AVSC00011202307

Issued 2023-07

Automated Vehicle Safety Consortium™ Best Practice

Automated Vehicle Safety Consortium™
A Program of SAE ITC

# AVSC Best Practice for Continuous Monitoring and Improvement after Deployment

**Citation:** Automated Vehicle Safety Consortium. 2023. AVSC Best Practice for Continuous Monitoring and Improvement after Deployment. SAE Industry Technologies Consortia.

## Rationale

Successful scaling of automated driving system (ADS) technology and realization of its full potential will require developers and service providers to continuously monitor performance of their fleet and enact prompt improvements should issues arise. ADS developers and manufacturers can use the data collected from vehicles in active deployments (e.g., safety performance data) to proactively confirm initial risk assumptions and feed other safety management processes. The operating environments for active deployments are complex and can evolve over time. Continuous monitoring of the automated driving system-dedicated vehicles (ADS-DVs) makes it possible to identify and address new risks related to changes in the environment. This also means the validity of operational design domain (ODD) related assumptions is periodically assessed.

Changes to the environment, such as road damage or new lane geometries, may be unplanned and not previously considered by the ADS developers. Unforeseen variations to the operating environment can impact the behavior of both the ADS-DV and other road users, potentially leading to lower predictability of intentions and negative safety outcomes. The ADS-DV can mitigate these risks with ongoing monitoring of its own safety performance and that of other road users. This can be accomplished by identifying unexpected behavior of both and examining the underlying causes, such as alterations to the environment or the validity of design assumptions.

This Automated Vehicle Safety Consortium™ (AVSC) best practice provides an approach to continuous monitoring and potential improvement of safety performance. It outlines approaches to analyzing data related to known and unknown variations in the ADS-DV's operating environment. It also complements other AVSC best practices that provide metrics and methods which can be used to monitor safety [AVSC00006202103, AVSC00008202111] while considering important factors pertaining to how data is collected, analyzed, and used [AVSC00004202009].

# Preface

The Automated Vehicle Safety Consortium™ (AVSC) is an industry program of SAE Industry Technologies Consortia® (SAE ITC). The AVSC shares information to inform and accelerate industry-wide standards and advance the safe development, deployment, and fleet operations of automated driving systems (ADSs). The members of this consortium have decades of accumulated experience including millions of cumulative miles of physical and simulated ADS testing focused on safer, reliable, high-quality transportation. They are committed to applying their experience and combined knowledge to earn public confidence in the safe operation of SAE level 4 and level 5 automated vehicles.

The wide range of technologies, use cases, and operating domains create unique challenges with public perception of ADSs. The consortium recognizes the beneficial role best practices and information reports can have for the industry and for the safe operation of SAE level 4 and level 5 automated driving system-dedicated vehicles (ADS-DVs). These technology-neutral documents provide key considerations for safely deploying ADS-DVs on public roads. AVSC documents are based on current state of the art technology and the experiences of the AVSC members. AVSC members currently support, or intend to support, the best practices or equivalent measures to set a bar for other industry participants to meet.

Technology advances rapidly and new information is becoming available at an increasing rate. The AVSC's best practices and information reports are living documents. As knowledge and experience grow, our publications will be revisited and updated, as needed, to continue to support the safer on-road use of ADS-DVs. Comments and open discussion on the topics are welcome in appropriate industry forums.

# Introduction

The safety performance of ADS-DVs is expected to evolve over time. Large volumes of operational data produced by ADS-DVs can be analyzed to identify patterns as well as anomalies. These results can be indicative of actual or potential performance changes. In the future, iterative improvements to ADS performance may occur, deployed as software updates—over-the-air (OTA) or otherwise—or hardware updates that have been enabled by new data or technology advancements.

It is expected that ADS-DVs will encounter scenarios and situations that occasionally challenge its perception or control algorithms. These types of events may be due to changes in the deployed operating environment of the ADS-DV that were unknown or unaccounted for at the time the operational design domain (ODD) was developed. They may also be due to incorrect assumptions about the ADS's performance in such situations. Capturing and analyzing performance data from such scenarios enables ADS developers to make updates to their fleet(s).

This best practice describes the methods that ADS developers may consider employing to continuously monitor and potentially improve ADS safety performance post-deployment. Applying these methods to deployed ADS-DVs will drive continuous improvement in ADS safety performance, as well as promote public trust.

# Table of Contents

# 1. Scope

This Automated Vehicle Safety Consortium™ (AVSC) best practice describes an approach for continuous monitoring of the safety metrics identified in AVSC00006202103. In addition, this best practice describes data sources and methods that can be used to identify safety-relevant information. The insights gained about the operating environment can support manufacturers or fleet operator's continuous improvement of ADS-DV safety performance post-deployment.

The described approach enables improvement of safety performance by identifying unknowns and regularly evaluating the validity of assumptions made about the ADS-DVs' operating environment. It also references change risk management approaches [AVSC00010202304] and describes approaches to analyzing and segmenting data according to intended behavioral competencies [AVSC00008202111].

## 1.1 Purpose

This best practice is intended for use by the technical community (developers, manufacturers, testers, fleet managers, etc.) to aid in the development, testing, and safe deployment of ADS-DVs. It may also be useful to public agencies and stakeholders, including standards bodies and governmental decision-makers, who have an interest in better understanding the safety posture of ADS deployments.

This best practice supports public and private organizations in preparing for and deploying ADS-DV systems. For example, it may be used by ADS manufacturers and developers to document the aggregate safety performance of vehicles within the target ODD during deployment.

