, and the traveled way is wide enough to maintain a safety envelope threshold without crossing the median. No traffic control devices are present with the exception of an easily visible speed limit sign. Lane markings are clearly visible, and no crosswalks are detected in the area. The relative positions of the detected objects are determined[18] and the headings and speed of the detected objects are expressed as velocity vectors[19] (refer to AVSC00004202009). ADS competence is evaluated utilizing metrics and the methods to establish threshold criteria described in AVSC00006202103.

[18] From SAE J3197. Coordinates relative to the ADS-DV defined coordinate system, which may be system specific.
[19] The velocity vector is defined as the first derivative of position with respect to time of the object reference point. This value may be determined by differentiating the salient object(s) detected – relative position (Section 5.2.19 in AVSC00004202009) data element over time.

FIGURE 2 Example illustration of behavioral competency responding to VRU while maintaining a lane



NOTE: In Figure 2, the path plan curves to allow appropriate lateral distance (d_{lat}) between itself and the detected object to its right.

TABLE 4 Example contextual elements to specify for responding to VRU while maintaining a lane (based on Figure 2)

ADS Behavioral Competency		Context (Examples)
Roadway infrastructure	Maintaining a lane	[ ] Traffic signals [x] Lane markings [x] Roadway geometry [ ] Designated crosswalk(s) [ ] Dedicated lane(s) for VRU [ ] Other
Dynamic conditions	Responding to VRU	VRU type: [ ] Pedestrian [ ] Pedal cyclist [ ] Road worker [ ] Micromobility vehicle [ ] Disabled assistive device [x] Unclassified (but VRU cannot be ruled out) Activity and behavior: [ ] Crossing (inside or outside crosswalk) [x] Traveling parallel (in lane, dedicated lane, shared land, sidewalk, shoulder) [ ] Standing still [x] Following traffic code [ ] Disobeying traffic code [x] Behavior indicators (gait, tracked path/history, attention) [x] Trajectory relative to ADS (parallel, intersecting, erratic, in lane, dedicated lane, shared lane, sidewalk, shoulder)

A VRU interaction while navigating an intersection is shown in Figure 3. In the example, an ADS detects multiple objects while traveling along a two-lane roadway with bi-directional traffic approaching a four-way intersection. The objects are confidently classified as VRUs (one pedal cyclist and three pedestrians). The expected behavior of the ADS is to negotiate the right turn in its lane without exceeding thresholds for safety metrics. Forward conditions allow adequate sight distance/visibility (e.g., horizontal or vertical curvature) to determine no other road users are present. The roadway geometries are known. A traffic signal controls traffic at the intersection. Pedestrian crossing signals are synced with the traffic light. Lane markings are clearly visible and crosswalks are detected in the area. The relative positions of the detected objects are determined[20] and the headings and speed of the detected objects are expressed as velocity vectors[21] (refer to AVSC00004202009). ADS competence is evaluated utilizing metrics and the methods to establish threshold criteria described in AVSC00006202103.

FIGURE 3 Illustration of behavioral competency responding to VRU while navigating an intersection

