# Key Considerations in the Development of Driving Automation Systems

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## Abstract

The historical roles of drivers, vehicle manufacturers, federal and state regulators, and law enforcement agencies in automotive safety is well understood. However, the increasing deployment of driving automation technologies to support various comfort, convenience, efficiency, productivity, mobility, and possibly safety features has the potential to alter this understanding. In order to facilitate clarity in discussing the topic of driving automation with other stakeholders and to clarify the level(s) of automation on which the agency is currently focusing its efforts, the National Highway Traffic Safety Administration (NHTSA) released a Preliminary Statement of Policy (SOP) concerning Automated Vehicles that included its automation levels.

In this paper, we present key factors for consideration in each automation level which are based upon SAE J3016. These factors focus on adding more specificity with regard to the distribution of the driving tasks between the driver and the automation system. The result of this effort has led to a refinement of our understanding of the automation levels based on the nature of the vehicle control aspect provided by the feature, the nature of the environmental sensing and response, the fallback strategy employed, and the feature's scope of operation.

## Introduction

The Automated Vehicle Research (AVR) for Enhanced Safety Project (i.e., the AVR Project) was initiated in September 2013. The project is being conducted by the Crash Avoidance Metrics Partnership (CAMP) AVR Consortium (Ford, General Motors, Nissan, Mercedes-Benz, Toyota, and Volkswagen/Audi). It is sponsored by the National Highway Traffic Safety Administration (NHTSA) through NHTSA Cooperative Agreement No. DTNH22-05-H-01277, Project Order 0009 and is scheduled to run 19 months through April 30, 2015.

The AVR Project, initiated within the electronic control systems segment of NHTSA's research program, has the following goals:

- Develop a list of potential driving automation applications that may be emerging on vehicles in the future
- Develop detailed functional descriptions for emerging operational concepts within each automation level
- Develop potential test and evaluation methods that map to the functional description of the automation levels
- Coordinate activities with other driving automation research projects

Task 3 focused on describing functional characteristics of driving automation systems. It also maps the sets of automation functions to the defined automation levels. This report presents the results of the work conducted in Task 3.

The AVR project is focusing on the functional building blocks and interactions between functions at the vehicle level as well as the dependencies on, and interaction with, the environment which define different levels of automation.

**Rationale on Why Driving Automation Levels Are Needed**

The increasing deployment of driving automation systems may begin to alter the historical roles of drivers, vehicle manufacturers, federal and state regulators, and law enforcement agencies in maintaining automotive safety. Maintaining safety throughout this transition is an important concern. In order to support the development and deployment of driving automation technologies it is important to consider and communicate the way in which these roles may change. The task of driving can be divided into three types of activities necessary to operate a vehicle (Michon, 1985):

- Operational behaviors such as longitudinal and lateral control as well as object and event detection and classification
- Tactical behaviors such as speed selection, lane selection, object and event response selection, and maneuver planning
- Strategic behaviors including destination planning and route planning

The operational behaviors of longitudinal and lateral control refer to the actions that drivers traditionally perform using closed-loop control of vehicle speed (using the accelerator and/or brake pedals) and position within the driving lane (using the steering wheel). Object and event detection, classification, and response (OEDR) refers to the perception of any circumstance relevant to the immediate driving task, and the appropriate reaction to such circumstance. In the remainder of this report, object and event detection, classification, and response is referred to as OEDR.

Within the overall task of driving, the operational and tactical behaviors relate directly to the dynamic aspects of driving and are thus grouped into what is referred to as the dynamic driving task, or DDT (SAE, 2014). An examination of changes in the driver's role can become the basis for categorizing driving automation systems.

It is important to clarify the difference between the systems for which these categories are intended and those for which these categories are not intended. For purposes of this paper, driving automation systems are designed to provide sustained operation of those subtasks of the DDT allocated to the system for extended periods of time, thus changing the driver's role. (The driver's continued involvement includes such things as engaging the system and resuming control.) Non-driving automation systems do not complete a subtask of the DDT, but do provide temporary or partial support to the driver by augmenting driver operation or intervening in critical situations, and hence the driver's role does not change. For example, a system such as electronic stability control (ESC) only provides temporary support to the driver for short periods of time by intervening in specified situations, enhancing the driver's performance rather than altering their role. Thus driving automation systems differ fundamentally from non-driving automation systems in their intent, extent and/or duration, and the role of the driver.

Traditionally, the design of the machine or automobile has focused around responding to the driver inputs in a predictable and prescribed way with high reliability. The use of the machine and the commands issued to the machine are a role entirely performed by the driver based upon their perception, experience, and desired outcomes. Figure 1 depicts the combined man-machine interface that constitutes the traditional DDT for human operation of a vehicle without a driving automation system.

