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Master’s Dissertation
2017

Concept Definition of an Automated Driving System by Characterizing the Solution Space

- The Need for Perception -

Masaatsu Kusunoki
（Student ID Number：81534577）

Supervisor　Hidekazu Nishimura

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Graduate School of System Design and Management,
Keio University
Major in System Design and Management

SUMMARY OF MASTER’S DISSERTATION

Student Identification Number	81534577	Name	Masaatsu Kusunoki

Title

Concept Definition of an Automated Driving System by Characterizing the Solution Space - The Need for Perception -

Abstract

This study explores the development of the Automated Driving System (ADS) towards realization. The ADS is a rapidly developing suite of technologies with the potential to transform many of the transportation platforms, yet has many hurdles engulfed in complexity to face before realization. The introduction of the object and event detection and response, which falls under the complete responsibility of the system while it performs the dynamic driving tasks points to the additional capabilities required by the ADS in perception and in response. In order for the ADS to be realized and introduced on the market, regulators must provide the safety certification of the technology. The focus of this study is on the perception capability for the ADS, and the use of a Systems Engineering (SE) approach to address the technology uncertainties faced during product development, to define the operational concept on which safety cases can be made.By considering the system life cycle stages as commonly defined and by implementing a conceptual system model for the ADS operation stage, it is shown that deeply technical challenges complex in nature can be addressed and improved. Moreover, the concept definition and characterization of the solution space is done by Model Based Systems Engineering (MBSE), which allows for iterative design reconciliation as the entire model is traceable. The study concludes with a preliminary architecture comparison, and the proposal of a safety certification case. In the future, this work can be expanded to include further analysis into the system definition, to include additional life cycle stages, and to conduct further studies on required technologies for sensory data collection and perception.

Key Word(5 words)

Automated Driving System, Perception, Safety Certification, Concept Model

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1. Introduction

1.1. Roadmap of Automobile Transport

Personal transportation modes that are fast, reliable, as well as affordable are important existences to human civilization. Among the historical modes are those utilizing natural elements such as bodies of water and snow, and animals such as horses, cows, and even other humans. In 1886, the first automobiles with gasoline engines began to appear with the introduction of a patent for a “vehicle powered by a gas engine” [1]. Since then, and with various other power sources introduced, developments have allowed for much faster transportation with the aid of large scale traffic infrastructures. With the industry finding continuous improvements to the design of automobiles, reliability, in terms of endurance, has increased. Many manufacturers currently offer automobiles that can log a mileage of over 200,000 miles which is double the mileage of a typical car of 50 years ago[2], [3]. Mass production methods, of which arguably the most famous is the lean production method, has allowed for an ever more affordable automobile. Having undergone these improvements since its conception, and facing competition from futuristic incubations such as the flying car, what is the future for the automobile?

This dissertation focuses on the development of the Automated Driving System (ADS), particularly the definition of the perception capability, for safety certification and the eventual adoption of the ADS by society.

1.2. Motivation – Certification of Safety

Many of the consumer products that are on the market, especially those that present hazardous risk in certain uses, are regulated and certified for sale. Leading towards the adoption of the ADS by society, the feasibility study for Autonomous Vehicles by Fagnant and Kockelman [4] recommends that a framework or set of national guidelines need exist on a state level for the US so that a standard set of requirements to meet can be generated for manufacturers. While the dissertation does not focus solely on development in the United States, nor utilize the terminology of Autonomous Vehicles, it is clear that the existence of standards will be necessary for large scale systems, such as the ADS, to be accepted by regulators and eventually adopted by consumers. Kalra, Anderson and Wachs [5] in a technical report for the California PATH Program, suggest that standardization of the operation of the technologies will be important for the technology to function in materially the same way regardless of the manufacturer. Beneficial aspects to this can be gained from the reduction of confusion of the user when switching between manufacturers, and also in safety certification testing. Standardization will allow for generic tests to be defined, rather than specially tailored tests for each manufacturer, or perhaps even the specific models of a manufacturer. Therefore, a key motivating question is, “what baseline of certifiable safety can be made available for the development of the ADS?”.

1.3. Motivation – Reduction of Road Accident Numbers and Severity

Worldwide every year, almost 50 million people are injured and 1.2 million people die in road accidents. It is forecasted that by the year 2030, road accidents will become the second largest cause of healthy life years lost [6]. In fact, this UN study points to a daily number around the world of 140,000 injured in traffic accidents, and 3000 dead from fatal accidents. Although this number has many affecting factors such as number of cars on the road, and number of registered drivers, as well as quality of weather conditions, a fundamental factor affecting the numbers above is the safety technology available within an automobile. It can be said that the use of increasing quality and quantity of safety technology for automobiles has had positive impacts on these numbers.

For example, the number of road deaths and occupant fatality rates in Japan have been steadily decreasing for over 20 years since 1993 [7], [8]. The number of accidents and casualties is in fact increasing on average, with the highest number of injuries seen in 30-39 year-olds and 16-24 year-olds, while on the other hand the number of fatalities is decreasing on average, with the largest number of road fatalities seen in the age group of 65 and over (around 40%). The literature includes some study on automobile safety technology as factors affecting the overall decrease in road accident fatalities. One of the factors attributed to affecting the decrease, is the rise in seat belt usage from 71.7% in 1995 to 93.8% in 2014. An overlay of the seat belt usage with the automobile occupant fatality rate (calculated by automobile occupant fatality ÷ automobile occupant casualties × 100) shows the key period where increase in seat belt usage occurred between 1995 and 2001, coinciding with a significantly large reduction in fatality rate from 0.84 to 0.5. Additionally, the increase in the use of Anti-lock Braking Systems, from 86.1% in 2005 to 98.1% in 2014 is also cited as a possible contributing factor. The study concludes with the observation of the decrease in road accident fatalities reaching a plateau. The once steady decrease in fact saw a slight increase between 2012 and 2014, and the National Police Agency remarks on how the current situation shows a potential difficulty in further reducing the number of fatalities.

Similarly in the EU, road fatalities have also been decreasing steadily between 2004 and 2014 [9]. In the US, the deaths per 100 million miles has been decreasing on average since 1980 [10]. Both show a slight reduction in rate of decrease in recent years.

To take the next step in reducing the number of road accident fatalities, various technologies are being planned by the auto-manufacturers, leading to policy plans by government ministries. As an example, Advanced Driver Assistance Systems (ADAS) have increased in reliability to such an extent that the EU, the US, and Japan have all recently either implemented or are planning to implement regulations to make collision avoidance systems (or automatic emergency brake) a standard fitting onto all new cars [11]–[15]. Therefore, the government policy makers, the auto-manufacturers, and the eventual consumers as the major stakeholders of this technology are all affecting the safety developments of the electronic control of automobiles. With these developments, road accidents in some countries around the world are indeed becoming less severe and often than in the past.

On investigating the crashes in the US, it was found that in around 94% of the cases, the critical reason for the critical pre-crash event can be attributed to the drivers [16]. Further analysis of the driver-related critical reasons shows that in around 74% of these cases, the driver-related critical reason was either a recognition or decision error. The situations included within these reasons are the following:

- Inattention
- Internal and external distractions
- Inadequate surveillance
- Driving too fast for conditions, such as at a curve
- False assumption of others' actions
- Illegal maneuver and misjudgment of gap or others' speed

The study conducted by Nishimura et al [17] observes two types of recognition or decision error by drivers: executing a driver manoeuver prior to safety checks of the driving environment, and in omitting full safety surveillance in complex driving scenarios.

With the critical reason assigned to the human driver in most of the crashes investigated, the highest priorities to automobile safety and in ADS development is in further reducing accident occurrence and severity by reducing the chance for human error; in recognition, decision, performance, or other non-performance related matters.

1.4. Current Driver Assistance Technologies

Various driver assistance technologies are widely used in automobiles on the market. Some of them are introduced below in Figure 1. Gáspár et al [18] utilize three categories of varying assistance to distinguish between the technologies: warning, support, and intervention. Within these categories, the capability ranges from warning to partial control the driving tasks (in the form of lateral control, longitudinal control, or both). Figure 1 shows a depiction of two commonly introduced driver assistance technologies: lane keeping assistance and blind spot monitoring. The development of each new additional driving automation feature requires sensory information and the functional assistance of warning, or partial control of the driving task.

Following the increasingly progressive development of the driver assistance technologies, there were official announcements in 2016 in the EU, the US, and Japan to either implemented or plan to implement regulations for collision avoidance systems (or automatic emergency brake) to become a standard fitting onto all new cars in these markets [11]–[15].

Defining a driver assistance feature often includes defining the ideal sensor type and its specification for the specified task conditions. The information received from the sensors is processed, so that the correct commands and actions may be carried out by the ADS, dependent on its environment. With the variety of sensors available, each uniquely suited to certain uses, designing the accurate perception of the specified environment by a combination of multiple sensors becomes a complex challenge. This is particularly true when combinations of driver assistance systems introduce sensor redundancy.

The possibility to utilize different combinations of the driver assistance technologies is projected to greatly enhance the safety of automobile use on the road. Tt is clear that the automation levels are not as high as can be expected for an ADS, moreover, a higher capability of automation is required for a significantly impactful traffic safety enhancement. However, the modularity of key driver assistance functions, and the development and introduction of new functions is an important factor that is making development of an ADS more and more feasible.