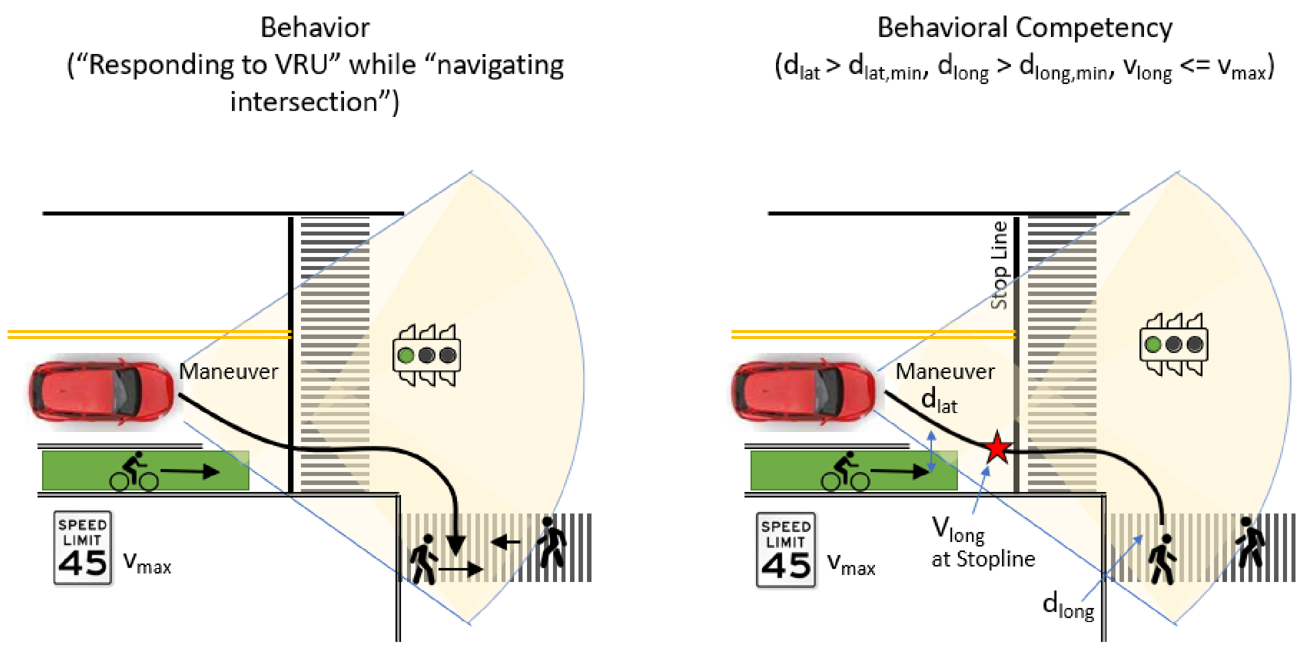


Table 5 breaks down additional context by roadway infrastructure and dynamic conditions based on challenges unique to VRU interactions at intersections. These lists are not exhaustive but provide an example that includes testable variables such as VRU type, VRU motion, and infrastructure elements involved in the evaluation of an ADS to competently respond to a VRU. ADS developers establish thresholds for pass/fail evaluation that consider the ODD, use case for the ADS-DV, traffic code, and risk tolerance.

[20] From SAE J3197. Coordinates relative to the ADS-DV defined coordinate system, which may be system specific.

[21] The velocity vector is defined as the first derivative of position with respect to time of the object reference point. This value may be determined by differentiating the salient object(s) detected – relative position (Section 5.2.19 of AVSC00004202009) data element over time.

TABLE 5 Example contextual elements to specify for responding to VRU while navigating intersection (based on Figure 3)

ADS Behavioral Competency		Context (Example)
Roadway infrastructure	Navigating intersection	[x] Traffic signals [x] Lane markings [x] Roadway geometry [x] Designated crosswalk(s) [x] Dedicated lane(s) for VRU [ ] Other
Dynamic conditions	Responding to VRU	VRU type: [x] Pedestrian [x] Pedal cyclist [ ] Road worker [ ] Micromobility vehicle [ ] Disabled assistive device [ ] Unclassified (but VRU cannot be ruled out) Activity and behavior: [x] Crossing (inside or outside crosswalk) [x] Traveling parallel (in lane, dedicated lane, shared land, sidewalk, shoulder) [ ] Standing still [x] Following traffic code [ ] Disobeying traffic code [x] Behavior indicators (gait, tracked path/history, attention) [x] Trajectory relative to ADS (parallel, intersecting, erratic, in lane, dedicated lane, shared lane, sidewalk, shoulder)

5.2 Applying Metrics for Behavioral Competency Evaluation

AVSC members evaluate behavioral competence against performance metrics described in AVSC00008202111, Section 5.2. Thresholds for these metrics depend on context, including ODD factors, use case, and traffic code for the area(s) in which the ADS is tested. In the example scenarios above (responding to a VRU while maintaining a lane, responding to a VRU while navigating an intersection), once an object is detected and potentially classified, there are many considerations that must be accommodated to plan an appropriate response and complete the OEDR. In addition to VRUs, ADS developers and manufacturers are likely to plan to have safety margins to all object classes when the AV is in motion.