# 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 applies. 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.

AVSC00003202006 AVSC Best Practice for Passenger-Initiated Emergency Trip Interruption

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 (ADSs)

AVSC00008202111 AVSC Best Practice for Evaluation of Behavioral Competencies for Automated Driving System-Dedicated Vehicles (ADS-DVs)

AVSC00010202304 AVSC Information Report for Change Risk Management

SAE J3016_ 202104 Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles

SAE J3216_202005 Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles

SAE JA6268_202303 Design and Run-Time Information Exchange for Health-Ready Components

SAE 2019-01-1048 On-Board Predictive Maintenance with Machine Learning

### 2.1.2 Other Documents


[1] Yasukuni, Tanaka, M., and Ichikawa, K. (2001). *High-speed track inspection car in new Dr. Yellow*. Available at https://www.semanticscholar.org/paper/High-Speed-Track-Inspection-Car-in-New-Dr-.-Yellow-Yasukuni-Tanaka/92cffbc841d4e8f23959418a8db507092243eaa8.

[2] DOT. (2023). *Work zone data exchange (WZDx)*. U.S. Department of Transportation (DOT). Available at https://www.transportation.gov/av/data/wzdx.

[3] VICS. (2013). *VICS: VICS supports drivers in relaxed and safe driving. Vehicle Information and Communication System Center (VICS)*. Available at https://www.vics.or.jp/en/know/about/pdf/vics_pamph.pdf.

[4] TechLink. (2020). *Proactive alerts: Updated service procedures and warranty information. General Motors*. Available at https://gm-techlink.com/?p=13307.

[5] Ford. (2021). *A matter of trust 2.0: Ford's approach to developing self-driving vehicles*. Ford Motor Company. Available at https://media.ford.com/content/dam/fordmedia/North%20America/US/2021/06/17/ford-safety-report.pdf.

[6] Aurora. (2021). *Voluntary safety self-assessmen*t. Aurora. Available at https://prismic-io.s3.amazonaws.com/aurora-dev/eca92b55-80e9-4240-93b9-61683da1f875_Aurora_VSSA_2021_Final.pdf.

[7] General Motors. (2016). *Chevrolet Silverado service manual*. General Motors. Available at https://cdn.dealereprocess.org/cdn/servicemanuals/chevrolet/2016-silverado1500.pdf.

[8] White, R. (2016). *High river RCMP investigate shotgun vandalism to road signs*. CTV News. Available at https://calgary.ctvnews.ca/mobile/high-river-rcmp-investigate-shotgun-vandalism-to-road-signs-1.2879236.

[9] ISO. (2022). *Road vehicles—Safety of the intended functionality* (Standard no. ISO 21448:2022). International Standards Organization (ISO). Available at https://www.iso.org/standard/77490.html.

[10] ANSI/UL. (2022). *Standard for safety for the evaluation of autonomous products* (Standard no. ANSI/UL 4600). Underwriters Laboratories Standards and Engagement (ULSE). Available at https://ulse.org/ul-standards-engagement/presenting-standard-safety-evaluation-autonomous-vehicles-and-other-1.

[11] ISO. (2019). *Road vehicles—Safety of the intended functionality* (Standard no. ISO/PAS 21448:2019). International Standards Organization (ISO). Available at https://webstore.ansi.org/standards/iso/isopas214482019.

# 3. Definitions

## 3.1 Behavioral Competency

Expected and measurable capability of an ADS feature operating a vehicle within its ODD.

NOTE 1: Competency refers to the term “expected” in the definition. Using skills, knowledge, and abilities, an ADS executes behaviors competently according to performance criteria set by the ADS developer.

NOTE 2: While SAE J3164 does not preclude it, the AVSC definition used here differs from the SAE J3164 definition by explicitly stating the competency is measurable.

## 3.2 Operational Design Domain (ODD) (SAE J3016_202104)

Operating conditions under which a given driving automation system, or feature thereof, is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, or the requisite presence or absence of certain traffic or roadway characteristics.

## 3.3 [Safety] Metric

A measurement used to evaluate and track safety performance.

## 3.4 Safety Outcome Metrics

A direct measurement of actualized outcomes or adherence to societal norms.

NOTE 1: Safety outcomes temporally lag deployment. It can take considerable time to collect a sufficient sample size to establish statistically significant measurements.

NOTE 2: Societal norms may differ by industry, geographic regions, and application.

NOTE 3: Although ADS technology is expected to have benefits to other societal outcomes, such as mobility and accessibility, the focus of this work is on safety outcomes only.

NOTE 4: ADS technology safety outcome metrics concern a variety of ADS technology market penetration rates but are generally assumed to be commercial-scale deployments, and not pilots with vehicles operated by highly trained drivers employed by ADS technology developers or small-scale demonstrations, such as very low-volume deployments, limited geographic regions, or tightly limited ODD.

## 3.5 Scene

A snapshot of the environment including the scenery, dynamic elements, and all actor and observer self-representations, and the relationships between those entities.

NOTE 1: This document specifically references operational scenes encountered by an ADS-DV.

NOTE 2: Only a scene representation in a simulated world can be all-encompassing (e.g., an objective scene or ground truth). In the real world, the scene is incomplete, incorrect, uncertain, and from one or several observers’ points of view (e.g., a subjective scene).

NOTE 3: A scene is a descriptive representation of the state of the world at a point in time. A scenario consists of a sequence of scenes.

Scene example: At an instant in time, an ADS-DV is traveling at 35 km/h, in the right-hand lane on an arterial roadway in clear conditions, while another human-operated vehicle travels in the adjacent left lane at 33 km/h with the ADS-operated vehicle located in the blind-spot of the human-operated one.

### 3.6 [Operating] Scenario

A description of the temporal development through several consecutive scenes in a sequence of scenes.