Automation of elements of the DDT is not new to the automotive industry. However, successful automation to date has focused on rather specific functions designed to provide assistance to the driver while he or she otherwise maintains overall authority of the vehicle. These functions improve the interface between the driver and the vehicle in such a way as to provide better control or more convenient operation but do not fundamentally alter the roles of the driver and vehicle in executing the DDT. Consider conventional cruise control as an example. The driver must turn the feature on and select a desired speed. Once turned on, the automation system (conventional cruise control) will maintain that speed until cancelled by the driver. The automation system is not assessing the driving environment to decide appropriate speed limits, nor making an attempt to assess the safe speed for the current conditions. The automation system is also not considering potential collisions with other vehicles or infrastructure objects.

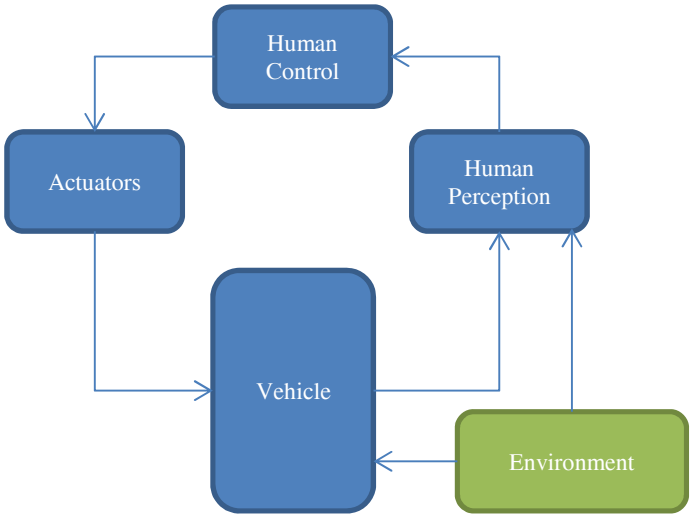


**Figure 1: Human Operation of a Traditional Vehicle – the Dynamic Driving Task**

Thus for conventional cruise control, avoiding safety-related hazards is a role entirely performed by the driver even though the machine executes its task, i.e., maintains the driver set speed. In this sense, safety is an outcome of the man-machine combination executing all facets of the DDT in unison. The advent of new driving automation technologies which enable additional portions of the driving task to be reallocated from the driver to the vehicle could potentially alter the traditional driver-vehicle relationship. Consider Figure 2 where both the human driver and the machine may have the ability to control the vehicle.

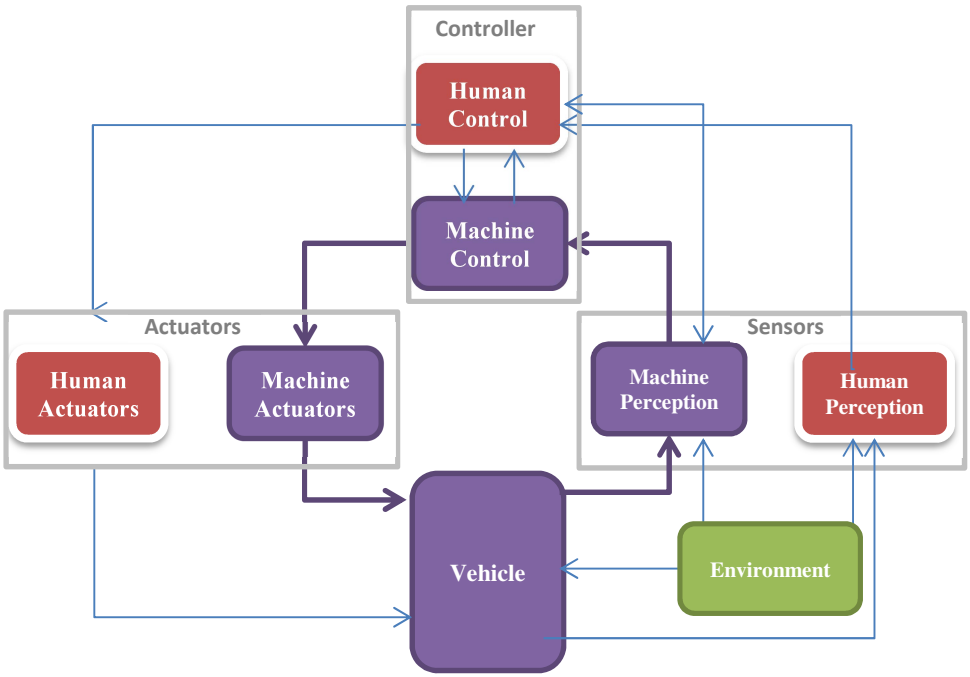


**Figure 2: The Introduction of Machine Automation to the Dynamic Driving Task**

As previously noted, the DDT includes lateral control, longitudinal control, and object and event detection and response (OEDR). These have not necessarily been altered in number or scope but they may now be expected to be

performed by the human driver, the automated machine, or both. It is this design allocation of the various subtasks which make up the DDT (and the subsequent role of the machine and the human driver in performance of the DDT) that motivates the discussion of categories or "levels" of automation. Engineers, designers, and policy makers benefit by having a way to categorize degrees of automation of the DDT in order to assist in communications between these stakeholder groups. However, it may also help drivers understand their role in the DDT in relation to the designers' intended usage of a driving automation system. The coordination of the driver and the driving automation system in the execution of the DDT (i.e., which elements of it are distributed between man and/or machine) is key to the safe operation of the vehicle.