In the Figure 2 example, the ADS detects an object while traveling along a two-lane roadway with bi-directional traffic. If a detection and classification-based method is used, then after detection, classifying the object allows the ADS to apply class-based margins, and the application of these margins can lead to more than one behavioral outcome depending on situational context. For example, if the object is classified as a cyclist in Figure 2, the ADS would apply the appropriate margins to that cyclist, which could be derived from minimum distances to cyclists as stated in traffic code. One outcome of this scenario could be that the ADS biases in lane to maintain the appropriate margin. However, if the lane is not wide enough to pass the cyclist with the required margin, the ADS may remain behind the cyclist while applying the appropriate following distance to a lead actor. Overall, the outcome of the AV's behavior may vary from scenario to scenario depending on the roadway structure (i.e., lane width), other traffic participants, etc.

Table 6 shows examples of foundational ADS safety metrics that may be applied to evaluate this behavioral competency (refer to AVSC00006202103). Manufacturers may have additional, customized metrics specific to their system, the operating environment, use case, and risk management policies.

Safety performance during ADS-DV and VRU interactions can be evaluated independently from mobility performance using ADS safety performance metrics such as maintenance of a safety envelope, contextually safe vehicle motion control (measured by acceleration and jerk), and the amount of time between an observed VRU behavior and the ADS's reaction (OEDR reaction time) (refer to AVSC00006202103).

TABLE 6 Example application foundational metrics for responding to VRU

ADS Behavioral Competency		Relevant Foundational ADS Safety Metric	Example Application of the Metric
Roadway infrastructure	Maintaining a lane	Compliance with traffic regulations	Lateral spacing requirements as codified in traffic code (e.g., 4 feet clearance in PA[22]).
Roadway infrastructure	Navigating intersection	Compliance with traffic regulations	Lateral spacing requirements as codified in traffic code (e.g., 4 feet clearance in PA[22]).
Dynamic conditions	Responding to VRU	Maintaining safety envelope	Do not exceed relative safety envelopes (separation distance) as a function of VRU type, relative and absolute velocity, and other contextual factors, etc. [12] Lateral distance between ego vehicle and VRUs are >x meters. Longitudinal distance (if crossing) between ego vehicle and VRUs are >x meters for y% of the time.
		OEDR reaction time	The OEDR reaction time (defined as the time from when the ADS detects an object or event to the time when a measurable response as appropriate is applied as a result).

5.3 Defining Acceptance Criteria and ODD-Relevant Thresholds

This section describes how acceptance criteria are influenced by context and ODD. Evaluation depends on the setting and relative frequency of the measurement. These concepts are described generally in AVSC00002202004 Section 5.3 and applied here for the “responding to VRUs” behavior.

Testing an ADS-DV’s capability to predict the movement or behavior of VRUs and accounting for the likelihood of potential conflicts is an important aspect of testing interactions. As with human drivers who interact with VRUs, ADSs predict the potential future positions of objects or available free space by making assumptions about objects, including their capacity to move. To help standardize some of these assumptions, IEEE [13] has identified an initial set of assumptions and formulas related to object kinematics that can be incorporated into safety models for ADS. To utilize the voluntary standard, manufacturers define a range of values for VRU kinematics such as heading angle, rate change of heading angle, velocity, braking ability, and other factors. Data sources such as naturalistic driving data and ODD characterization should help inform these values. Additional assumptions may also be tested for reasonable combinations of values (e.g., rate change of heading angle combined with velocity) to help to define reasonably expected object behaviors.

U.S. and Euro NCAP Pedestrian AEB tests can inform ADS VRU testing, but the temporary nature of vehicle control should not be confused with sustained control of the DDT by an ADS. Behaviors of the ADS-DV in an NCAP scenario may be different from a human-driven vehicle in the same scenario [14] [15].

[22] Developers may establish additional margin in their safety envelope minimum margin values based on vehicle performance to increase robustness to misclassification or unexpected VRU behaviors.

6. VRU Expectations

What a VRU expects from an interaction with an ADS-DV influences the interaction as it happens; therefore, calibrating expectations can lead to more predictable and safer interactions between ADS-DVs and VRUs [16] [17]. Compliant VRUs do not alter their maneuvers in the presence of an ADS.

6.1 What VRUs Should Know

The number one recommendation from NHTSA for pedestrians to be safe on roadways is “be predictable” [18]. The recommendation to pedestrians for safety is “follow the traffic code and obey signs and signals.” Similarly, ADS-DVs that can more reliably predict the behavior of VRUs are more likely to have safer interactions VRUs can better calibrate their expectations for interactions with ADS-DVs when the behavior of the ADS-DV is contextually safe and predictable in a manner compliant with traffic code. Performance against expectations is an important component of technology acceptance [19].