NOTE 1: Every scenario starts with an initial scene. In contrast to a scene, a scenario spans a certain amount of time. Actions and events can be specified as transitions between scenes to characterize the temporal development within a scenario. Scenes in a scenario can also be augmented with goals, values, and beliefs of the traffic participants, resulting in a sequence of situations.

NOTE 2: Scenarios may be defined over varying durations. A scenario may overlap with or be completely contained within another scenario. For example, an overtaking scenario may be decomposed into three scenarios: lane change scenario, followed by lane maintenance scenario, followed by lane change scenario.

NOTE 3: Scenarios may be defined at varying levels of abstraction, ranging from individual quantitative scenarios to quantitative classes of one or more scenarios, to qualitative scenario classes with narrative descriptions.

NOTE 4: This document specifically references emergency and non-emergency scenarios encountered by ADS-DVs.

NOTE 5: The term "operating" in this scenario definition refers to dynamic driving task (DDT) performance (as opposed to, for example, a post-crash scenario in which a first responder is interacting with an ADS-equipped vehicle that is no longer performing the DDT). It also comprehends all types of operating scenarios, such as test scenarios (whether on track or in simulation), as well as scenarios encountered on-road.

## 4. Continuous Monitoring and Improvement

### 4.1 Continuous Monitoring

Safety risks related to changes after deployment or invalid design assumptions may be identified and addressed through continuous monitoring of the ADS-DVs' performance. Continuous monitoring is an approach created or adopted by an ADS developer for collecting, aggregating, and analyzing ADS-DV performance data to identify anomalies or irregularities in safe performance in an operating environment. Continuous monitoring is not intended to imply "constant" for the purposes of this best practice but instead refers to periodic (i.e., daily, weekly, monthly) and on-going monitoring that is appropriate for the scope of the deployment. ADS developers and manufacturers should continuously monitor the safety performance metrics described in AVSC00006202103.

Certain trends or anomalies may indicate changes have occurred within the ADS-DV's operating environment or inaccuracies in assumptions made prior to deployment.

Table 1 provides an example of how the data for continuous monitoring can be obtained using a combination of sources.

NOTE: Data sources listed in Table 1 are for example purpose only. An ADS technology developer may or may not use these sources.

**TABLE 1** Sample data sources relevant for continuous monitoring

| Data Source | Collection Method | Description of Relevant Sources |
|---|---|---|
| ADS-DV on-board systems | Sensor systems | On-board sensors (such as cameras, RADAR, LiDAR, etc.) can measure or inform analyses of safety envelope violations, contextually safe vehicle motion, and crashes. |
| ADS-DV fleets | Shared data from other ADS-DVs and infrastructure | Vehicle-to-everything (V2x) communications through an intelligent transportation system can be monitored to evaluate the effectiveness of data sharing features and keep track of changes in the operating environment. |
| | Third party sources, e.g., Work Zone Data Exchange (WZDx), Hardware as a Service (HaaS) alerts | Third party systems connected to an intelligent transportation system can provide information on transient hazards such as emergency response activities, potholes, black ice, pop-up construction sites, etc. |
| Infrastructure owners/operators (IOOs)* | Traffic sensor cameras | Traffic sensor cameras can provide information on changes in traffic flow, traffic patterns, accidents, severe weather, etc., which can help in monitoring changes in the operating environment. |
| | Notification about changes to infrastructure | Official notification systems can alert ADS developers and manufacturers to significant changes to infrastructure affecting ADS-DVs' operating environment(s) (e.g., lane closure, diversions, work zones). |
| Emergency behaviors | Passenger-initiated emergency trip interruption (PETI) activations | PETI activations (e.g., passenger-on-passenger violence, bridge collapse, earthquake, etc.) can provide valuable information on ADS-DVs' performance in such situations. AVSC00003202006 recommends processes surrounding aspects of PETI activations. |
| Police reports | Police reports (violations, crashes) | Police-reported incidents involving ADS-DVs can provide valuable performance data regarding vehicle responses before, during, and following hazardous events. They are also helpful in cases where the ADS-DV is "pulled over" for a traffic violation. |
| Customer call centers | Post-trip surveys, Live trip feedback | Passenger or other road user reported incidents or live feedback can generate real-time trip reports about ADS-DV performance, violations, changes to operating environment, etc. |
| Publicly available data* | News, media, city, DOT websites | Publicly available data from online communities, media articles or city websites can provide valuable performance data regarding unusual incidents, customer preferences, and overall acceptability. |
| Inspection and diagnostic reports | Pre- and post-trip inspection and diagnostic checks | Performance inspections by trained personnel can be used to establish integrity of electrical and electronic components and physical subsystems. |
| Specialized probe vehicles | High fidelity data collection | A specialized vehicle fitted with an array of high-fidelity sensors for collecting data is calibrated frequently and tested against ground truth data. This can serve as a reference for assessing the performance of the ADS-DVs in a deployed fleet. An example of such a concept exists on "Doctor Yellow," a high-speed test train in Japan used on the Shinkansen lines [1]. |

*Note: Can be used as supporting information in accordance with deployment risk plan, as available.

Data generated by sources identified in Table 1 should be assessed using data segmentation and normalization methods described in safety performance metrics from AVSC00006202103.

Example performance metrics can include:

- Metrics for aggregate on-road performance (e.g., frequency of safety envelope violations, frequency and severity of citable offenses, and severity of crashes).
- Metrics for specific behavioral competencies (e.g., ADS-DV performance following violation of its safety envelope by misbehaving road user).
- Metrics for specific geographic regions (e.g., frequency of emergency evacuation orders).
- ADS developer-specified metrics for latency limits and perception accuracy in identifying and responding to hazardous events.