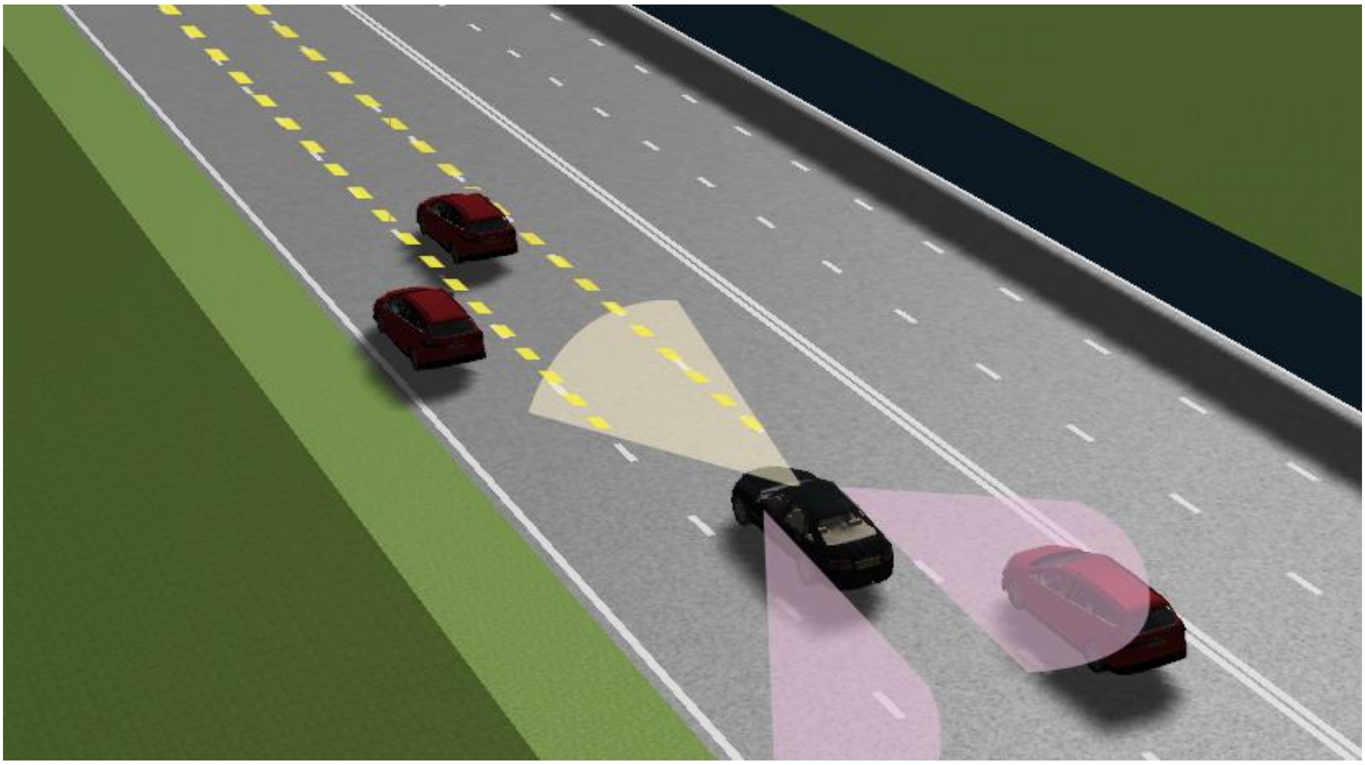
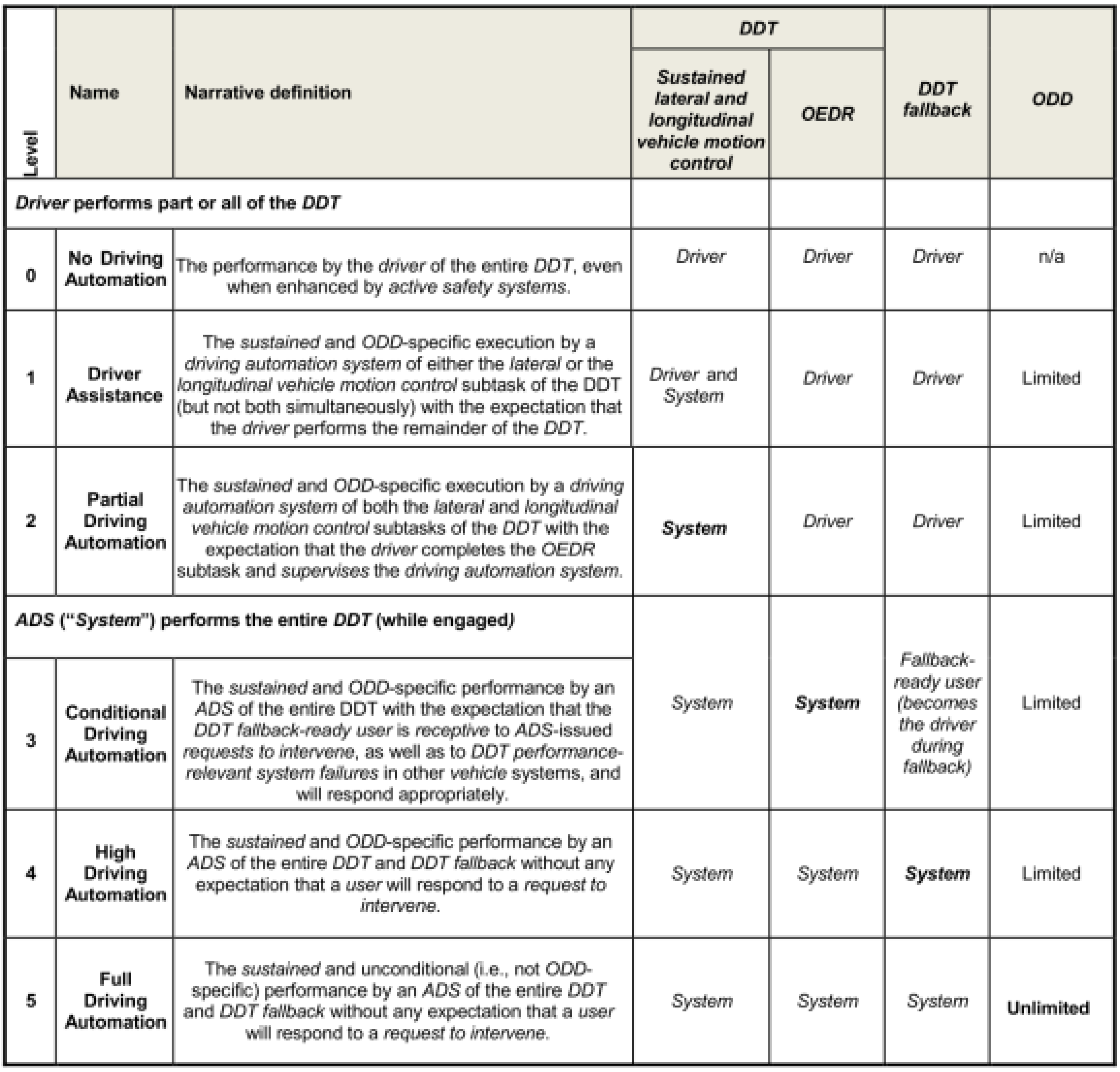


Figure 1: Depictions of lane monitoring, and blind spot assistance technologies

2. ADS and ADS Architectures in the Literature

2.1. SAE Taxonomy of Driving Automation

In order to facilitate development towards the next generation of automobiles with driving automation, a common language, or standard ontology, is needed. Alongside the government policies setting aims and regulations to support the developments, and the continuing research by private companies and academia alike, the Society of Automobile Engineers (SAE) [19] provides a taxonomy and key definitions for on-road motor vehicles with driving automation systems. The driving automation systems, systems that perform part or all of the Dynamic Driving Task (DDT) on a sustained basis, are organized in six levels ranging from no driving automation (0) to full driving automation (5), as can be seen from Figure 2. Many of the terms that are used throughout this work are based upon these definitions, provided in the appendix of this document.



Level	**Name**	**Narrative definition**	***DDT***		***DDT fallback***	***ODD***
			Sustained lateral and longitudinal vehicle motion control	***OEDR***		
Driver* performs part or all of the *DDT						
0	**No Driving Automation**	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	**Driver Assistance**	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	**Partial Driving Automation**	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
***ADS* ("*System*") performs the entire *DDT* (while engaged)**						
3	**Conditional Driving Automation**	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	**High Driving Automation**	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	**Full Driving Automation**	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

Figure 2: Summary of levels of driving automation

2.1.1. OEDR capability

The ADS refers to driving automation systems with a level of 3, 4, or 5. Most critically, an ADS must perform the entire DDT in specified ODD, leading to a major change into level 3 when compared to level 2 and below. This major change comes in the form of a shift in responsibility of the OEDR to the system, representing the additional capabilities of detection, recognition and action. Of course, the subject of the discussion is a hypothetical system that is yet to be made. An ADS has not yet been designed, certified and used on the road. However, the aims of the ADS clearly aligns with the background motivation discussed in 1.2, of reducing the chances of human error, by replacing the human driver with the system as the controller of the DDT for prolonged periods of time.

On further inspection, levels 4 and 5 are proposed to be systems that require no human fallback, meaning that once the ADS takes control of the DDT, a human driver would not need to be called upon to take over from the system in certain scenarios. Depending on the auto-manufacturer, offerings of these levels of ADS may allow for the human driver to request to take over the driving task. With a decreased need for supervision by the human driver of the ADS, these levels are expected to provide a reliably safe DDT in most ODD.

2.1.2. Intervention and Fallback

The increased automation that is presented by the ADS creates behaviors such as driving task delegation, and fallback to receptive driver. A vehicle with an automation that is below level 2 requires a human driver to be attentive at all times towards the driving task, and in most cases, being in control of the acceleration, brake, and steering of the vehicle. A vehicle with an automation that is above level 3 will be occupied by a driver who will no longer need to remain attentive while the ADS is responsible for the dynamic driving tasks. Moreover, the driver becomes free to focus on tasks that are seemingly unrelated to the dynamic driving task. In these instances, a lack of preparation, or prolonged periods being outside of the control loop, presents risks to safety in the event of a fallback scenario. The introduction of delegation of predominant tasks between the human driver and ADS raises new challenges to human-machine interaction design for ADS.

2.2. ADS and Architecture Definition

The full definition of the ADS given by the SAE [19] (also given in the appendix) is as follows:

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

The key defined difference that was observed from levels 2 to 3, between vehicles that do not have an ADS (current situation) to vehicles with an ADS, is the responsibility of the system to carry out the OEDR. Thus, the major new inclusion to the certification of ADS for safe use becomes the OEDR capability.

The increasing number of driver assistance systems appearing both in academia and on the market discussed above provide pieces of the puzzle towards achieving an ADS. Additionally, many of these have been successfully implemented in consumer products with a degree of acceptance. With market validation already existing, it remains to develop an ADS with the capability of more than just these single functions, that can carry out the entire DDT for sustained periods of time.

Rieth and Raste [20] predict that the geometrically expanding increase in mechanical and electrical/electronic (E/E) components teaming up with software will cause the complexity of E/E architecture to skyrocket, thus requiring successful modularization through new solutions to architectural concepts. The need for OEDR in ADS must be realized by overcoming the challenges of integrating current capabilities.

The EU funded Highly Automated Vehicles for Intelligent Transport Project (HAVEit) offers a design of the joint system driver co-system [21]. The reference design includes the driver interface for interacting with the human driver, a perception layer to sense the outside environment, a command layer that uses algorithms to compute actions, and an execution layer that carries out the motion control vector. Figure 3 is an adaptation of this proposal that describes these layers as subsystems of the ADS.

The perception layer and driver interface components are described as contributors of environmental information to the command layer. The command layer then has a relay of information with the execution layer. With the transition of OEDR to the system as the SAE level reaches 3 for ADS, the quality of the decision made by the command layer depends on the quality of data gathered and processed by the perception layer.