Consider, for example, an automated parallel parking application. Some current production implementations require the driver to engage the system to look for a parking space on a particular side of the vehicle. Upon scanning an available parking space, the system provides either a confirmation of the ability to park or a denial if no suitable physical space is found. If the system finds a space and the driver confirms the desire to park, the system will automate the lateral control portion of the DDT to enter the space while the driver performs the longitudinal control as well as OEDR portions of the DDT. In making the decision to allow the vehicle to park, the driver is also judging the performance of the automation and ultimately maintaining control of the vehicle. If the steering might lead to a collision or makes the driver uncomfortable, the driver has the ability and is expected to stop the parking maneuver. The system is assisting the driver in executing a steering maneuver just as cruise control assists the driver in maintaining a desired speed, but the driver has the role and ability to make decisions and take actions to avoid collisions. The elements of Figure 2 are preserved, but the functions expected of the driver and system are different than parallel parking executed according to Figure 1.

As driving automation technologies begin to alter the allocation of subtasks that make up the DDT between driver and vehicle, the coordination of the driver and the driving automation system in the execution of the DDT is key to the safe operation of the vehicle. The automation system manufacturer should be conscious of all aspects of the DDT when considering the safety of these systems and consider how the system and the driver individually or together perform all of the dynamic driving task.

This paper discusses the categorical divisions (or "Levels") for driving automation based on the different roles for the driver and driving automation system.

**Rationale for Specific Levels of Driving Automation**

As discussed in the prior section, the driving automation system and the driver must individually or together perform all facets of the DDT. In addition, it should be noted that this may occur in some or all driving conditions, modes, and/or geographical locations. Under all these circumstances, either the driver or the automation system needs to provide fallback capability in the event that the automation system reaches the limits of its operational authority, or an automation system or vehicle failure occurs.

The most basic level of driving automation only has the functional capability to perform either longitudinal or lateral control with limited sensing capability. With these systems, the driver continues to perform the other motion control task (lateral or longitudinal) as well as the remainder of the object and event detection and response subtask of the DDT. Such systems have been widely researched and deployed (e.g., adaptive cruise control and advanced parking assistance (steering only) systems). Thus, with less capable driving automation where only part of the DDT can be automated, the functional capability to perform either or both longitudinal and lateral control is the relevant distinction to determining the level of the automation. With somewhat more capable driving automation, the system performs both longitudinal and lateral control simultaneously, but cannot perform the complete OEDR subtask. With these systems, the driver continues to perform the remainder of the OEDR subtask.

With highly capable driving automation, the systems can perform the complete DDT, providing appropriate responses to relevant objects and events. However, some systems may only be operational under specific driving conditions, such as during specific driving modes, under prescribed conditions, and/or in limited geographical locations. These systems have "conditionality." Additionally, such a system expects the driver to be able to take over in the event certain types of failures occur (i.e., under conditions that exceed its operational capabilities).

More capable automation systems are able to bring the vehicle to a "minimal risk condition" ( SAE, 2014) without driver action in the event that the system is no longer operating in the conditions for which it is designed or the system and/or vehicle experiences a failure, and no driver intervenes. This is also sometimes referred to as "fallback" capability. Thus, conditionality and "fallback" capability are the characteristics that separate higher

levels of automation. Therefore, the automation levels are differentiated according to the following functional characteristics (which are further defined within SAE J3016 as well as German BASt documents):

- These subtasks of the Dynamic Driving Task:
  - Lateral control subtask
  - Longitudinal control subtask
  - OEDR subtask
- These Functional Capabilities:
  - Driving mode, circumstance and location capabilities
  - Fallback capability

Using these functional characteristics, and considering that higher degrees of automation exceed and include lesser automation capabilities, the following defines step-wise levels of increasing driving automation that provide a framework for creation of an automation classification method.

Table **1** provides a visual overview of the SAE/BASt levels and illustrates the distribution of functions by automation level to either the driver or the automation system. Following the table is a detailed description of each level in the taxonomy that are used for the purposes of our research project.

**Table 1: Distribution of Functions by SAE/BASt Driving Automation Level**

| Automation Level Name | Dynamic Driving Sub-Tasks | | Functional Capability | |
|---|---|---|---|---|
| | Sustained Execution of Lateral and/or Longitudinal Control | Object & Event Detection and Response (OEDR) | Fallback Performance of Dynamic Driving Task | Driving Mode Circumstance, Location Capabilities |
| **0 No Automation** | Driver | Driver | Driver | None of the DDT is automated |
| **1 Driver Assistance** | Driver and system | Driver | Driver | Some driving modes |
| **2 Partial Automation** | System | Driver | Driver | Some driving modes |
| **3 Conditional Automation** | System | System | Driver | Some driving modes |
| **4 High Automation** | System | System | System | Some driving modes |
| **5 Full Automation** | System | System | System | All driving modes |

**Level 0: No Automation** – Vehicle features in this level do not automate any of the dynamic driving subtasks on a sustained basis. Thus, it has no driving automation. The driver of a vehicle without any automation performs the complete dynamic driving task. The driver provides the appropriate responses to all driving conditions. Additionally, alert systems that support the driver's OEDR performance, and systems that intervene momentarily in affecting lateral and/or longitudinal control of the vehicle to prevent or mitigate collision (e.g., crash imminent braking systems, electronic stability control, anti-lock brake systems, dynamic brake support, etc.) are included in this level of automation, as they do not automate any part of the DDT on a sustained basis.