VRUs should expect an ADS to follow traffic code. Compliance with traffic code is an important safety metric for ADS-DVs (AVSC00006202103). In cases where the law either requires or implies judgment or subjective assessment by a [human] driver, an ADS can be expected to behave in a manner consistent with the traffic and conditions in which it was trained to operate.

VRUs and human-operated vehicles do not always follow the law and sometimes decide to prioritize mobility or speed over safety. Past experiences or false consensus bias may lead some people to expect similar behaviors of other drivers (possibly both human and ADS). ADS-DVs that always follow traffic code could potentially cause conflicts with VRUs or other road users individually prioritizing mobility over safety. **In non-safety-critical instances where a human’s mobility priorities conflict with regulation or traffic laws, it should be expected that an ADS will follow the traffic code.**

An ADS may make refined assumptions about detected objects that have been confidently classified as a type of VRU. The context in which a VRU is encountered can influence expected behavior and assist an ADS preparing an appropriate response. Use of standardized assumptions about VRU kinematics, such as values for speed, acceleration, rate of heading change, and others [13] may help ADS manufacturers establish common expectations for VRU interactions. As with current driving scenarios involving human drivers, all interactions between VRUs and ADS-DVs are or will have probabilistic outcomes, so expectations and assumptions about behaviors cannot be taken as guaranteed behaviors.

There may be instances where unreasonable VRU behaviors result in a crash with an ADS [13]. For example, a VRU entering a roadway with the right-of-way at a crosswalk from behind an occlusion might be a predictable and preventable scenario; however, in an urban ODD, a VRU that suddenly appears from behind an occlusion may increase the likelihood of a crash. VRUs purposefully interfering with, testing, or otherwise attempting to influence the trajectory of the ADS-DV may also create scenarios that increase the likelihood of a crash because ADS-DVs, like other road vehicles, have significant mass and require distance to bring to a stop.

6.2 ADS-DV Communication with VRUs

Anyone who uses a roadway coordinates their movement with other road users [20]. VRUs and human drivers alike maximize their mobility goals within a level of safety acceptable to them while interacting with others behaving according to their own safety and mobility priorities. To facilitate interactions between road users, humans communicate their intentions using a wide range of methods. Direct vehicle communication tools such as turn signal indicators and brake lamps broadcast information about the vehicle state (e.g., braking) and a driver’s intended motion or path plan (e.g., turn signals). Indirect communication also exists between human drivers and VRUs, noted as a predictive system metric, “Contextually Safe Vehicle Motion Control” defined in AVSC00006202103. Both direct and indirect communication can be used by other road users and VRUs to infer goals (e.g., “I am changing lanes” or “I am slowing down” or “I am slowing down in order to change lanes”).

Research in other direct vehicle communication technology, such as wireless communication or new exterior lighting, between VRUs and ADS-DVs is ongoing. ADS developers and fleet operators will continue to utilize existing vehicle communication signals required by law to broadcast braking (brake lights), directional intent (turn signals), and special situations outside nominative driving scenarios (hazard lights). For example, ADS-DVs will always utilize turns signals as required by traffic code to indicate the intention to turn right, left, or change lanes. This communication method can lead to shared situation awareness when VRUs may be otherwise distracted or unaware of the vehicle [21]. These signals enhance vehicle conspicuity so VRUs are more likely to see an approaching vehicle, share an understanding of its intended path, and adjust or maintain their paths accordingly. This shared understanding can help manage safety risk and encourage safer and efficient interactions. It is important to note that new or refined communications to augment safety for ADS-DVs is still an active area of research. Common methods for communication between ADS DVs and VRUs that leverages this ongoing work may help maximize effectiveness and minimize confusion during interactions.

7. Summary

As the number of ADS-DVs on the road increases, so will the amount of interactions between ADS-DVs and VRUs. It is important that ADS manufacturers reasonably account for the complexity, variety, and other challenges associated with VRU detection and response. This best practice provides considerations that ADS manufacturers and developers can take into account in order to promote safe VRU interactions. It outlines types of VRUs and the challenges associated with detecting and classifying them. This document also provides context for building behavioral competencies around safely responding to VRUs and applying metrics to evaluate those behavioral competencies. Finally, communication and properly calibrated expectations on the part of both ADS and VRUs will help ensure safe interactions.