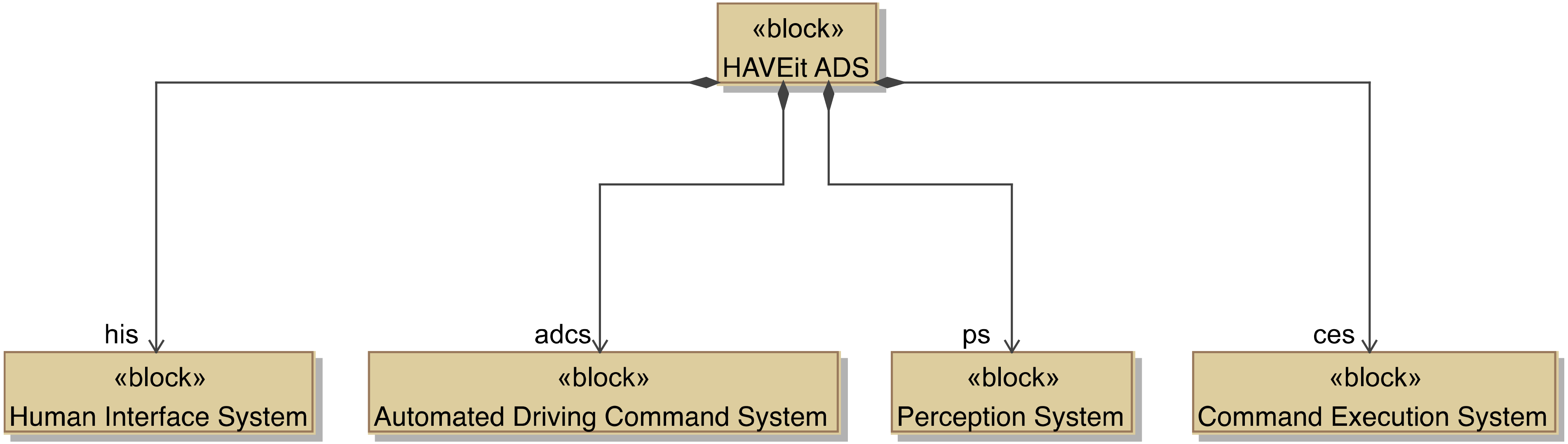


Figure 3: ADS Architecture using reference design from [21]

2.3. Development areas for ADS

As the automated driving capability of vehicles increase, each newly developed ADS will need to undergo some process to certify a base level of safe use. The 6-level taxonomy defined by the SAE, and the increments in level shows an increased capability transfer of the Dynamic Driving Task (DDT) from the human driver to the system. The particular addition as discussed earlier, is the transfer of responsibility of OEDR to the system at levels 3 and above. At these SAE levels, the priorities among the many issues to be addressed include "How should the high standard of ADS performance quality be ensured?" and "What are the key capabilities required to realize OEDR, to gain the foundational information and understanding on which to command and execute in ADS?".

In order to effectively carry out the OEDR, the ADS will need to be developed upon a standard definition of what it means to "perceive the environment" which in itself will be useful to plan tests for safety certification. For the problem of certification, many engineering methods and tools exist to aid design and testing in the field of Autonomous Systems, with the purpose of gaining confidence between functional and physical design. As the complexity of use scenarios increase, the existing tools become more difficult to use and computationally non-deterministic, making rigorous design through existing formulaic calculation a barrier to technology insertion [22]. To tackle this problem, Helle et al [23] suggest a list of 7 "things to do", of which one is to use models to communicate the intended operational behavior. A method to certify safety for the ADS is required before the ADS can be developed for road use. Thus an architecture that can safely carry out OEDR arising from the definition of a "perception system", the stakeholder needs and operational concept is modeled in this study.

2.3.1. Environment Sensing

Further to this problem is the way in which the environmental information can be sensed. Anderson et al [24] in "A Guide for Policymakers" discuss the outperformance by humans over robots in making sense of the world, through the sophistication of the human eyes used as sensors. However, the discussion concludes with the critical advantage that an autonomous vehicle may have over humans in the much wider array of sensor technologies available than cameras alone. Figure 4 describes the types of sensors available, including radar, ultrasonic, infrared, digital, and lidar. Since the variety of sensors on the market each have their advantages and disadvantages, it becomes necessary to compare the possible combinations for an optimal selection of sensors. Sensor fusion is being investigated in the literature to obtain complementary information depending on the strengths and weaknesses of different kinds of sensors. Gerónimo et al [25] in their work make a survey of the investigations on sensor fusion, concluding from analysis that it is an open area of research where much work is still required before convincing results will be achieved in real scenarios due to fundamental unreliability of some sensors in certain situations.

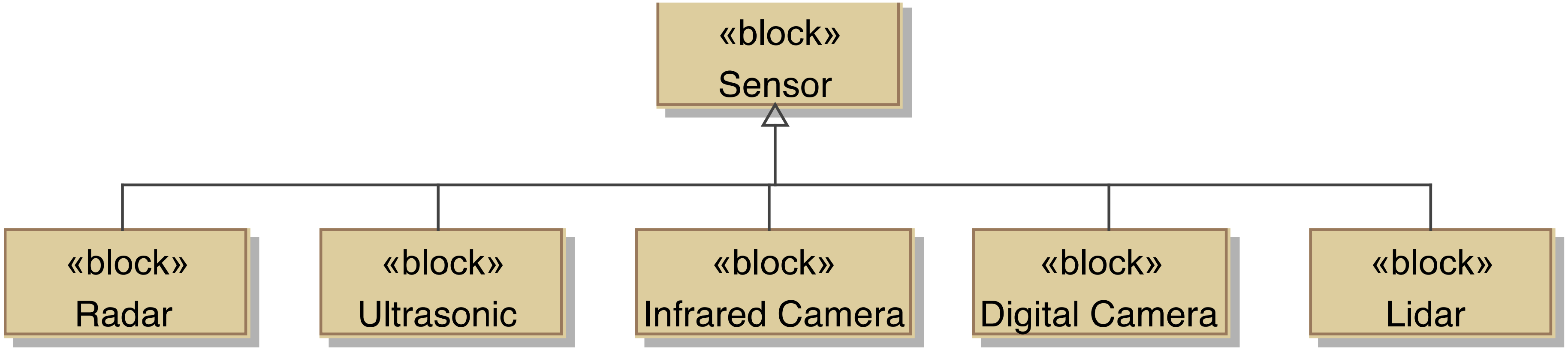


Figure 4: Types of technologically available sensors for ADS use

In fact, selecting the best, given its context of use, is not trivial. Sensor selection problems are known to be generically NP-hard while being a D-optimal experiment design problem [26]. Joshi and Boyd [27] use a convex relaxation and a local optimization method to solve the concave objective of minimizing error in estimating given parameters, where a potential sensor can be chosen at most once. The result includes not only a suboptimal choice of measurements, but also a performance bound on the globally optimal choice.

Ramsden [28] utilizes an approach to sensor optimization through coverage and connectivity problems for sensor placement with an extension into lifetime maximization. These results show that noise, error estimation, coverage and lifetime can be used as criteria for sensor selection, one criteria at a time, through optimization. Corne et al, [29] make a comparison of Pareto based multiobjective optimization methods to find a “best performing: multiobjective evolutionary algorithms. They conclude using test cases that the Pareto Envelope-Based Selection Algorithm generally outperforms the other methods in varying constraints of time limit.

The existing optimization methods have both the hardness presented by the problem itself and the constraints on the number of variables that can be inserted into one calculation instance. Although the techniques generally produce a near optimal solution, the selection of key variables and evaluation criteria are critical. Given the motivation to achieve a level 3 system, the technological barrier presented by this sensor selection problem must also be overcome. In order to develop the ADS to be safe, to be performing reliably, and to be cost-effective, it is hypothesized that the criteria for sensor selection must be given in a concise and testable manner from the mission of “perception”.

2.3.1. Perception

Sensing of the external environment is the first of the key functions needed for the ADS mission. This can be achieved by a variety of sensors on the market. In addition, various works have pointed to the need of development in sensor technology before ADS can be used commercially. Notably, the Boston Consulting Group [30] present their findings of sensors that require further development after conducting a review and analysis, showing the costs and capabilities of available sensors (in 2015). Nevertheless, after the sensing has been done, the complexity of the target (external environment and driver) requires meaning to be extracted out of the individual parameters sensed. This meaning, as was described in 3.2, is often carried out by layers or subsystems that bear the tag of “perception”.

There are various related works surrounding the issue of gaining the foundational information on which to command and execute in ADS. Generally, the proposals come in the form of sensing information through hardware, and processing the information through software. Similar to the perception layer of HAVEit, perception is often included in the literature within architectures for vehicles that are autonomous in nature. Maurer and Dickmanns [31] describe an architecture where the knowledge-based level is represented by capabilities of perception, decision, and control. The BMW Group Research and Technology [32] reported their experience and findings based upon a prototype hardware and software architecture, noting that it is not only the sensor configuration that is important, but also the perception algorithms used to extract the environmental models.

The term perception is used to refer to the information gathering and processing ability to generate or “perceive” an environment perception model. Sometimes the perception layer is also referred to as the perception system, and is made up of sensors and sometimes a sensor data fusion [18], notably used by Boss in the 2007 DARPA Urban Challenge [33]. The definition used for the architecture of Boss [34] describes the perception system to be responsible for providing a model of the world to the subsystems that require this information. Interestingly, HAVEit offers no written definition or reference to the use of the term “perception layer”. There is clear importance, however, in providing a high-quality environment model which later becomes the foundation for command generation. The performance quality of ADS will rely on a reliable environment model that has been generated from sensing and processing of the available information on the surrounding environment. What exactly is the ability of “perception”, and how can this “perception” capability be realized by ADS? Furthermore, we seek to define “perception” as a standard definition will become necessary for future testing towards safety qualification.

3. Hypothesis and Method

3.1. Hypothesis

In order for the eventual development of the ADS, its acceptance by regulators, and the adoption by consumers, the ADS requires overcoming of several complex challenges that are not only in technology research, but also in regulation of safety, in policy development, and in standardization. Firstly, realizing the replacement of the human driver with the ADS as the full primary driver requires scrutiny of the human driver's behavior. Recognizing the behaviors to replace should allow for a comparative technology to be developed, and thus allow for better understanding in regulation and in policy development.

Secondly, certification of safety for the ADS will require the behavior and performance to be evaluated. The performance quality of ADS will rely on a reliable environment model that has been generated from sensing and processing of the available information on the surrounding environment. This paper proposes a definition for the perception capability that an ADS will require. A standardized definition of the term for the environment perception of an ADS would most certainly become a foundation towards future testing criterion. What exactly is the ability of "perception", and how can this "perception" capability be realized by ADS?

Thirdly, the environment to be sensed and perceived should be defined. Identifying and grouping the environmental actors by a context analysis is hypothesized to become a key enabler to succeeding in formulating a test case for the ADS.

3.2. Method

First, in order to clarify the perception capability, a literature review of perception was made across different fields. The term perception is not a new term for academia, therefore its use was explored in similarly technological fields, and traced back to more classical studies and definitions used in psychology.

As stated in the introduction, a Systems Engineering approach, or MBSE approach of generating a system model in particular, is utilized to clarify the problem space. The heuristic search begins with the assumption of a business or mission analysis. With the aim of developing a verification and validation (V&V) plan that is directly related to the architecture description of the system, the ADS is conceptually modeled for the utilization (or operational) stage [35]. Therefore, the stakeholders and operational environment or context surrounding ADS was defined. For an engineering challenge such as ADS, where the entire context is significantly large and interacts in an interweaving manner, capturing the whole picture in an easily interpretable depiction is meaningful to the process towards architecture. Following the context analysis, a mission use case analysis was done. A set of three stakeholder concerns were assumed, matching the mission needs of reducing accident occurrence numbers and in reducing the severity of injuries caused by accidents. The mission use cases were formulated from the three stakeholder concerns, and then described as a single mission activity flow. The mission activity flow was allocated into two architectures: the first architecture being the HAVEit co-system design, and the second being a slight modification of the first. The architectures were compared, and a test case for safety certification was proposed. The test case proposed takes both the outputs of the SE approach, and also the definition of the perception capability as input.