**Level 1: Driver Assistance** – Driving automation systems in this level automate, on a sustained basis, either the lateral control subtask of the DDT, or the longitudinal control subtask of the same. It does not automate both simultaneously. In conjunction with performance of either the lateral or longitudinal control subtask, a Level 1 automation system does perform part, but not all, of the OEDR subtask associated with that aspect of vehicle control. That is, the driver of a vehicle equipped with an active Level 1 automation system performs the remainder of the DDT in all on-road conditions.

**Level 2: Partial Automation** – Driving automation systems in this level automate, on a sustained basis, both the lateral and longitudinal control subtasks of the DDT simultaneously. In conjunction with performance of the lateral and longitudinal control subtasks, a Level 2 automation system may also perform part, but not all, of the OEDR subtask. That is, the driver of a vehicle equipped with an active Level 2 automation system performs the remainder of the dynamic driving task (i.e., the remainder of the OEDR subtask) in all on-road conditions.

> **Note on Terminology**
>
> It should be noted that at this point in the hierarchy of levels, we are distinguishing preceding and following levels. Namely, Levels 0-2 encompass features that automate either none or some of the DDT, but not all of it, whereas Levels 3-5 encompass features that automate the entire dynamic driving task, whether on a part-time basis (limited range of on-road operational capability) or full-time basis (unlimited range of on-road operational capability). Because automation systems in Levels 3-5 are capable of performing the complete DDT, providing appropriate responses to relevant objects and events, they are referred to in this report as higher automated vehicle systems.

**Level 3: Conditional Automation** – Higher driving automation systems in this level automate the complete DDT, providing appropriate responses to relevant objects and events. However, the automation is situationally-limited in functional capabilities both in terms of driving modes, circumstances, and/or locations and in terms of fallback performance capability. That is, Level 3 higher driving automation system applications are capable of performing the complete DDT under limited conditions, outside of which the driver performs the complete DDT. In the event that the driving automation system is nearing the end of its operating capabilities (i.e., is about to transition out of the driving mode, conditions, and/or location(s) for which it is designed or experiences a relevant failure in the automation system), the system will warn the driver of the need to resume performance of the DDT far enough in advance to permit an orderly and controllable transfer. If the driver fails to respond in time to such a takeover warning, the automation system may not be able to achieve a minimal risk condition in all cases. In addition, the driver's fallback role includes detecting vehicle failures. The driver's role here includes passive monitoring, both for automation system-initiated takeover requests. Active supervision of the automation operation or the driving environment is not part of the driver's role in Level 3 automated operation. This differentiation may be operationalized with respect to driver visual attention. The driver's visual attention is not required to monitor the roadway for purposes of performing the OEDR subtask of the DDT in Level 3 operation. However the driver still has the role to sense (through visual, auditory, haptic and/or kinesthetic senses) if there is a takeover request issued by the automated driving system. The details of this driver fallback capability are a human factors topic and is outside the scope of the project. Other NHTSA research efforts (e.g., the current Human Factors Evaluation of Level 2 and Level 3 Automated Driving Concepts Project) will address some of the issues in this topic.

**Level 4: High Automation** – Driving automation systems in this level automate the complete dynamic driving task, providing appropriate responses to relevant objects and events. However, the automation is situationally-limited in operational capabilities in terms of driving modes, circumstances, and/or locations. In the event that the system is nearing the end of its operating capabilities (i.e., is about to transition out of the driving mode, conditions, and/or location(s) for which it is designed *or* a relevant failure in the system and/or vehicle occurs), the automation system

will warn the driver of the need to resume performance of the DDT far enough in advance to permit an orderly transfer. If the driver fails to respond in time to a such a takeover warning, the system will automatically achieve a minimal risk condition. (Note that the difference between a Level 3 and a Level 4 driving automation system is that the latter will reliably achieve a minimal risk condition without driver support, whereas the former will not reliably do so.)

**Level 5: Full Automation** – A driving automation system in this level automates the complete dynamic driving task, providing appropriate responses to relevant objects and events without situational limits in functional capabilities. That is, Level 5 systems are capable of completely performing the dynamic driving task under all on-road conditions in which a human driver can legally drive a motor vehicle today.