ADS developers should monitor these segments for data irregularities that contradict previously defined expectations and assumptions or other signals that indicate an update to the ADS-DV or the off-board systems should be considered.

Table 2 describes a list of sample contraindications to design or operating assumptions that are detectable by the ADS-DVs or infrastructure owner/operators.

**TABLE 2** Sample list of irregularities and potential detection methods

| Change to Environment | Potential Detection Methods |
|---|---|
| Changes in the road infrastructure including lane markings, signage, traffic lights, temporary speed restrictions, work zones, etc. | Changes or irregularities in the road infrastructure can be detected by monitoring safety performance metrics using data sources identified in Table 1; e.g., on-board sensor systems or IOOs. Potential detection method includes:<br>• On-board detection using sensor systems.<br>• Using maps that contain parameters about the 3D contours (e.g., grade, bank angle, super-elevation, etc.).<br>• Analysis of differences between the road as mapped and what is sensed; may indicate the road surface has been disturbed (e.g., sink hole, washout, etc.).<br>Note: The U.S. DOT Work Zone Data Exchange (WZDx) can also be used as a source. WZDx provides information about planned conditions occurring on roads, such as repair and construction activities [2]. |
| Differences in driving behavior of other road users | Changes in predictable vehicle motion control could indicate a different than expected behavior of other road users. Predictable vehicle motion control of other vehicles can be detected through safety performance metrics like acceleration or jerk. These can potentially provide indication of changes or degradation to road conditions. Japan's Vehicle Information and Communication System (VICS) traffic probe looks for driving patterns of road users to predict likely road damage [3]. An example of such a scenario may be vehicles swerving to avoid a pothole in the road. |
| Presence of vulnerable road users (VRUs) with behaviors that are uninterpretable by the ADS-DV | The presence of VRUs can be detected using on-board sensor systems or IOOs traffic sensor reports. An example of such a scenario would be traffic diversion via police officer in emergency scenarios or via construction worker in work zones. |

## 4.2 Continuous Improvement

ADS developers and manufacturers should strive to continuously improve upon safety performance over time by reducing or preventing irregularities and strengthening confidence in design assumptions. To do this, the occurrence of irregularities may be continuously monitored as described in 4.1, and a response may be developed, tested, and implemented to mitigate the risks associated with identified irregularities.

Improvements may be achieved by validating and adjusting as appropriate, assumptions made about the operating environment and the ADS-DV's performance in the ODD. Examples of improvement may include:

- Updated maps, whether stored on-board or off-board.
- Enhanced behavior prediction for other road users.
- Enhanced planning for improved conflict or collision avoidance.
- Improved motion control for increased precision with which the ADS-DV executes its own planned motion.
- Enhanced fault detection capabilities; e.g., the ADS technology's ability to detect faulty or degraded sensor performance.

Additionally, the change risk management framework identified in AVSC00010202304 can be utilized for managing risk related to planned and unplanned changes as a means of improvement.

ADS technology developers could use various predictive and reactive methods to improve safety performance of on-board systems (e.g., addressing degradation in performance of perception sensors could result in safety envelope violations). Vehicle health and preventative maintenance are two such approaches recommended in this best practice:

- SAE aerospace and ground vehicle standard SAE JA6268 provides requirements, best practices, and methods for implementing an integrated vehicle health management (IVHM) system. IVHM can be used to forecast failures in vehicle components and systems, enabling preventative repair or replacement.
- Automotive, aerospace, defense, and commercial vehicle industries have well-established preventative maintenance techniques which can be applied to ADS-DVs (see Table 3).

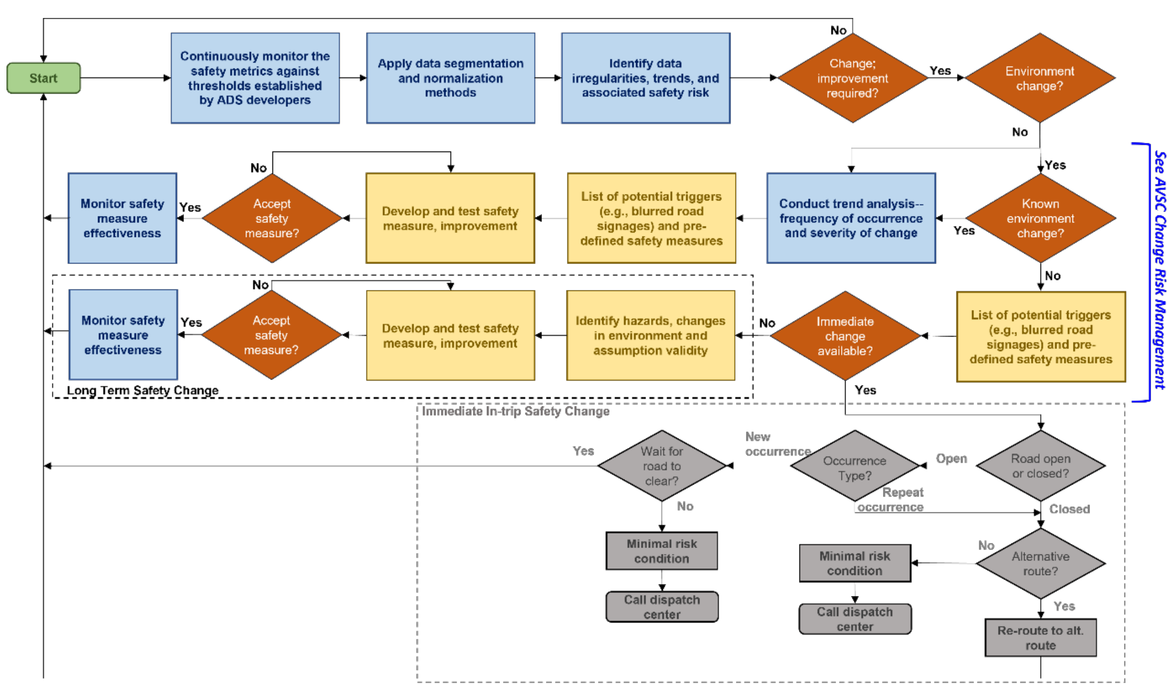
**TABLE 3** Examples of possible preventative maintenance techniques