The additional chapters in Section **Error! Reference source not found.** discuss some further works that were done during the research. First, a study on the human-machine interface for an ADS, and the utilization of simulation software for experimental purposes is described. The key new challenge of “supervisory control by the driver of the ADS, and the ADS of the driver” is studied. Secondly, the sensor technology development in the automotive industry is studied and described.

3.3. Extensions

During the research, further problems of sensor selection and human-machine interface were studied as extensions. These two problems provide more insight into sensing and perception.

Firstly, for the sensor selection problem, the existing optimization methods have both the hardness presented by the problem itself and the constraints on the number of variables that can be inserted into one calculation instance. Although the techniques generally produce a near optimal solution, the selection of key variables and evaluation criteria are critical. Given the motivation to achieve a level 3 system, the technological barrier presented by this sensor selection problem must also be overcome. In order to develop the ADS to be safe, to be performing reliably, and to be cost-effective, it is hypothesized that the criteria for sensor selection must be given in a concise and testable manner from the mission of “perception”.

Secondly, for the problem of the human-machine interface, the rise in automation level introduced by the ADS presents supervision problems for the complex task of driving an automobile. This is described as an irony of automation: increasing the automation to decrease the tasks required by the operator leads to increasing the complexity in supervisory operator tasks. A simulation is done to illustrate the control problem within the modeling of the concept. Lastly, prototyping of a human interface cockpit design is done utilizing a computer software.

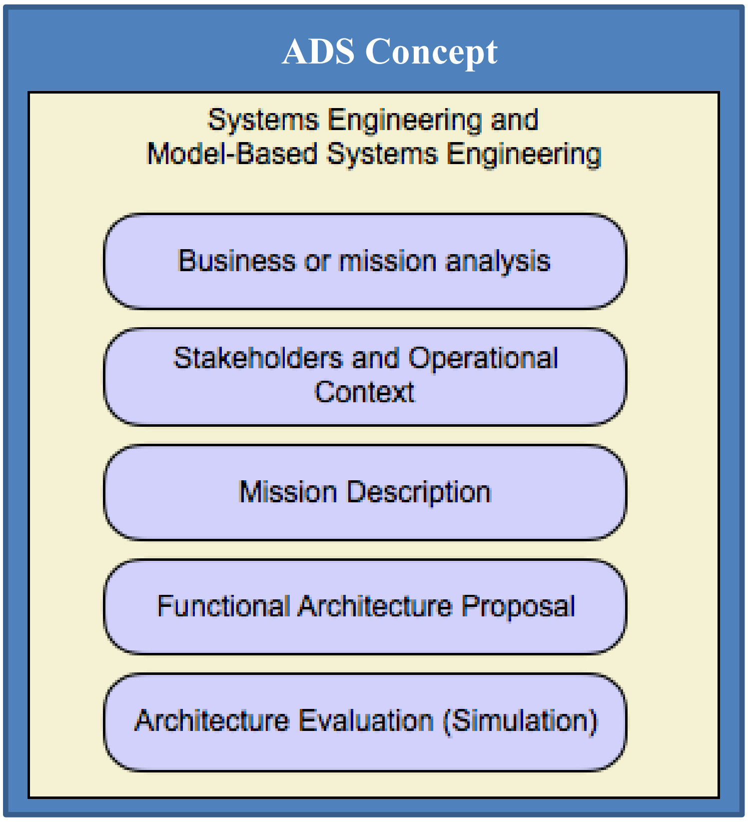


Figure 5: Method of research behind this paper

4. Conceptually Modeling the ADS

4.1. Defining Perception for the ADS

4.1.1. Human Driver Perception

The ADS, from the lens of functionality, is defined in a way that it will become a system that drives the vehicle as a replacement to the human driver. Replacing the human driver as a controller of the DDT requires the ADS to have capabilities that in comparison to the human driver's capabilities, is at least as good. The OEDR responsibility shifting from the human driver to the system serves as an example to this. The focus in this subsection is in this OEDR capability, particularly in the perception which follows sensory input. First, a literature review of perception by the human driver is made.

From the perspectives of psychology and of neuroscience, many studies have been conducted to analyze human driver behavior in perceiving the driving environment. Green [36] in an analysis of perception-brake time, utilizes response components of mental processing time, movement time, and device response time, to measure the overall response time. The parameters used in this study make some indications for needs to be replaced, with the mental processing time defined to include the following:

- *Sensation*: the time taken for object detection
- *Perception*: the time needed to recognize the meaning of the sensation
- *Response selection and programming* : the time taken to decide an action response

Lund and Rundmo [37] make a cross-cultural comparison of the several driver related issues including risk perception. Their work builds upon literature (such as [38]) that suggest a link between risk perception, the ability to assess the probability of experiencing a negative event within a given traffic scene, with gender, age, and culture. A driver with a background experience in a country where accidents are more likely to happen, due to circumstantial reasons such as population density, was found to be more sensitive to traffic risks. Perception differs between human drivers, with a potential main cause being the experience of each individual.

4.1.2. Perception used in other fields

Perception, which is not so well defined in ADS literature, is often found in the research into the architecture of the Internet of Things [39]–[41]. These works similarly provide a definition of perception in a form that requires sensor data and a processor that generates a perception model of the world. The definition provided is a functional description of the behaviour of the entity responsible. For a vehicle with ADS that requires a high level of quality in the information that should be sensed and processed, what is the functional behaviour required?

Perception is a larger topic of study in various scientific fields, most notably in psychology. Angell [42] in 1906 describes the perceptual process in two stages; a mental manufacturing of the information following a stimulation of the senses, and the combination of the present with a foregone experience. This combination of novelty with familiarity, the old with the new, called apperception, is described as being the way in which form and meaning is given to the "raw material" provided by the senses. Bernstein [43] separates sense and perception. Perception is then described as being more than a passive process of absorbing and decoding incoming sensations, that it shapes experience by influencing one’s thoughts, feelings, and actions. Goldstein [44] presents the perception process as a three part loop of stimulus, electricity (message), and experience and action. Perception here occurs in the third phase, where perception and recognition occur due to knowledge, a fourth factor that is placed outside of the cycle. In all three of the definitions, it is clear that there is more to perception than to sense and process, but to also utilize and compare against one’s own knowledge and experience. For a technology that needs to perceive a highly complex operational context such as ADS, or autonomous system in general, the hypothesis may be elaborated to state that such a perception system needs to be built exist, and the ability to compare with the relevant experience and knowledge must be evaluated.

An interesting side note to this is provided by the Buddhism concept of Skandha. It refers to human existence, or being, by detailing the temporary grouping of five aggregates: form, sensation, perception, mental formations, and consciousness. These early studies and the arising understanding of being and acting may provide insight towards functional architectural solutions to ADS, and also to systems that are autonomous, or self-governing, in nature.

4.1.3. Perception for the ADS: a definition

The above review highlights key defining elements that form the ability of perception by human beings. Arguably the ADS requires also an ability to at least match the human driver’s abilities. Therefore, the following definition is provided to characterize the solution space for the ADS:

Perception is the ability to gather sensory input, to compare with relevant experience and knowledge, and to gain new knowledge through previously unencountered experiences.

Thus, the abilities are divided into the following activities, with a description for the activity flow offered in Figure 6:

1. Gain sensory input
2. Search and compare with relevant knowledge from past experiences
3. Formulate understanding of current environment situation
4. Preserve any new experiences as knowledge for future reference

The above complements the developments by automobile suppliers with a focus on sensor and processing technologies, for carrying out the perception capability. The ADS should be able to carry out perception through not only sensing, but in storing, accessing and referencing, and in generating knowledge of driving scenarios. By defining such a perception capability, and by showing the effectiveness of its performance, it can be proposed that the ADS can indeed replace the human driver as the primary controller of the DDT, and that road accident occurrence and injury severity may indeed be reduced.

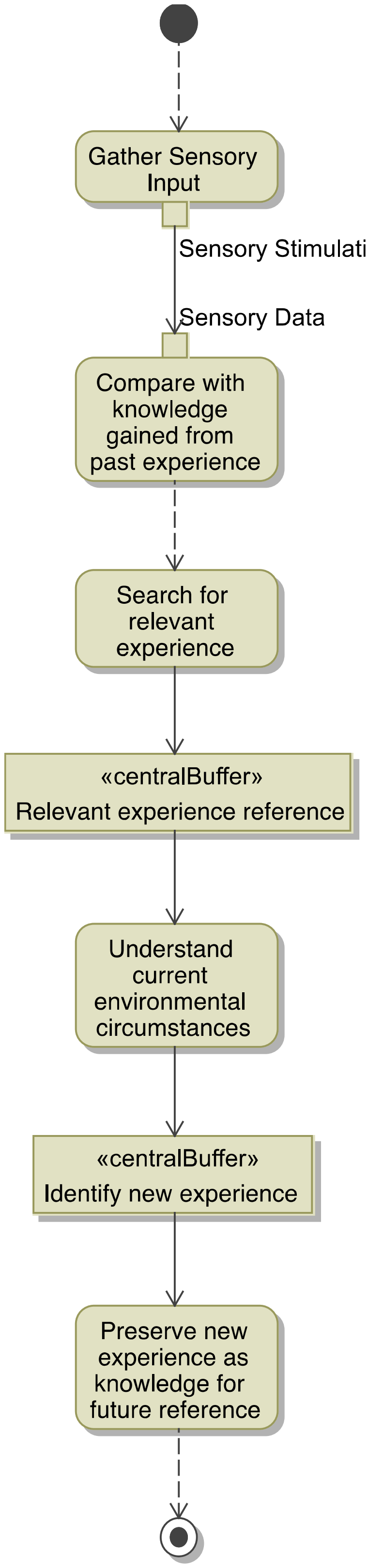


Figure 6: Description of activities within the ability of perception for the ADS

4.2. Analysis of ADS Context

Having described the motivation towards ADS, it is clear that increasing road safety by reducing the possibilities for crashes caused human error is both a problem space and a key opportunity. As a secondary related factor to motivation, it can also be said that a rise in automation level will increase the functionality of an automobile on the roadmap towards a driverless car. The operation in which this work takes place focuses on the development of the next generation of driving automation, namely a level 3 on-road motor vehicle for use on National Expressways and National Highways, with the vision of extending to include Prefectural Roads in Japan (i.e. roads with clear markings and directions for driving in sufficiently spacious road spaces) [45]. The analysis begins with a breakdown of the ADS context: the stakeholders and its operational environment.

4.2.1. Stakeholders of ADS

There are many stakeholders to ADS as can be seen in Figure 7, described by using SysML (Systems Modeling Language [46]). Aside from the ADS itself and the environment in which it operates, there are the customers with expectations and needs, the automotive industry that develops these products for consumers, the government authorities that plan and guide the development of automobiles, and the insurance organizations that assess safe daily use of such a technology. The supporting environment is also mentioned within the analysis.