**Methodology for Classifying Features to Driving Automation Levels and Example Classifications**

As shown previously in

Table **1**, there are four important characteristics, which differentiate the levels of automation:

1. The performance of the DDT (lateral and longitudinal subtasks)
2. The nature of immediate, situationally-relevant environmental sensing and response
3. The fallback capability
4. The scope and range of operational capability

By their very nature, these factors address the system design and driver role in mitigating the hazards associated with on-road performance of the complete dynamic driving task (DDT). The basic hazards to be considered are as follows:

1. Staying on the road surface
2. Avoiding collisions with other objects on the roadway
3. Maintaining the stability and controllability of the vehicle during normal operation
4. Maintaining the stability and controllability of the vehicle in failed conditions

**Discussion of Levels**

A Level 0 feature is characterized by no sustained automation of the DDT, it is the driver's role to execute the basic functions of, and to mitigate the basic hazards associated with, the DDT at all times. Vehicle design can support the driver with these roles through intervention and monitoring aids such as stability control, forward and/or lateral collision warning or crash imminent braking, but the driver performs the DDT.

As automation begins to relieve the driver of certain functions such as longitudinal spacing or lateral positioning, the role of the machine and the driver in avoiding hazards may become less easily distinguishable. It is, therefore, through these definitions of higher automation levels that we seek to clearly define the distribution of driving tasks between the driving automation system and the driver at each level of automation.

A Level 1 driving automation system is characterized by sustained longitudinal or lateral control subtask performance of the DDT. It may be capable of avoiding some collisions within its control and sensing capabilities but it cannot completely avoid all possible crashes with objects. Thus, the driver supervises the automated vehicle system performance and intervenes as necessary to perform all remaining aspects of the DDT. For instance, adaptive cruise control traditionally performs longitudinal control within limits of maximum acceleration to mitigate stability issues on wet or slippery roads. However, it cannot make lateral avoidance maneuvers nor unlimited braking applications. It may also only respond to metallic objects moving within certain operational constraints. The feature automates a limited scenario and the driver is tasked with maintaining lateral control to stay on the road, maintain lanes, and avoid objects laterally and longitudinally if required. By the nature of the driver's role in the complete system operation, drivers are attentive to the external driving environment (ACAS FOT, 2005). Objects not within the defined operational set, such as accelerations required above the system limitations and vehicle dynamics limitations due to road surface conditions, are monitored, and responded to, by the driver. The vehicle

may warn if adverse conditions are detected but the driver intervenes when the system limitations are, or imminently may be, exceeded.

A Level 2 driving automation system is characterized by sustained lateral and longitudinal control subtask performance of the DDT but again within a defined boundary of operation. For example, pending conditions, the system may see some road lines but perhaps not road edges. It may see vehicles with large metallic content but it may not see pedestrians or small animals particularly those entering the scene laterally from behind an occluding structure. A Level 2 system has lateral and longitudinal control capability that may appear expansive but has limits both in actuator and sensing capability that may make it suitable only for some specific automation tasks and only under prescribed operating conditions. Drivers still monitor the external environment and make judgments about the suitability for use of the automation with Level 2 systems. Drivers intervene as needed if the limits of the automation system's design range of authority are reached, or if a system or vehicle failure occurs, to ensure all possible hazards are mitigated.

A Level 3 driving automation system has full sensing and actuation capability to mitigate all of the DDT -associated hazards but within a prescribed operating envelope. An example might be low-speed parking operations with all vehicle functions operating normally, or an application designed to operate the vehicle in dense traffic conditions on limited access freeways. The driver does not monitor the driving environment but responds to prompts from the automation system directing him/her to resume control in a reasonable time frame. These prompts would occur in the event that the system operational range has been exceeded (e.g., no longer in a parking area), or a relevant system or vehicle malfunction has occurred. It is worth noting that at the machine level, the appearance of a Level 2 and a Level 3 feature may be indistinguishable to drivers not aware of the design intent. Subtle limits of sensing capability or handling of particular vehicle failures might distinguish a Level 2 from a Level 3 system and without detailed design documentation and access to specific internal data, a driver may not be able to properly classify a new feature.

Level 4 and Level 5 driving automation systems are distinguished from lower levels because the driver does not intervene or play any role in the avoidance of the hazards associated with the DDT. A Level 4 system may have a limited scope of operation such as highways only, but it will have authority to achieve its mission and avoid all hazards associated with that mission within its scope of operation and also have the capability to reach a minimal risk condition. A Level 5 system will have these same capabilities except without a limit of scope other than the confines of the legal road system and infrastructure. Thus it will provide full-function, point-to-point driving automation with the ability to use all surface streets as it deems appropriate to the mission.

Given these characteristics of driving automation features and automation levels, the following methodology can be used to assign a new automation feature to one of the automation levels described above Figure 3 shows a flow-chart which distills the methodology for classifying automation features to levels of automation. The encircled numbers shown in the figure are the automation levels, resulting from following the Y(es) or N(o) paths when answering the specified questions sequentially from top to bottom.