8. About Automated Vehicle Safety Consortium™

The objective of the Automated Vehicle Safety Consortium™ (AVSC) is to provide a safety framework around which automated vehicle technology can responsibly evolve in advance of the broad use of commercialized vehicles. The consortium will leverage the expertise of its current and future members and engage government and industry groups to establish safety principles and best practices. These technology neutral principles are key considerations for deploying SAE level 4 and level 5 automated vehicles on public roads.

AVSC Vision:
Public acceptance of SAE level 4 and level 5 automated driving systems as a safe and beneficial component of transportation through industry consensus.

AVSC Mission:
The mission of the Automated Vehicle Safety Consortium™ (AVSC) is to quickly establish safety principles, common terminology, and best safety practices, leading to standards to engender public confidence in the safe operation of SAE level 4 and level 5 on-road vehicles ahead of their widespread deployment.

The AVSC will:

- Develop and prioritize a roadmap of pre-competitive topics;
- Establish working groups to address each of the topics;
- Engage the expertise of external stakeholders;
- Share output/information with the global community;
- Initially focus on fleet service applications.

9. Contact Information

To learn more about the Automated Vehicle Safety Consortium™, please visit https://avsc.sae-itc.org.

Contact: AVSCinfo@sae-itc.org.

10. Acknowledgements

The Automated Vehicle Safety Consortium™ would like to acknowledge the contributions of the member organizations during the development of this document:

Aurora, Ford, Honda, Lyft, Motional, Toyota, and VW.

11. Abbreviations

ADS	Automated Driving System
ADS-DV	Automated Driving System-Dedicated Vehicle
AV	Automated Vehicle
AVSC	Automated Vehicle Safety Consortium™
DDT	Dynamic Driving Task
DV	Dedicated Vehicle
MaaS	Mobility as a Service
MRC	Minimal Risk Condition
ODD	Operational Design Domain
SA	Situation Awareness
SAE ITC®	SAE Industry Technologies Consortia®

APPENDIX A. Best Practice Quick Look

Clear definitions for VRUs (4.1) can help narrow discussions around safety performance and interactions between ADS-DVs and other road users. AVSC believes that VRUs are human road users that meet three criteria:

- They at a higher risk of being injured as a result of a crash than those inside a vehicle and thus offered protection from the vehicle and its passive safety systems [7].
- The kinematics that define their movement are very different (in terms of their range of kinematic parameters governing their motion) from on-road vehicles.
- The regulations that govern their interactions with other road users are distinct from on-road vehicles.

Numerous challenges and considerations (4.2) face ADS developers, manufacturers, and fleet operators when designing and testing ADS-DVs for safer operation in the presence of VRUs. The AVSC's pre-crash perspective is important to the discussion of ADS-DV interactions with VRUs intended to avoid or reduce the risk of crashes.

- Developers should design and test their ADS end to end system level performance to ensure safe execution of the dynamic driving task in the presence of reasonably expected variations in shape, color, density, texture, lighting variation, environmental conditions, etc.
- An ADS must consider classification and prediction errors.
- ADS Developers should design the ADS-DV to follow traffic code.
- Robust motion planning should consider both compliant and reasonably foreseeable non-compliant behaviors by VRUs.

AVSC member companies utilize a behavioral competency framework to develop applicable metrics, relevant acceptance criteria, and metric thresholds for VRU testing. Examples for "responding to VRUs" are illustrated using the framework (5.1).

Calibrating expectations between ADS-DVs and VRUs can lead to more predictable and safer interactions.

- VRUs should expect an ADS to follow traffic code.
- In non-safety-critical instances where a human's mobility priorities conflict with regulation or traffic laws, it should be expected that an ADS will follow the traffic code (6.1).

APPENDIX B. Future Research for VRUs

There are various areas which require further research and discussion among stakeholders to enhance the safety of VRUs.