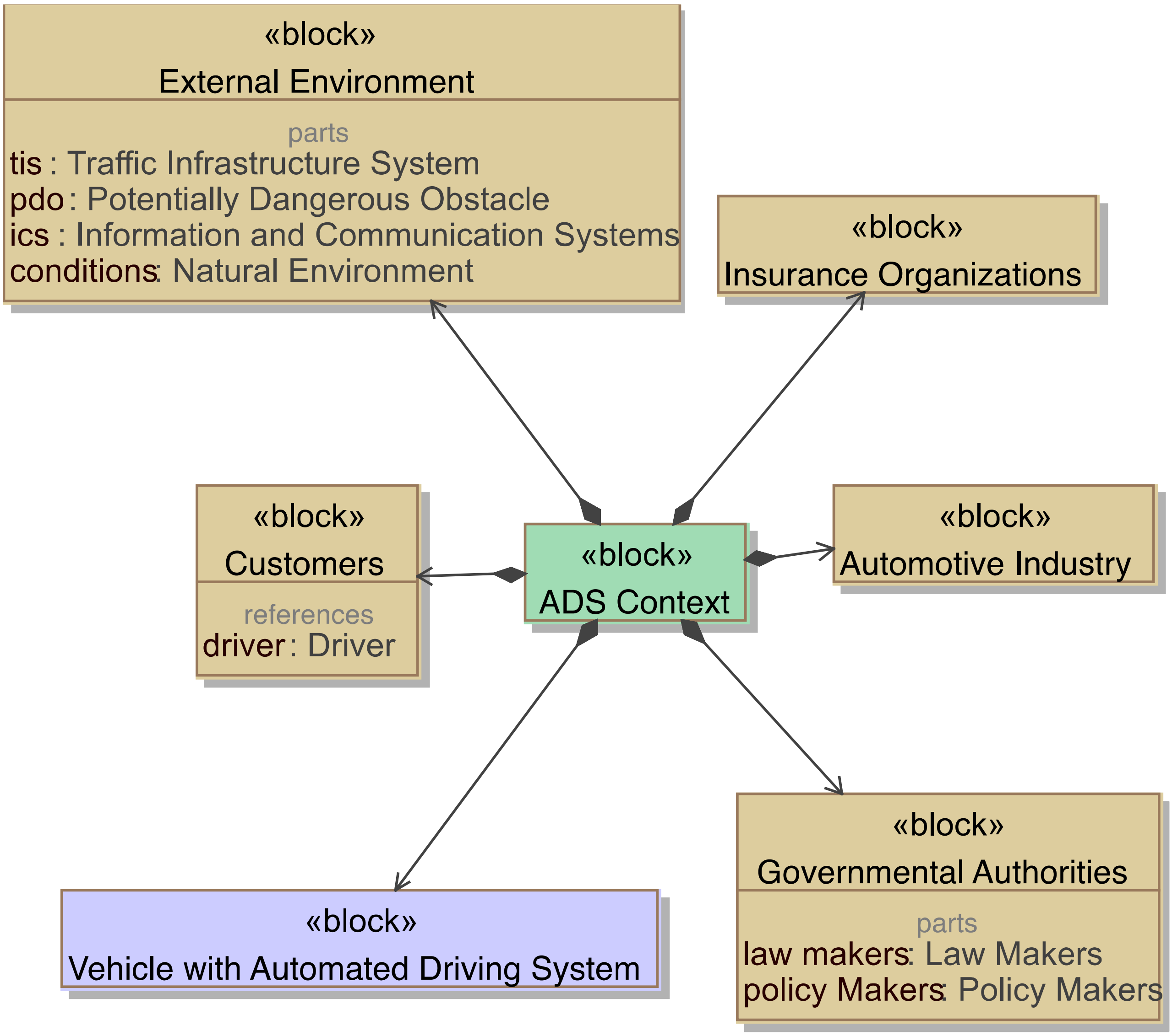


Figure 7: Context of ADS depicting stakeholder analysis

Supporting the technological progress that ADS needs is the government authorities. They provide policies, regulations and acts in conjunction with leaders and specialists from the automotive industry, insurance organizations, judicial institutions, and also academia. In Germany for example, an act was drafted[47] to not allow on the road any driving systems with no driver onboard, that controls the vehicle completely[48]. Also in 2017, the Centre for Connected & Autonomous Vehicles at the Department of Transport of the UK[49] responded to a proposal of a pathway to support advanced driver assistance systems and automated vehicles. The positive response, including a promise for continued regulations in the rolling program of reform, includes a proposal for motor insurance. The UK motor vehicle insurance model requires a change in approach from insuring the driver of the vehicle to insuring the vehicle itself, when considering vehicles that are able to carry out driving automation for prolonged periods of time, when the “driver is out of the loop”.

The Japanese government through the Cross-ministerial Strategic Innovation promotion Program (SIP) Automated Driving for Universal Services (ADUS)[50] facilitates the development of vehicles with high driving automation within the country. This organization has in fact included in its discussions, “citizens” who are to become the eventual consumers.

With so many parties with an interest in ADS, and many issues in design, regulation and certification yet to be overcome, the communication leading to agreement between all stakeholders should become crucial. This is due to the final produce by the automotive manufacturer, a vehicle that may perform dynamic driving tasks on a sustained basis, will operate in a way that is significantly different to vehicles with lower levels of driving automation installed. The environment in which it should operate is also drastically different. Arguably, the ADS will be one of the most complex commercially available engineered system.

4.2.2. Operational context of ADS

The operational context of ADS proves to be a significantly more challenging analysis. The ADS observes a shift in the responsibility of detection and response from the driver to the system, while in driving automation systems of level 2 or lower it is solely the responsibility of the driver. Driving tasks require focus and attention on the surrounding environment. Any driver of motor vehicles on the road will understand the difficulty in correctly modeling such a vastly encompassing external driving environment in a cleanly organized fashion. This observation and perception of the environment in an ADS is no longer the responsibility of just the human driver. The system must be designed in a way that it is able to do so at a level that is comparable to that of the human driver, if not better. A high-level description of the operational context of a vehicle with ADS can be seen in Figure 8. Here, one is reminded of the stakeholder needs. One of the needs is for the system to be responsible for the full OEDR as it must carry out the entire DDT for sustained periods in specific ODD. It must also be able to request an intervention by a responsive driver, in a manner that is effective. Thus, the vehicle is described as interacting mainly with the external environment and the driver, where the external environment enablers and actors that define the ODD. Exact placement of the driver in

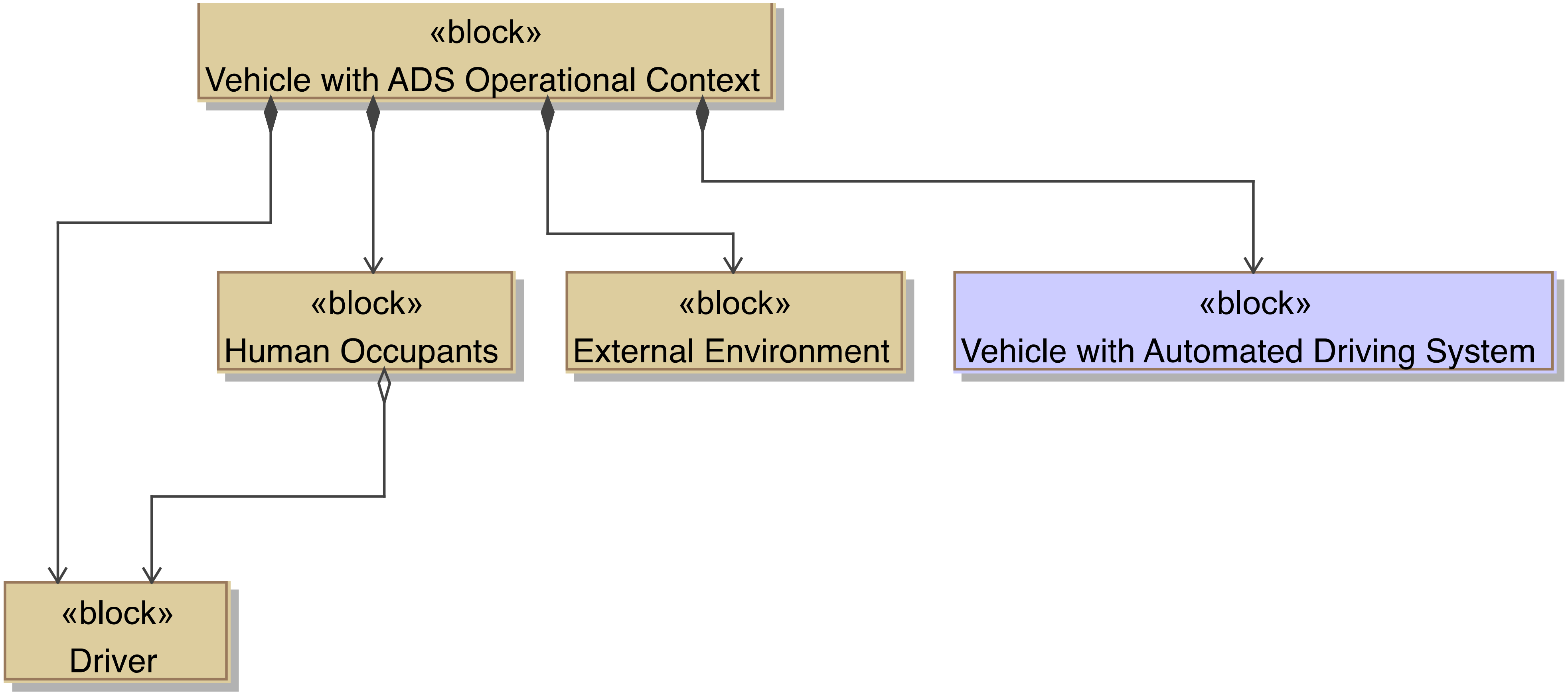


Figure 8: ADS operational context diagram

the context is debatable: as part of the operational context or the human occupants. Here it is considered as being part of the context, as the driver is critical to the mission of ADS.

Although seemingly trivial, the above consideration can be answered once the behavior of the ADS is defined. Many studies point to the need of detecting and monitoring of the driver, some of which utilize a system model [51]. As is discussed in the literature, the ADS when operating the DDT must delegate control to the driver for safety reasons in certain situations, and must be able to detect the receptive state of the subject. For this reason, the driver is presented as being a part of the operational context.

Further description of the external environment follows in Figure 9. The research on the operational context extends upon the work by Nishimura et al [17] (report is in Japanese). The external environment to the operating vehicle with ADS is classified into traffic infrastructure systems, environmental conditions, information and communication systems, and potentially dangerous obstacles.

The traffic infrastructure, shown in Figure 10, includes the roads and traffic management infrastructure such as road signs and traffic lights, forming the basic areas on which a vehicle may drive. In many places around the world, there are ministries that manage the road infrastructure. The placement of roads, the choosing of a road surface material, and the selective installment of safety measures such as guard rails, highway lamps and traffic lights are all tasks undertaken by these ministries. Additionally, research and testing is underway to make traffic management more intelligent. These intelligent systems are capable of sensing the traffic situations to carry out actions such as correctly transmit data to drivers in traffic, or transmitting control commands to various mechanisms. This includes an intersection with the field of connected cars.