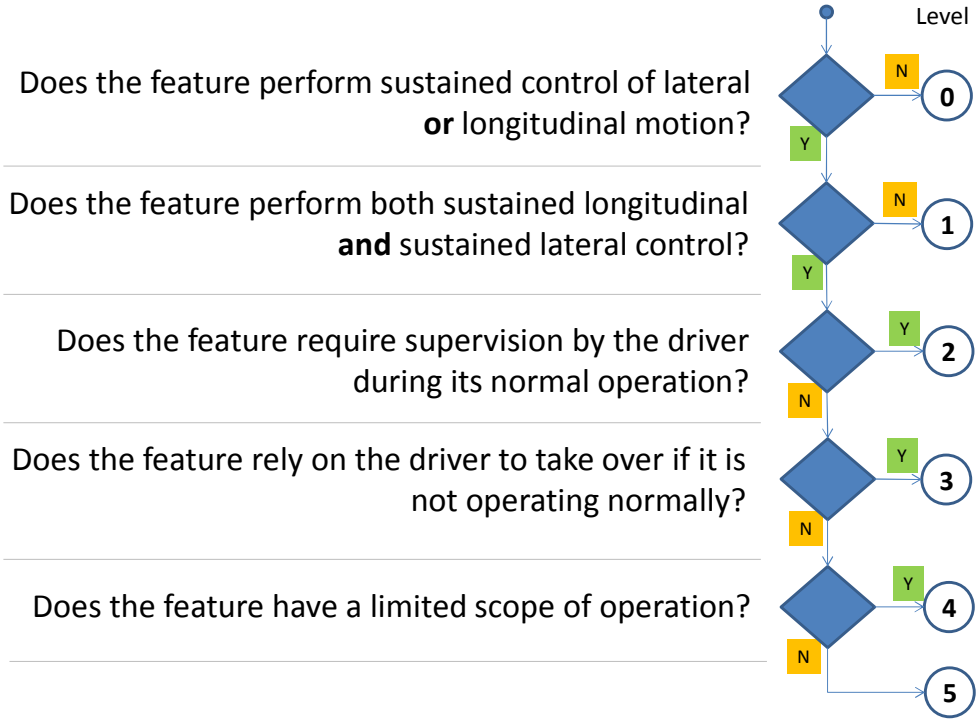


**Figure 3: Flow Chart Illustrating the Methodology for Classifying Automation Features to Levels of Automation**

**Example Classification of Driving Automation Features Using the Methodology**

The following list of driving automation features is provided to illustrate the use of the classification methodology. The descriptions are reproduced from the corresponding references, whenever available:

- Cruise Control (CC): Once this feature is engaged, the vehicle will perform longitudinal control (i.e., maintain the driver specified speed) within a limited driving domain (e.g., speed range, acceleration and deceleration/coast capability) until disengaged by the driver or due to a detected fault
- Adaptive Cruise Control (ACC): While engaged, it performs longitudinal control within a limited driving domain (e.g., speed range, acceleration and deceleration/coast capability, environmental conditions). ACC may perform distance (headway) control to some detected objects (again within its limited domain) in addition to its speed control capabilities. As with conventional cruise control, the driver supervises.
- Cooperative Adaptive Cruise Control (C-ACC): Same as ACC except the ACC-equipped vehicle and other vehicles in front of it are equipped with vehicle-to-vehicle (V2V) communication capabilities so as to inform each other of their current speed and other operationally relevant parameters (Nowakowski et al., 2010).
- Super Cruise: "Super Cruise is capable of semi-automated driving including hands-off lane following, braking and speed control under certain driving conditions. The system is designed to ease the driver's workload on freeways only, in bumper-to-bumper traffic and on long road trips; however, the driver's attention is still required" (General Motors, 2013).
- Automatic Parking:
    - "Toyota's Intelligent Parking Assist (IPA): This system assists with the steering wheel operation while parallel parking or parking in garages. When the driver sets the designed parking position on the monitor, the system assists the steering wheel operation" (Toyota Motor Corporation, 2014).

- "The Audi technology works through a mobile app. A driver exits the car at the entrance to a parking garage, then simply touches the app on a mobile device so the driverless car can scour the garage for an open space. It then parks itself. When the driver returns, he or she simply selects the app again and like valet parking, the car returns to the entrance" (Mearian, 2013).

- Traffic Jam Assistant: "The traffic jam assistant helps you in monotonous situations on the motorway. In dense traffic at speeds of up to 40 km/h, the system allows you to move easily along with the traffic and stay relaxed. It automatically maintains the desired distance from the vehicle ahead and regulates the car's speed right down to standstill – as well as providing active steering support, too. This helps you stay on track, providing you keep at least one hand on the steering wheel" (BMW AG, 2013).
- Highway Driving Assist: "Toyota's Automated Highway Driving Assistant: The first part of the system is the Cooperative-adaptive cruise control, essentially a next-gen automated cruise control. The system uses 700 MHz band vehicle-to-vehicle ITS communications to gather acceleration/ deceleration data from the vehicles ahead and maintain a safe, uniform following distance. The second part of AHDA is Lane Trace Control, which Toyota described to us as a more advanced form of its Lane Keeping Assist system. Current-generation lane systems simply provide a warning or minimal amount of steering feedback when the vehicle begins to stray from the lane, but Toyota's Lane Trace adjusts the steering angle, torque and braking in order to maintain a driving line within the lane" (Weiss, 2013).
- Closed Circuit Automatic Shuttle/Delivery Vehicle: A vehicle that drives along a fixed route (i.e., a particular form of limited driving domain, limited to a specific route; the system may have other domain limitations such as weather conditions). The passenger (or goods) can enter and exit the vehicle at a set of stops (i.e., point-to-point). The system does not need an on-board driver control interface to operate within specified operational conditions.