| Technique | Description |
|---|---|
| Sensor-level analysis and on-board predictive maintenance | Computer analysis of vehicle sensor or diagnostic data to predict the probability of a failure, based on historical data [SAE 2019-01-1048]. |
| Proactive alerts | When the monitored system performance degrades to pre-determined levels, the off-board system sends an alert identifier. The affected system is then identified within the alert identifier by a service message, which prescribes a maintenance procedure [4]. |
| Event data logging | Utilizing on-board data collection systems, event data logging system monitors vehicle health and reports any abnormal data or trends found such that the failure would not propagate to the rest of the fleet [5]. |
| Pre- and post-trip inspection and diagnostic checks | Inspections are performed by trained personnel to evaluate the performance, availability, and integrity of electrical and electronic components, as well as the mechanical integrity of physical subsystems [6]. |
| Event-based maintenance | Identifying unusual events that trigger the need for maintenance on a component or system. For example, driving off-road may automatically trigger maintenance service. |
| Time-based or condition-based maintenance | A time-based trigger signals the need for maintenance based on service life [7]. May be modified by operating conditions that hasten degradation (snow, ice, unpaved roads, etc.). |
| OTA updates issued by developer | Monitoring of deployed and operational systems to identify a requirement or opportunity to issue an OTA software update which can be installed while the vehicle is in use. |

## 4.3 Recommended Framework for Analysis and Improvement

The framework recommended in this best practice provides a standard approach for the continuous monitoring and improvement required to deal with changes in performance, design assumptions, or other irregularities resulting from a change in the operating environment. Figure 1 is a conceptual illustration of a framework for continuous monitoring and improvement of behavioral competency within a broader safety assurance framework. Many of the stages can occur in parallel with other forms of ADS-technology monitoring and risk assessment. Refer to AVSC00010202304 for more information on risk assessment.

**FIGURE 1** Framework for analysis and improvement



AVSC recommends the high-level steps outlined in the flowchart (Figure 1) to analyze safety performance trends and continuously refine ADS-DV decision making. Detailed explanation of this process flow is included in 5.1 and 5.2 for the two use cases of known and unknown changes to the operating environment.

# 5. Changes to the Environment

Changes to the operating environment may cause an ADS-DV to behave in an unpredictable or unsafe manner. As defined in SAE J3016 and described in further detail in AVSC00002202004, the ODD for a fleet of ADS-DVs is characterized, in part, by geographical and environmental elements. It also includes a variety of factors such as time-of-day restrictions and various traffic, roadway, or infrastructure characteristics. Furthermore, some factors may be driven by business or policy concerns, rather than by the ADS-DV’s technical capabilities.

Changes in the operating environment may be known pre-determined elements or may be unknown change elements in the current or planned ODD. Known changes would have been considered by the ADS developer during the development phase. Unknown changes were not included in a developer's analysis and may require some additional mitigations/countermeasures to be thoroughly assessed. The examples in this section consider both types of situations.

## 5.1 Known Changes to the Environment

ADS-DVs rely heavily on on-board perception systems to interpret the environment in which they operate. For example, road infrastructure can experience deterioration as shown in Figure 2. Such conditions increase the risk for an ADS-DV of departing from its intended behavior. In general, cases of road infrastructure deterioration may include:

- Damaged road signs.
- Fading lane, pavement, and road markings.
- Deteriorating road surfaces.

**FIGURE 2** Vandalized road sign [9]

Poor road conditions may cause violations or anomalies in manufacturer-specific safety performance parameters such as predictable behavior and latency requirements. Every time a departure from the intended specification of behavior occurs, it may be manually or automatically logged into a database. Trends from this database can then be analyzed to refine decision making over time. An ADS developer should have safety measures in place to identify and analyze behavior specification violations or anomalies resulting from infrastructure deficiencies.

ADS technology developers should consider the framework in Figure 3 to address known changes to the ADS-DV environment. Steps include:

**Step 1:** Determine if an event-related change occurred. Changes or irregularities in observed trends for the metrics may prompt an in-depth analysis to evaluate whether changes in the operating environment are affecting the ADS-DV safety performance. This can be done by continuously monitoring the safety metrics against established thresholds, following the methods described in AVSC0008202111.

- Example: While approaching an intersection, an ADS-DV exhibits anomalous longitudinal control behavior (high variability in stopping location). The irregular behavior under these circumstances triggers a review of this safety performance event. Camera views during this event reveal a degraded stop sign at the intersection in the ADS-DV lane. The degraded stop sign could account for the ADS-DV's anomalous behavior while braking on approach to this intersection.

**Step 2:** Conduct trend analysis to determine if a metric threshold has been violated. Then assess if the frequency and severity of the violation exceeds the ADS technology developer's defined limit.