The natural environment, shown in Figure 11, plays an important role within the external environment as a factor that directly affects the nature of a driving task. In moments of thick fog or heavy rain it becomes very difficult for a human driver to see the driving environment. This danger to the recognition ability of the controller responsible for the DDT is also present in some situations for the ADS. The ADS is technologically constrained by the sensory information that is available, as is discussed later in section **Error! Reference source not found.**.

The information and communication systems, shown in Figure 12, contains enablers such as global positioning systems, map services, and satellite communication services. These are used in many cars on the market currently for on-board navigation systems, to accurately position the vehicle on a map that is sometimes updated via transmissions. In the future, this area has potential to grow in use, with more data connections being made possible. One example is over-the-air updates of ADS control algorithms, to handle a situation where a traffic code or law has been altered.

The fourth composition of the external environment is the potentially dangerous obstacle, shown in Figure 13. Rather than the conventional approach of analyzing the full list of potential threats to the system of interest, this term is a source of originality for the dissertation. Pedestrians and Surrounding Mobility (itself described in more detail in Figure 14) are described as reference parts that can compose the potentially dangerous obstacles.

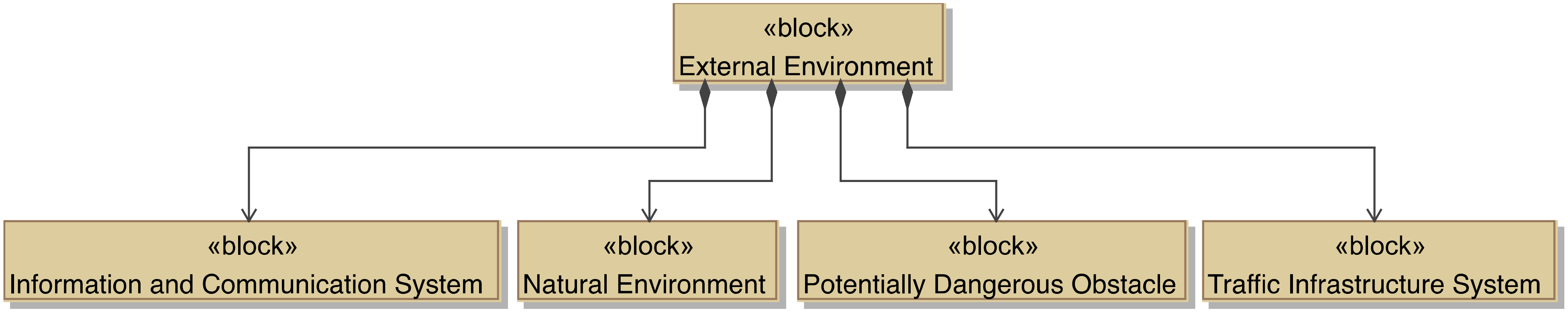


Figure 9: The description of the external environment to the vehicle with ADS

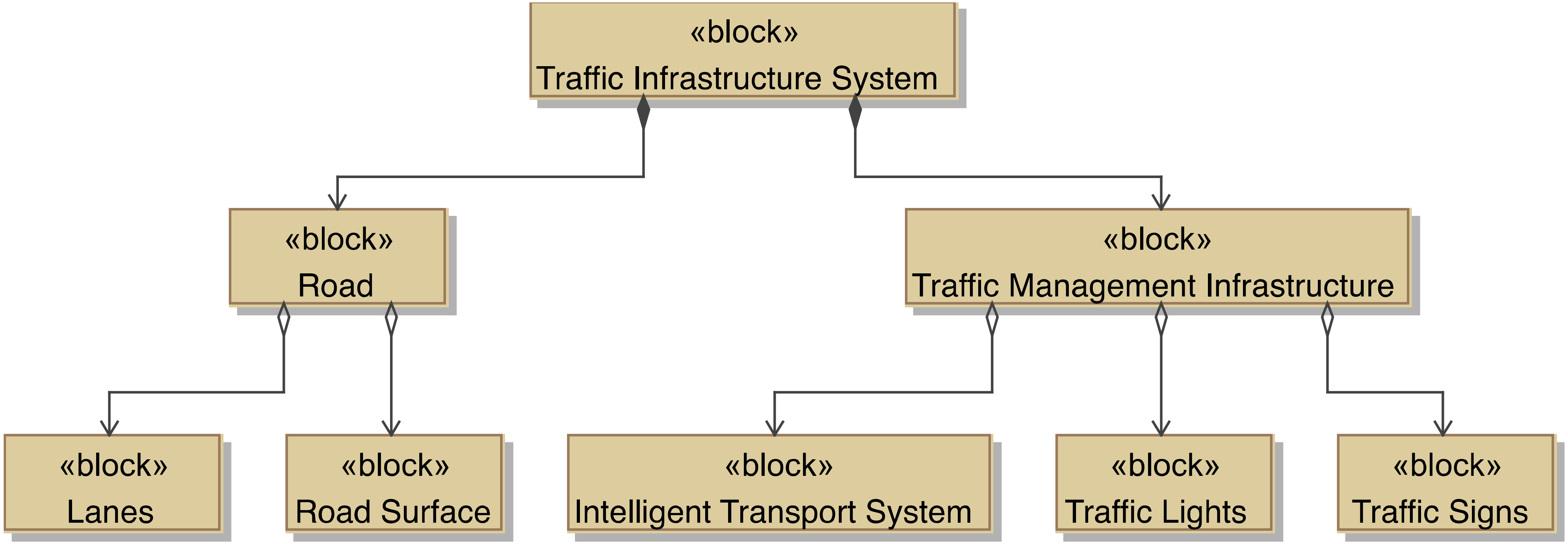


Figure 10: Description of the traffic infrastructure system in the ADS operational context

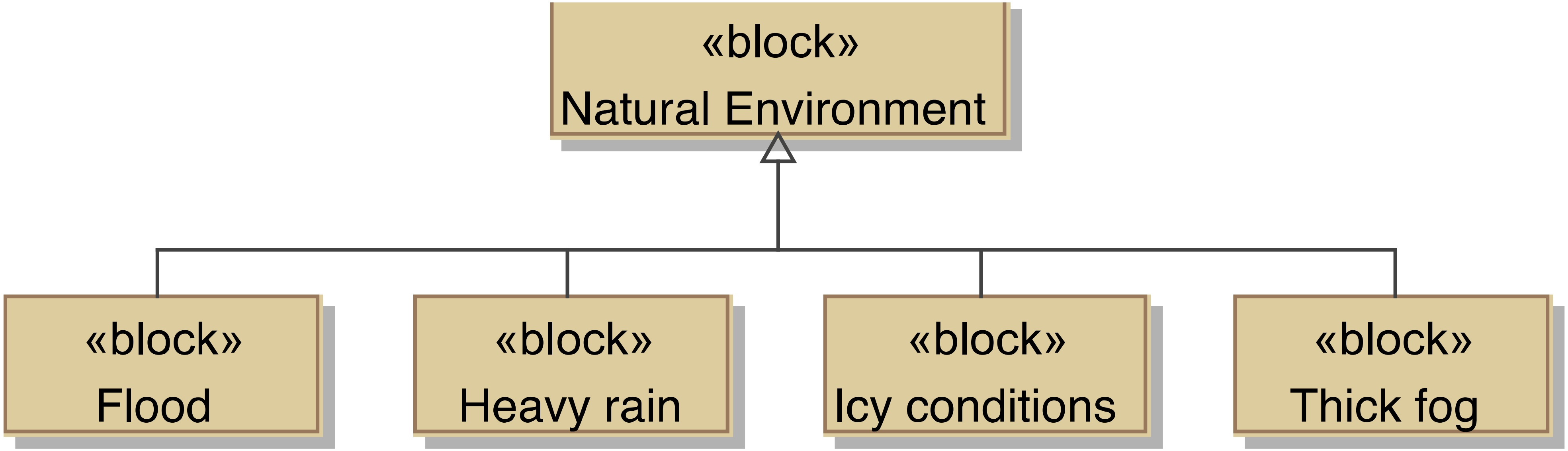


Figure 11: Description showing example types of some elements within the natural environment

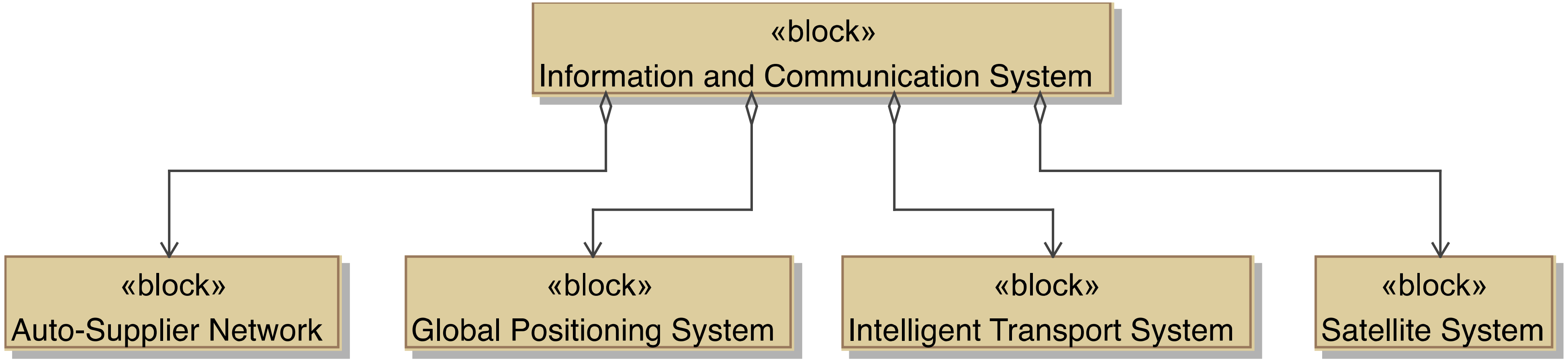


Figure 12: Description of information and communications systems surrounding the ADS

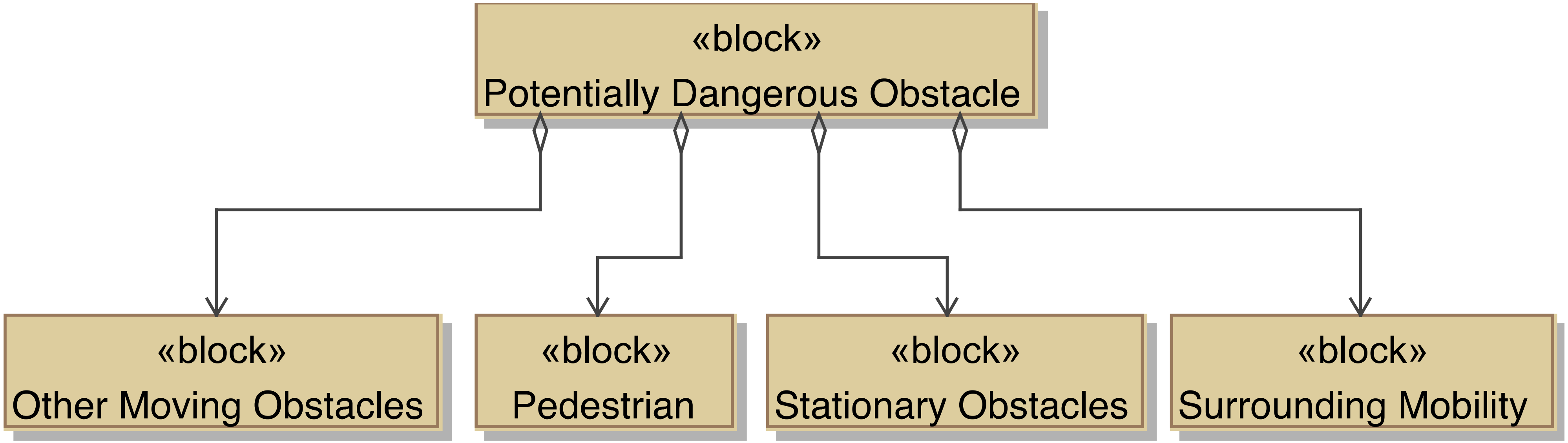


Figure 13: Description of composition of the potentially dangerous obstacles surrounding the ADS