Table 2 illustrates example features derived from the automation features listed above, as well as additional information available to the project team. A generic description based on the information above is provided for each feature in the table. Automation feature descriptions are also provided to illustrate the nature of the variation and facilitate classification of the feature to an automation level. The feature descriptions needed to categorize the levels are shown in the columns on the right side of the table.

**Table 2: Exemplar Driving Automation Features**

| | | Descriptions required to categorize levels | | | |
|---|---|---|---|---|---|
| | | | | Only required if driver does not have supervisory role | |
| **Feature** | **Description** | Sustained Control | Sensing and Response Capability (Driver's supervisory role) | Fallback | Operational conditions |
| Cruise control | Once this feature is engaged, the vehicle will perform longitudinal control (i.e., maintain the driver specified speed) within a limited driving domain (e.g., speed range, acceleration and deceleration/coast capability) until disengaged by the driver or due to a detected fault (see also in Section 2 of this report). | Sustained Longitudinal control | Driver must supervise | | |
| Adaptive Cruise Control (ACC) | While engaged, it performs longitudinal control within a limited driving domain (e.g., speed range, acceleration and deceleration/coast capability, environmental conditions). ACC may perform distance (headway) control to some detected objects (again within its limited domain) in addition to its speed control capabilities. As with conventional cruise control, driver supervision is required (see also in Section 6.1 of this report). | Sustained Longitudinal control | Driver must supervise | | |
| Cooperative Adaptive Cruise Control (C-ACC) | Same as ACC except the ACC-equipped vehicle and other vehicles in front of it are equipped with vehicle-to-vehicle (V2V) communication capabilities so as to inform each other of theirs current speed and other parameters (Nowakowski et al., 2010). | Sustained Longitudinal control | Driver must supervise | | |
| GM Super Cruise | "Super Cruise is capable of semi-automated driving including hands-off lane following, braking and speed control under certain driving conditions. The system is designed to ease the driver's workload on freeways only, in bumper-to-bumper traffic and on long road trips; however, the driver's attention is still required" (General Motors, 2013). | Sustained Lateral and Longitudinal control | Driver must supervise | | |
| Toyota Intelligent Parking Assist | "This system assists with the steering wheel operation while parallel parking or parking in garages. When the driver sets the designed parking position on the monitor, the system assists the steering wheel operation" (Toyota Motor Corporation, 2014). | Sustained Lateral control | Driver must supervise | | |
| Audi Parking System | "The Audi technology works through a mobile app. A driver exits the car at the entrance to a parking garage, then simply touches the app on a mobile device so the driverless car can scour the garage for an open space. It then parks itself. When the driver returns, he or she simply selects the app again and like valet parking, the car returns to the entrance" (Mearian, 2013). | Sustained Lateral and Longitudinal control | No driver required, therefore no supervisory requirements | Driver is not required | Low speed, parking lot only |
| Traffic Jam Assistant | "The traffic jam assistant helps you in monotonous situations on the motorway. In dense traffic at speeds of up to 40 km/h, the system allows you to move easily along with the traffic and stay relaxed. It automatically maintains the desired distance from the vehicle ahead and regulates the car's speed right down to standstill – as well as providing active steering support, too. This helps you stay on track, providing you keep at least one hand on the steering wheel" (BMW AG, 2013). | Sustained Longitudinal control | Driver must supervise | | |
| Toyota Highway Driving Assistant | "Toyota's Automated Highway Driving Assistant: The first part of the system is the Cooperative-adaptive cruise control, essentially a next-gen automated cruise control. The system uses 700 MHz band vehicle-to-vehicle ITS communications to gather acceleration/ deceleration data from the vehicles ahead and maintain a safe, uniform following distance. The second part of AHDA is Lane Trace Control, which Toyota described to us as a more advanced form of its Lane Keeping Assist system. Current-generation lane systems simply provide a warning or minimal amount of steering feedback when the vehicle begins to stray from the lane, but Toyota's Lane Trace adjusts the steering angle, torque and braking in order to maintain a driving line within the lane" (Weiss, 2013). | Sustained Lateral and longitudinal control | Driver must supervise | | |
| Robotic Taxi | A vehicle that can pick up passengers (or goods), then drive them to the place of their choosing (i.e., point-to-multi-point). The system is not required to have an on-board driver control interface to operate within specified operational conditions. The system does not have limited domains of operation, it can operate within any legal road system and under any environmental conditions deemed acceptable by road system authorities (i.e., when roads are open). This hypothetical vehicle is claimed to be one of the future products of Google's self-driving car program (see, e.g., Fitzsimmons, 2013). | Sustained Lateral and Longitudinal control | No driver required, therefore no supervisory requirements | No driver required | any publicly available roads |
| Closed Circuit Automatic Shuttle/Delivery Vehicle | A vehicle that drives along a fixed route (i.e., a particular form of limited driving domain, limited to a specific route; the system may have other domain limitations such as weather conditions). The passenger (or goods) can enter and exit the vehicle at a set of stops (i.e., point-to-point). The system is not required to have an on-board driver control interface to operate within specified operational conditions. | Sustained Lateral and Longitudinal control | No driver required, therefore no supervisory requirements | No driver required | fixed route |