- Example: In this case, the severity and frequency of the anomalous lateral control behavior while approaching the intersection across the ADS-DV fleet is deemed to be minimal. The lateral deviations are small enough to occur entirely within the current lane of the ADS-DV.
- Note that a more significant intervention, such as grounding of the entire fleet, may be warranted until the appropriate mitigations and countermeasures are implemented if the severity and frequency of the anomalous lateral control behavior were deemed to be high due to significant lane breaches by the ADS-DV during this event.

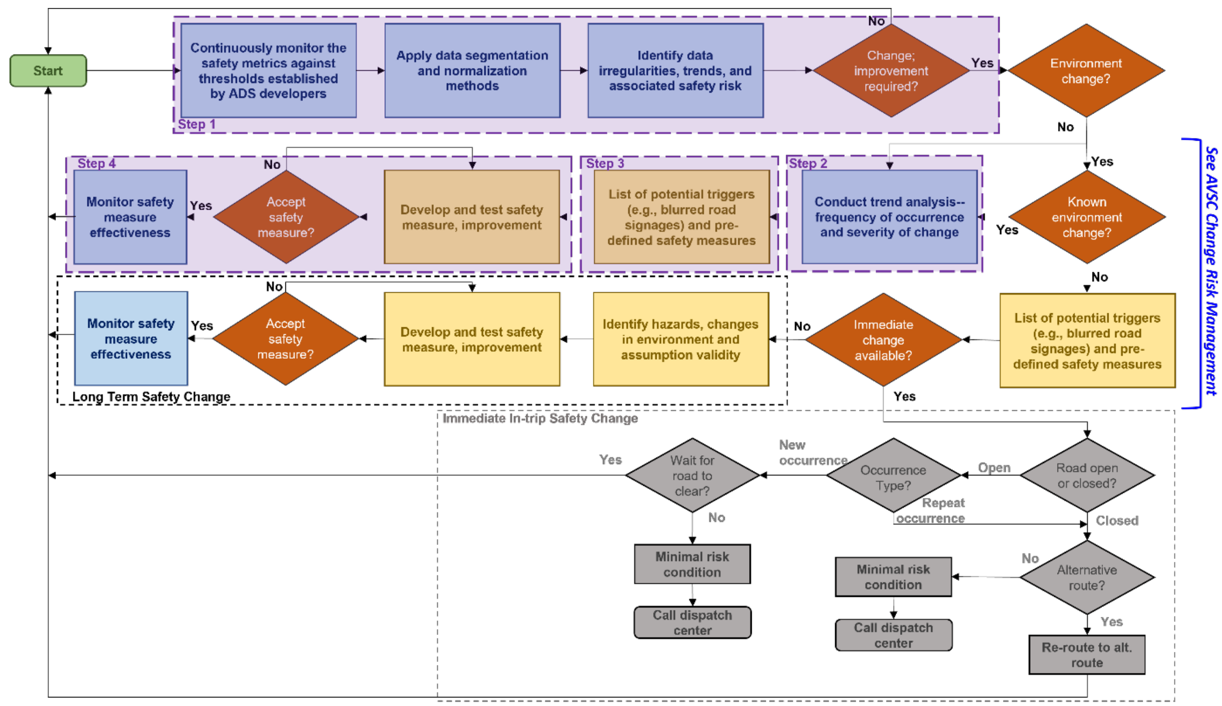
**Step 3:** Determine if the event or trigger is on the standard list[1] of potential safety performance events with pre-defined safety measures in place. An example standard list is defined in AVSC00010202304.

- Example: The assumption is that the damaged traffic control sign is on the standard list of potential safety performance events. The pre-defined safety measure specified is to notify the ADS technology developers. The developers then locate the intersection and damaged stop sign. If the replacement of the sign is unlikely to occur in a timely fashion, the ADS technology developers may evaluate design-specific fixes or take operational action that may also include de-scoping of the given intersection until the appropriate infrastructure maintenance is completed.

**Step 4:** Develop and test a new or improved safety measure, accept, or decline proposed safety measure(s), and determine effectiveness.

[1] An event or trigger not listed but requiring a safety measure or improvement should be added to the standard list.

**FIGURE 3** Framework to analyze and improve known changes




## 5.2 Unknown Changes to the Environment

Even when environmental elements or changes are known as described above, it remains challenging to consider all possible combinations of environmental attributes and analyze their potential effect on the safety of a system. Unique characteristics specific to certain localities or unknown changes to the operating environment could result in undesired ADS-DV behavior. Table 4 provides some examples of unknown environmental changes that an ADS-DV may encounter.

**TABLE 4** Examples of potential unknown changes to an environment

| Changes to Environment | Example |
|---|---|
| New signals | New or modified lane markers, localization aide, signal, etc. |
| New noise sources | Adverse weather conditions like snow can be a noise source that could degrade perception and vehicle control. |
| New rules | Changed speed limit, changes to right turn on red (RTOR), etc. |
| New hazards | A newly installed traffic sign may provide an unplanned communication of a traffic law (rule) as well as deteriorating traffic sign could reach a state of neglect that may pose a heightened debris hazard (e.g., unhinging from a mount) that was not considered in the ADS-DV intended capabilities. |
| New actors | Includes cases like introduction of bicycle or public transportation lanes. |

In addition to the changes identified in Table 4, new areas of operation may have elements that are already known in other operating environments (e.g., signals derived from lane markers that serve as localization aides). Although these design elements are known in a particular ODD, they might have different performance requirements in newly defined ADS-DV operating environments.

An ADS developer may consider known elements from other ODDs and behavioral competencies to help define their safety measures for each newly defined operating environment or ODD expansion.

The ISO/PAS 21448:2019 [11] and ANSI/UL 4600 [10] stress the need for analyzing unknowns and reducing hazards that can be caused by them. Both standards refer to unknowns from an initial functional safety design perspective. Concepts highlighted in the standards can also be applicable to post-deployment safety monitoring and evaluation. This best practice provides a framework to identify and address previously unknown risks with immediate action and long-term safety measures once the ADS-DV has been deployed.