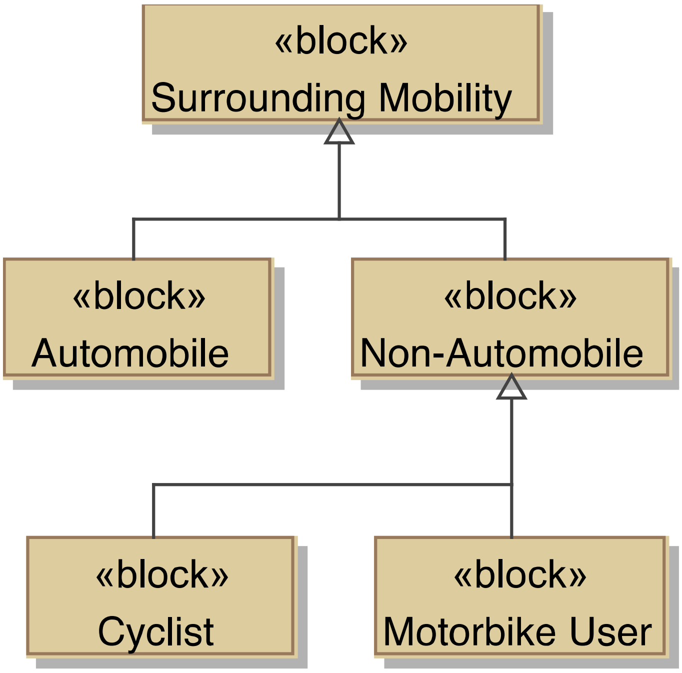


Figure 14: Description of some example types of surrounding mobility for the ADS

4.2.3. Potentially Dangerous Obstacles

The driving environment has many actors as obstacles who may or may not present a threat to the ADS and its DDT. An actor who does not present a danger at a given point in time, certainly has the potential to present danger to the ADS given a change in circumstance. Some examples to illustrate this are a car waiting to merge onto the road, a motorcyclist in traffic, and a child with a ball on the side of the road, etc. The stationary car waiting to merge may potentially accelerate suddenly onto a trajectory that is dangerous for the ADS DDT. A motorcyclist in traffic that is traveling with very little danger to the ADS has the potential to suddenly change course due to high wind or unpredictable road surfaces. Finally, the child with a ball on the side of the road may potentially release the ball in a trajectory that may then give rise to a situation where both the ADS and the child are at risk of danger. This is described as a state transition of the obstacle with respect to the ADS context in Figure 15. Simply stated, actors who become obstacles to the ADS may enter the operational context of the ADS, and be moving with an absolute vector, or be not moving with an absolute vector. It finishes its transition by leaving the ADS context.

Although abstract in definition, this complex behaviour of the environment is an additional consideration to the sensing of physical location or distance of the target, presenting potentially dangerous obstacles to the vehicle with ADS. Based upon the perception defined earlier, the driver, whether human or an ADS, will sense the object, then recognize the object. The potential danger level will be determined from this process. An ADS state transition for the perception of potential danger in obstacles in the ADS context is offered in Figure 16.

The transition begins with the idle phase of the ADS, the sensing of the context actors begins. The information gathered by the sensors on the context actors is used to identify the actors, and also to classify the object's threat level. Once identification and classification is done, the ADS then monitors the actors, prioritizing some over the others. Thus, the loop of perceiving the potentially dangerous obstacles comes to a close. At the end of the operational mission of the journey, the vehicle with ADS may receive a shutdown command, after which the perception can come to an end.

From the perspective of perception, the database of known actors or objects should be referenced here. This replaces the human driver's knowledge and experience on the road, so that the ADS may carry out the DDT effectively and without a comparative loss in driving quality. During the driving lifetime as a driver, one continuously gains experience and knowledge while carrying out the DDT. The same should be true for the ADS. However, the ADS has a major benefit over the human driver, in that the experience and knowledge is digital information that is shareable.

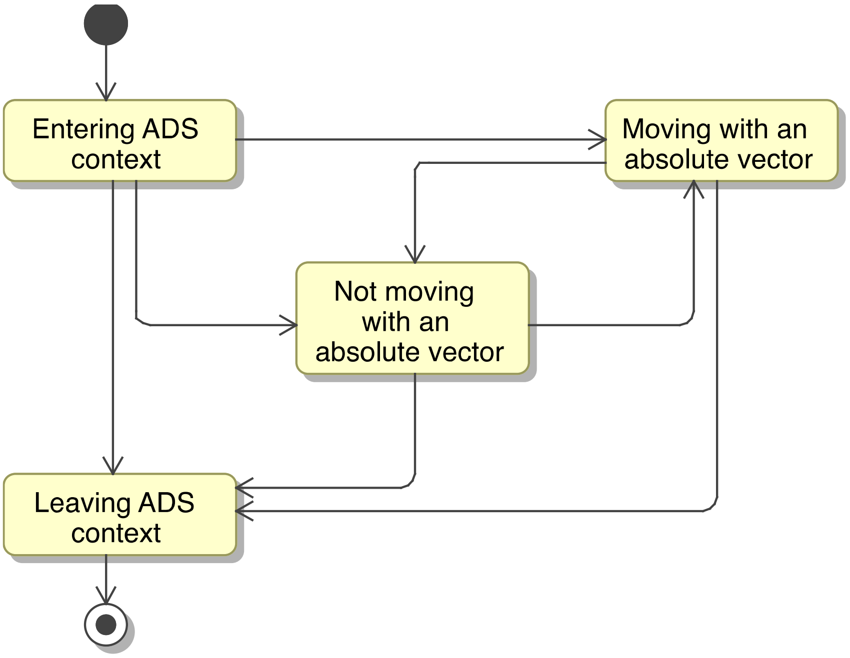


Figure 15: Description of obstacle states in relation to the ADS context

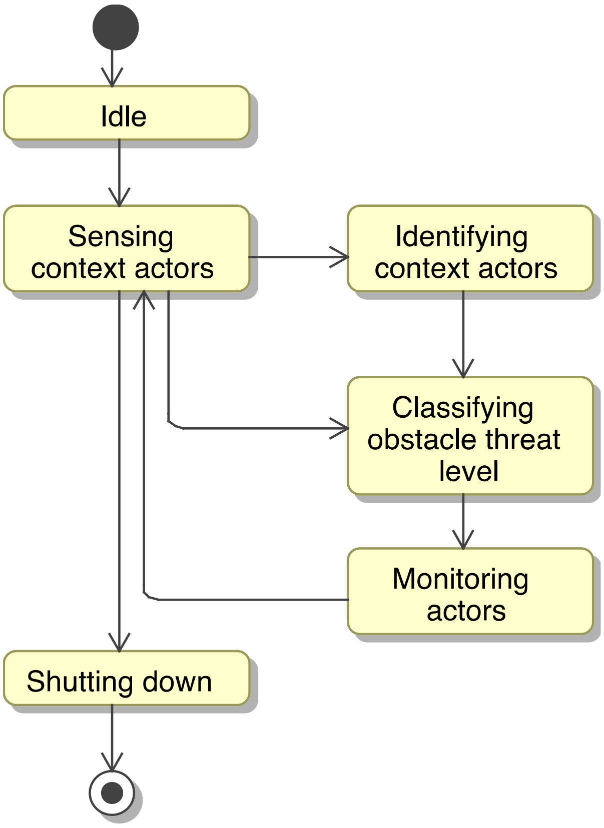


Figure 16: ADS state transition of perceiving the potential danger of obstacles in the ADS context

4.2.4. Human Driver Interaction

Having defined the above, and noted the complexity of potentially dangerous obstacles in the external environment to be sensed, and also the need for fallback or intervention of the dynamic driving task between the ADS and the driver mentioned, the problem space of this interaction accommodated by the human-machine interface is apparent. As is mentioned by Bainbridget [52] in 1983, the classic aim of automation to replace human manual control, planning and problem solving presents an irony reflected in the advanced and crucial control that is needed of the human operator as a contribution. This can be said to also apply to the case of a vehicle with ADS. König [53] describes the modified task to be undertaken by the driver as being less controlling parts and more supervising parts. Therefore, a key design challenge then becomes designing and testing of an operable human-machine interface.

Indeed, the ADS contains significantly more supervisory parts to be undertaken by the driver. Take for example the case of the passing of driving authority. With both the ADS and the driver capable of performing dynamic driving tasks, a failure in this delegation would not only be a cause a potential fatal situation for the human occupants of the vehicle, but also for the other vehicles. Figure 17 provides an abstract, simulated state machine of an interaction of this kind. The figure shows the state transitions of ADS in delegating control of driving authority, which is composed of requests, acceptance and rejection of requests, override, and emergency fallback as the outcomes. One may observe from a system perspective that not only does delegation require supervisory effort by the human driver of the system, but also the supervisory effort by the system of the human driver. Therefore, the system requires the ability to communicate clearly its own behavior and state to the driver, while also being able to gather adequate information and capability to analyze the driver's behavior and state.