TABLE B1 Example application foundational metrics for responding to VRU

Area	Description
Post-crash assistance	Infrastructure owner-operators (IOOs) and departments of transportation. In all jurisdictions, human drivers must stop and render assistance in the event of a crash that causes injury or property damage. ADS developers should design systems that adhere to applicable regulations relating to collisions (e.g., they may be required to stop in the event of a crash involving human injury and contact law enforcement).
Communications **from** ADS-DV to VRUs	In the absence of a human driver, pedestrians have expressed concerns over not knowing or understanding an AV's intention [22]. A clear understanding of intention can foster trust in an ADS-DV and ultimately acceptance [23]. Stand-off scenarios or situations (instances in time) with ambiguous or subjective rules, such as who has the right of way, are often resolved with some type of explicit communication between a human driver and a VRU. This is further complicated if the communication is required with a specific VRU who may be one among many [24]. Additional research and experience is needed to inform best practice recommendations for ADS to VRU communication to supplement existing signals [21].
Communication **to** ADS-DV from VRUs	Though not required for safely interacting with VRUs, ADS-DVs may account for pedestrian safety devices or messages that may be received from VRUs or the infrastructure (SAE J2945/9), when available. Additionally, SAE J3216 describes machine-to-machine communication that can facilitate cooperation between ADS-operated vehicles. These messages can include shared information about objects detected by other vehicles, including VRUs.

APPENDIX C. Excerpt from the FHWA Course on Bicycle and Pedestrian Transportation: Pedestrian and Bicycle Crash Types (Lesson 4)

The FHWA outlines a process [25] that places responsibility on both VRUs and (human) drivers to avoid crashes. All road users have a responsibility to be safe in and around traffic. Continuing to follow these steps will help promote safer interactions between VRUs and ADS-DVs.

> Whether you are a pedestrian, bicyclist, or motorist, you generally go through a similar sequence of actions leading from searching for and recognizing a potential crash situation to taking steps to avoid it.
>
> The steps in this sequence are described below. If any of these steps are overlooked by either party, a crash may result.
>
> Step 1: Search—Both driver and bicyclist or pedestrian scan their environment for potential hazards.
>
> Step 2: Detect—One or both parties (bicyclist, pedestrian, or motor vehicle) sees the other.
>
> Step 3: Evaluate—The threat of collision is recognized, along with the need for action to avoid it.
>
> Step 4: Decide—Assess risk and select the actions necessary to avoid a collision. This may involve judging location, closing speed, direction of travel, position in traffic, likely behavior, and other factors.
>
> Step 5: Action—This step involves the successful performance of the appropriate action(s) to avoid a collision.

APPENDIX D. Excerpt from the Federal Highway Administration University Course on Bicycle and Pedestrian Transportation

Publication Number: FHWA-HRT-05-133
Date: July 2006
https://www.fhwa.dot.gov/publications/research/safety/pedbike/05085/

Table 8-1. Walking characteristics and abilities of different pedestrian age groups.
Source: *Florida Pedestrian Planning and Design Handbook* and the *County of Sacramento Pedestrian Design Guidelines*[1,2]

Infants and Toddlers (ages 0 to 4)

At this age, walking skills are just being developed and the children require constant parental supervision. Infants and toddlers are very limited in ability and are:

- Learning to walk.
- Developing peripheral vision and depth perception.
- Impulsive and unpredictable.

Young Children (ages 5 to 12)

At a young age, children have unique abilities and needs. Since children this age vary greatly in ability, it is important for parents to supervise and make decisions on when their child is ready for a new independent activity. Children in this age range tend to be:

- Impulsive and unpredictable.
- Limited in their peripheral vision (a sound source is not easily located).
- Limited in training/lacking in experience.
- Thrilled or excited by close calls.
- Short and hard to see by drivers.
- Susceptible to darting or dashing out into the intersection.
- Likely to copy the behavior of older people.

Preteens (ages 13 to 14)

By middle school years, children have many of their physical abilities but still lack experience and training. Now there is greater desire to take risk. Preteens generally:

- Lack experience.
- Walk and bicycle more and at different times (have a higher crash exposure).
- Ride more frequently under risky conditions (in high traffic).
- Lack positive role models.
- Walk across more risky roadways (collectors and above).
- Get involved in more intersection dash collisions.
- Have a sense of invulnerability that makes them more willing to take chances.

High School Aged (ages 15 to 18)

By high school and college age, exposure changes and new risks are assumed. Many walk and bicycle under low light conditions. Other characteristics of this age group are that they:

- Are very active, can go long distances, and visit new places.
- Feel invincible.
- Still lack experience and training.
- Are capable of traveling at higher speeds.
- Will overestimate their abilities on hills, curves, etc.
- Attempt to use bicycles, in-line skates, etc., based on practices carried over from youth.
- Are willing to experiment with alcohol and drugs.