Consider the following example scenario involving crowds forming in the middle of a street or occupying an intersection, such as an impromptu protest. This scenario can represent an unknown environmental change to an ADS-DV traversing a commonly transited street. Human drivers might keep moving the vehicle forward, expecting the crowd to yield. However, for an ADS-DV, this may be considered a new occurrence that it has not previously encountered in this ODD. This scenario would fall under the “unknown” scenario category.

AVSC recommends immediate action and possibly short-term in-trip countermeasures for unexpected unknown scenarios that reveal a serious safety concern. A longer-term solution should then be evaluated to ensure the ADS-DV can recognize and appropriately respond in the future to these newly discovered conditions. In the following, we showcase how immediate in-trip action can entail seeking a minimal risk condition (MRC) state and go/no decisions for the ADS-DV and may further require support from remote assistance. The framework in Figure 4 illustrates high level steps that an ADS technology developer can use to analyze unknown elements to continuously refine ADS-DV decision making.

**Step 1:** Through continuous monitoring, identify the safety performance anomaly, irregularity, or trend and, if applicable, determine if the occurrence is a result of changes in the environment or perception of the environment. Monitor the severity and likelihood of the safety metrics against thresholds established by ADS developers following the methods described in AVSC00008202111.

- Example: In the scenario described above, the ADS-DV correctly recognizes and classifies the presence of many VRUs in the roadway but lacks an executable plan for proceeding to move slowly through the crowd. Doing so could violate safety envelope thresholds with respect to VRUs. In this case, the ADS-DV is unable to proceed forward and risk violating any safety metrics, given the proximity of multiple pedestrians.

**Step 2:** Determine if the event or trigger is on the standard list[2] of potential safety performance events with pre-defined safety measures in place. This current list of known events is defined as an example in AVSC00010202304. If the event is not part of the list of known events, then the event is classified as a “new” or “unknown” environment change.

**Step 3:** If the event is classified as new or unknown, it is recommended that the ADS-DV take the following actions:

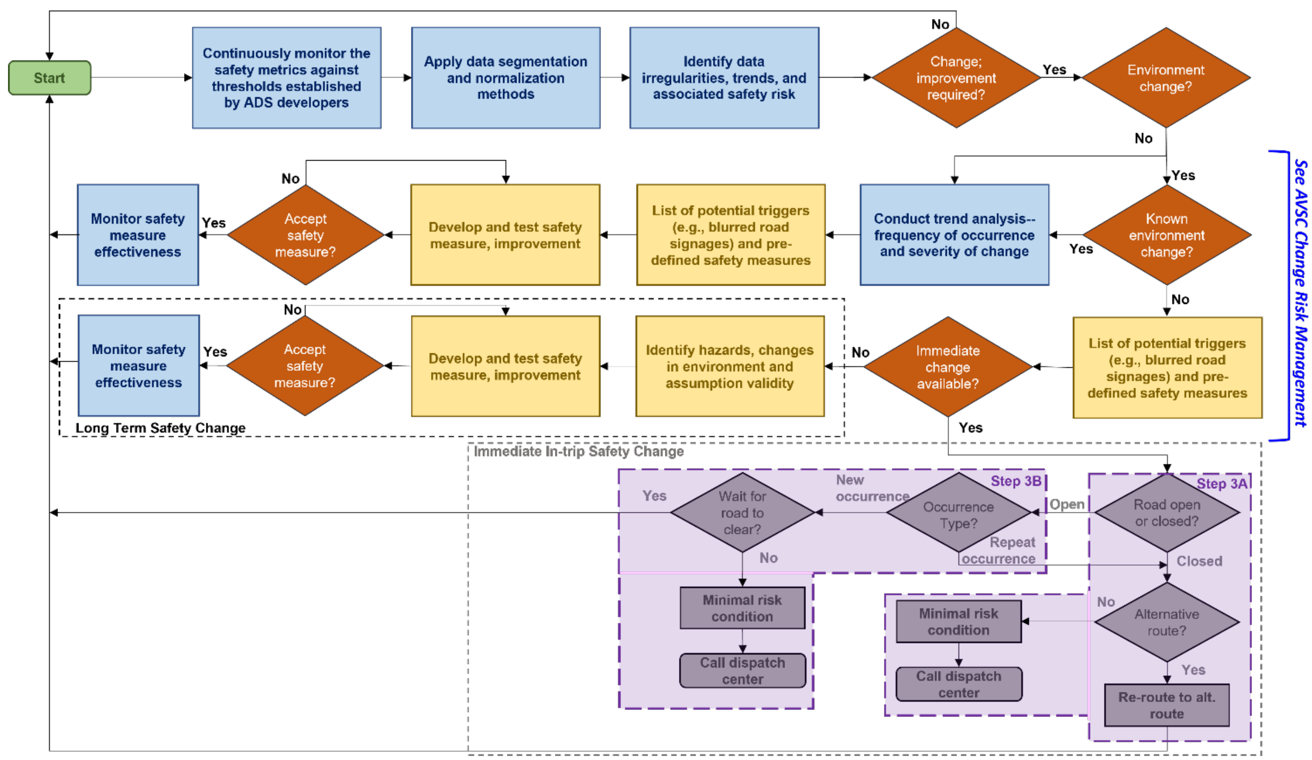
- Immediate, in-trip safety change:
    - **Step 3A:** Determine if the road is open or closed. If the road is open, move to step 3B.
        - If the road is closed and no alternative route exists, the ADS should bring the vehicle to (MRC and request support from the dispatch center.
        - If the road is closed but an alternate route exists, re-route the ADS-DV.
    - **Step 3B:** Make a go-no decision based on if the ADS-DV can maneuver without any safety goal violations and determine if this is a repeat occurrence or a new event.
        - If this event is a new occurrence and the road does not clear, the ADS should bring the vehicle to MRC and request support from the dispatch center.