Table 3 illustrates the application of the developed methodology to map the features into the automation levels. The methodology question from Figure 3 is shown in the first row. The feature's automation level results from answering "Yes" or "No" to the appropriate question. The arrows indicate whether to move to the next question (right-arrow) or to stop at the resulting level (up-arrow). Comments are also provided regarding assumptions made based on the feature description, whenever necessary.

It should be noted for the given feature, it is very important to have sufficient information in the description to be able to answer the methodology questions unambiguously. Consider Toyota's Automated Highway Driving Assistant as an example of classifying a feature to an automation level. According to the flow chart in Figure 3, the first question asked is whether the feature is capable of sustained control of either lateral or longitudinal motion in lieu of the driver. Clearly, the answer is yes, therefore, the logical flow proceeds to the next question. The answer to the second question is again yes, because the feature can control the vehicle both laterally and longitudinally on a sustained basis in lieu of the driver, according to the feature's description. The next question is whether the feature requires a driver's supervision during its normal operation. The feature description as provided above is not complete, however Toyota's current view is that the human supervision is necessary, meaning that the answer is yes and that the feature is thus classified as Level 2.

**Table 3: Mapping Automation Features into Driving Automation Levels**

| **Automation Methodology Question** | Sustained Lateral **OR** Longitudinal control? | Sustained Lateral **AND** Longitudinal Control? | Driver supervision required? | Driver required outside normal operation? | Limited scope of operation? | |
|---|---|---|---|---|---|---|
| Automation characteristic | **Control** | | **Sensing and response** | **Fallback** | **Operational conditions** | |
| Answer confirms level or proceeds to next question | Yes → | Yes → | No → | No → | No → | |
| | No ↑ | No ↑ | Yes ↑ | Yes ↑ | Yes ↑ | |
| **Automated level** | **0** | **1** | **2** | **3** | **4** | **5** |
| Cruise control | Yes → | No ↑ | | | | |
| Adaptive cruise control (ACC) | Yes → | No ↑ | | | | |
| Cooperative Adaptive cruise control (C-ACC) | Yes → | No ↑ | | | | |
| GM Super Cruise | Yes → | Yes → | Yes ↑ | | | |
| Toyota Intelligent Park Assist | Yes → | No ↑ | | | | |
| Audi Parking System | Yes → | Yes → | No → | No → | Yes ↑ | |
| Traffic Jam Assist | Yes → | No ↑ | | | | |
| Toyota Highway Driving Assistant | Yes → | Yes → | Yes ↑ | | | |
| Robotic Taxi | Yes → | Yes → | No → | No → | No → | ↑ |

## Conclusions

The introduction of higher levels of driving automation technologies has the potential to alter the traditional driver-vehicle relationship. However, in order to facilitate discussion about automated vehicle technologies, it is beneficial to define categorical divisions for driving automation based on the functional capabilities of the automation and the role of the driver in the DDT.

While there are several different automation level definitions under consideration at the time of this writing, this paper and the methodologies discussed have been based on the SAE J3016 (2014) and BASt levels. In addition, the automation levels developed in this research, including supporting terms and definitions, focus on:

a) The functional capability of the automation system (and the subsequent role of the driver vs. the automation system) to perform the complete DDT

b) The ability of the driver and the automation combined to provide the appropriate responses to relevant objects and events

c) The driving mode

d) The fallback capability of the automation system

Once a clear definition of the automation is provided, the minimum set of automation functions for each level of automation can be defined. It is important to note that the higher levels of driving automation include those functional capabilities found at the lower levels of automation, and that each increasing level of automation includes functions aimed at reducing the driver's role in completing the DDT.

Lastly, the methodology in this report that allows classification of new automation applications into the automation levels is based on the automation functions provided by the feature. These functions include the nature of the vehicle control aspect provided by the feature, the nature of the environmental sensing and response, the fallback strategy employed, and the feature's scope of operation. Given this information about an automation application, it is possible to classify potential automation features to an automation level by following the approach outlined in this paper. However, a detailed understanding of the driving automation system design is needed to make this classification correctly.

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