[2] An event or trigger not listed but requiring a safety measure or improvement should be added to the standard list.

- Long-term safety change:
  - **Step 3X:** Identify gaps in any previous hazards and risk analyses using methods outlined in AVSC00010202304.
  - **Step 3Y:** Develop, test, and implement a safety countermeasure and monitor its effectiveness. Longer term solutions may include improvements in fleet operation centers or hardware and software updates.

**Final step**: Identify the next unknown event and repeat steps 1 through 3.

**FIGURE 4** Framework to analyze and improve unknown changes




## 6. Summary

The frameworks discussed in this document describe how to continuously monitor and potentially improve safety performance in the presence of known and unknown changes in the operating environment. This continuous monitoring and improvement of behavioral competency is a key aspect of the broader safety assurance framework for building a safety case for ADS-DVs. The frameworks may introduce, augment, or replace existing monitoring and improvement methodologies. These methodologies and tools may help ensure ADS manufacturers and operators proactively monitor trends and anomalies that may indicate changes to the environment or invalid initial assumptions.

Consistent with other AVSC best practices, this document supports industry-led, voluntary approaches in the standards development community and is expected to evolve as technology matures. Public agencies may use this document to better understand the safety posture of ADS deployments. In addition to the technical development community, other audiences considered in the development of this best practice include standards bodies, public agencies, and other decision-makers that may influence the deployment of ADS-DVs.

# 7. 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 members and engage government and industry groups to establish best practices and provide stakeholders with ADS safety-related information. This technology-neutral content can form the foundation for 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 light-duty passenger and cargo 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.

# 8. Contact Information

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

Contact: AVSCinfo@sae-itc.org.

# 9. Acknowledgements

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

Aurora Innovations, GM/Cruise, Honda, Lyft, Motional, Uber, Volkswagen, and Waymo.

# 10. Abbreviations

| | |
|---|---|
| ADS | Automated driving system |
| ADS-DV | Automated driving system-dedicated vehicle |
| AVSC | Automated Vehicle Safety Consortium™ |
| DDT | Dynamic driving task |
| GPS | Global positioning system |
| GNSS | Global navigation satellite system |
| HD | High definition |
| IMU | Inertial measurement unit |
| ISO | International Standards Organization |
| MRC | Minimum risk condition |
| ODD | Operational design domain |
| OTA | Over-the-air |
| PETI | Passenger-initiated emergency trip interruption |
| SAE | Society of Automotive Engineers |
| UL | Underwriters Laboratories |
| V2x | Vehicle-to-everything (communications) |
| VICS | Vehicle information and communication system |
| VRU | Vulnerable road user |
| WZDx | Work zone data exchange |

# APPENDIX A. Quick Look

- **Continuous Monitoring**

  ADS developers and manufacturers should monitor the safety performance metrics described in AVSC00006202103 using data segmentation and normalization methods to identify irregularities that contradict previously defined expectations and assumptions or other signals that indicate an update to the ADS-DV or the off-board systems should be considered. (4.1)

  Example performance metrics can include:

  - Metrics for aggregate on-road performance (e.g., frequency of safety envelope violations, frequency and severity of citable offenses, and severity of crashes).
  - Metrics for specific behavioral competencies (e.g., ADS-DV performance following violation of its safety envelope by misbehaving road user).
  - Metrics for specific geographic regions (e.g., frequency of emergency evacuation orders).
  - ADS developer-specified metrics for latency limits and perception accuracy in identifying and responding to hazardous events.

- **Continuous Improvement**

  ADS developers and manufacturers should strive to continuously improve upon safety performance over time by reducing or preventing irregularities and strengthening confidence in design assumptions. (4.2)

  Improvement may be achieved by validating and adjusting as appropriate, assumptions made about the operating environment and the ADS-DV's performance in the ODD; applying a risk management framework as identified in AVSC00010202304; or leveraging various predictive and reactive methods associated with vehicle health and preventative maintenance.

- **Recommended Framework for Analysis and Improvement**

  AVSC recommends a standard approach to analyze safety performance trends and continuously refine ADS-DV decision making. (4.3)

  High-level steps to analyze safety performance trends include:

  - Identify the safety violation event related to the changes to the environment or perception of the environment by monitoring the safety metrics against thresholds established by ADS developers following the methods described in AVSC00008202111.
  - Determine if the event qualifies as severe and if the frequency of occurrence exceeds an ADS developer defined limit or threshold.
  - Check if the event falls under the standard list of potential safety violation events with pre-defined safety measures in place. This standard list is defined in AVSC00010202304.
  - Accept or decline proposed safety measure and determine its effectiveness.
  - Identify the next safety violation event and repeat the above steps.

- **Changes to the Environment**

  Changes in the operating environment may be known pre-determined elements or may be unknown change elements in the current or planned ODD. (Section 5)

  An ADS developer should have safety measures in place to identify and analyze behavior specification violations or anomalies resulting from known infrastructure deficiencies. (5.1)

  AVSC recommends immediate action and possibly short-term in-trip countermeasures for unexpected unknown scenarios that reveal a serious safety concern. A longer-term solution should then be evaluated to ensure the ADS-DV can recognize and appropriately respond in the future to these newly discovered conditions. (5.2)