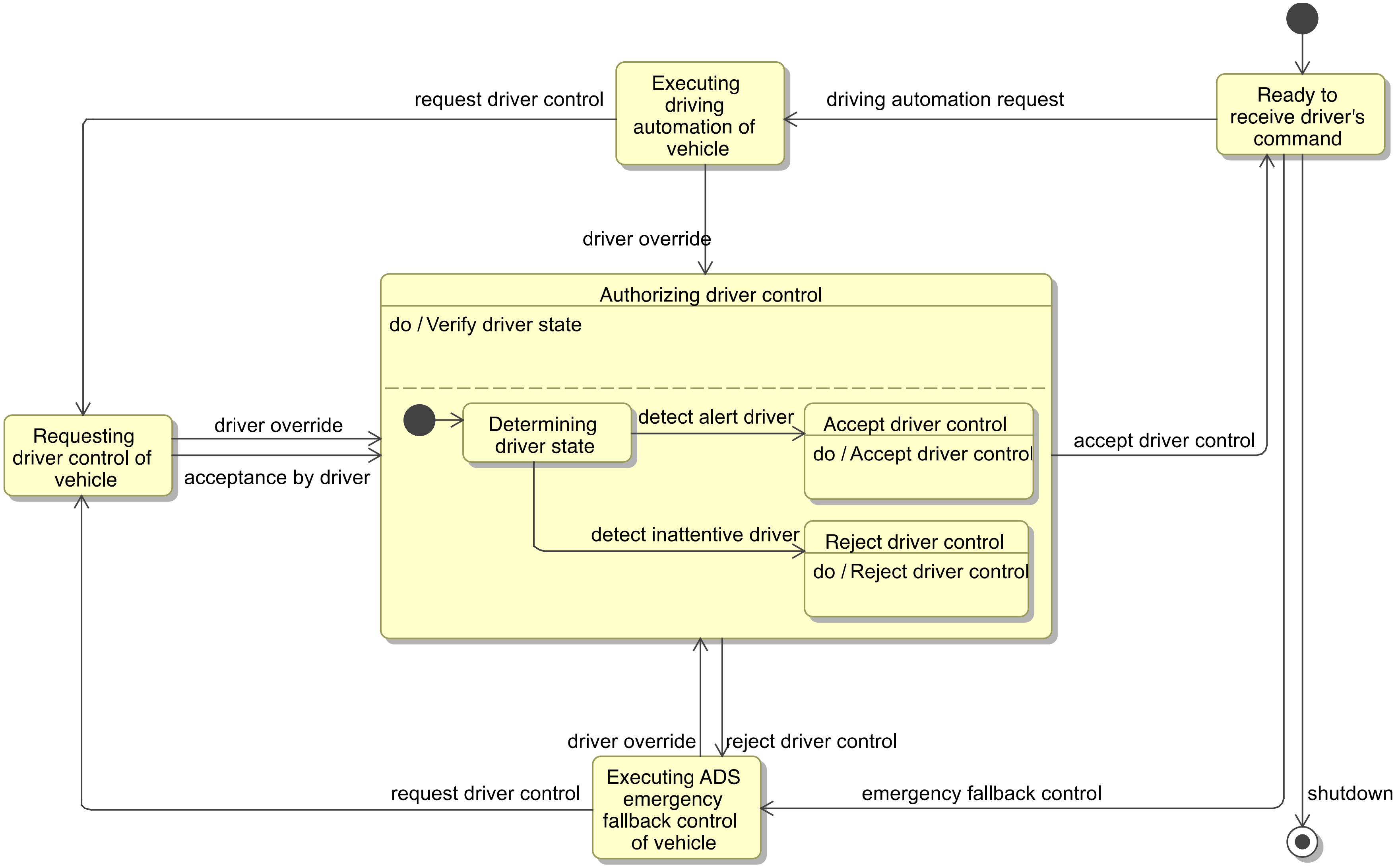


Figure 17: The state transitions of ADS in delegating control of driving authority

4.3. ADS Mission

Once the context surrounding a vehicle with ADS has been defined, forming the foundation for its operation, we begin to discuss the mission. Figure 18 describes stakeholder concerns that are assumed in this study, to fit with the concept of operation assumed in Section 4.2. Firstly, the vehicle with ADS must be able to drive in a way that is safe for its occupants on National Expressways and Highways in Japan. These are roads that are clearly marked and have a traffic code and infrastructure in which traveling speeds are managed in a safe manner. Secondly, the ADS must be able to collaborate effectively with the driver in order to safely carry out the dynamic driving tasks. When the ADS is carrying out the DDT, on evaluation of a situation where fallback is required, must communicate effectively with the driver and ensure that he/she is receptive to fallback. According to the operational mission, the ADS should also take charge in assisting the avoidance of dangerous situations when the human operator is in manual control of the DDT. Thirdly, the ADS must not harm other non-automobile road users, pedestrians in particular, when performing its tasks. These road users are most vulnerable on the road, and are also the most unpredictable. In fact, there are numerous debate type events hosted by governmental projects such as the SIP, attended by stakeholders to the legal system and also insurance systems regarding the issue of unintended harm caused by the ADS.

In order to carry out the above, it is clear that a “sense-plan-act” design [24] as is often used in robotic systems including autonomous vehicles will be a necessary and effective way to solve the above problem. The full human driver behavior model that was seen in the literature also points to the need for sensing, perceiving, responding, and executing (moving). In order to effectively carry these processes out, both the external environment and the driver must first be sensed. The traffic scenario must then be recognized and made sense of, then a plan of action to be undertaken must be computed, evaluated, and selected. The action must finally be executed. In order to confirm this, to verify that such a flow of activity is correct, mission use cases and an activity flow was considered.

4.3.1. Mission Use Cases: the need for perception

Having described the operational context of the ADS, it remains now to explain the behavior within the context. By describing the stakeholder needs, one may identify that the mission of the ADS is to fulfil these needs. Use case diagrams were drawn to describe the mission for an ADS as a top-level preliminary mission description. Thus, the first of the stakeholder concerns is described in Figure 19. The ADS is described to be interacting with 4 actors: the intelligent transport system, potentially dangerous obstacles, the traffic infrastructure system, and the road surface. In order to perform the DDT in a way that is safe for the occupants of the vehicle, the actions of motion chosen by the vehicle to execute must be determined to be safe. In order to do this, the vehicle must first gain information on the surrounding environment with the first use case of “detect and monitor driving conditions”. This should include monitoring of the road infrastructure, so that the vehicle may identify regions that are safe to drive in, monitoring of potentially dangerous obstacles, so that the vehicle may identify regions to avoid in its own path, and also monitoring of its own vehicle state, so that the vehicle may diagnose and plan safely.

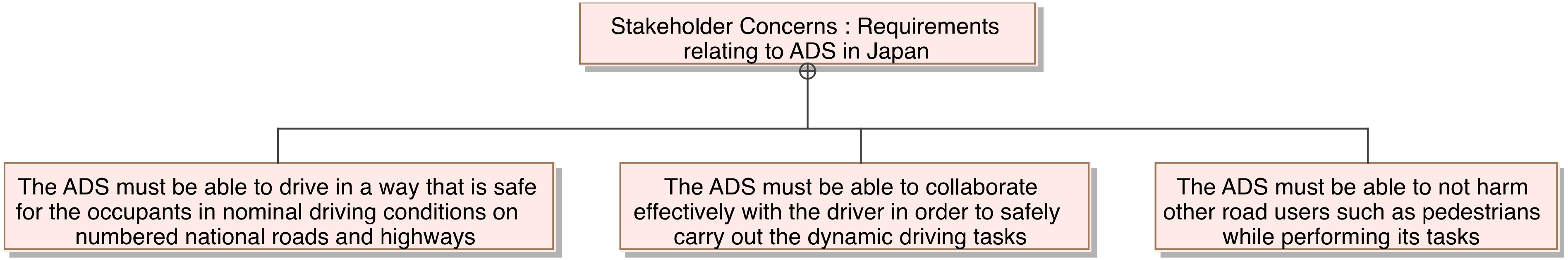


Figure 18: Stakeholder concerns describing needs to be addressed by ADS

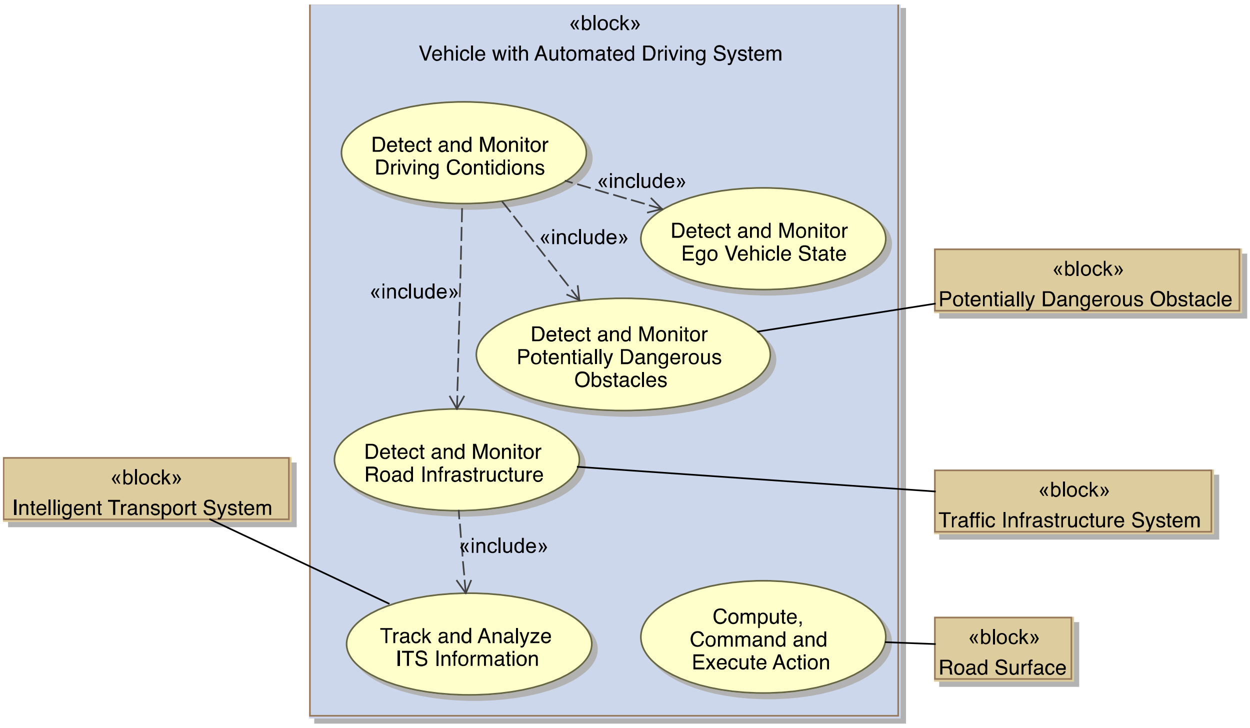


Figure 19: ADS mission use case of carrying out the DDT for occupant safety

The information offered by the intelligent transport systems will also be referenced, as is done often to monitor traffic information. Finally, there is a single use case of “compute, command and execute action”, which based upon the information gained as sensory input, carries out the determined safe task. Once the safest action is determined, and the command generated, the road surface receives the actuation force.

The second use case description can be seen in Figure 20. This time the ADS is described to be interacting with a different set of 4 actors: the driver, potentially dangerous obstacles, the traffic infrastructure system, and the road surface. The need that is being represented here adds a dimension of human factor. In order for the ADS to collaborate effectively and safely with the driver, the behavior and state of the driver must be understood. At times, the driver is prone to becoming inattentive while not engaged with the driving task. The telling signs of the driver must be sensed in order to deduce how the driver may perform. In fact, the same goes for the opposite direction; the driver must also be able to understand the ADS state in order for effective collaboration to occur. Thus, there is also a use case for “display ADS state”. This two-way nature in collaboration, where at times the ADS is supervising the human driver, and at times the opposite, is one of the new complex challenges to overcome. Both while supervising each other must be aware of the driving environment (consisting of the traffic infrastructure of the road, lanes and signs, and the potentially dangerous obstacles surrounding the vehicle), so that the supervisor is ready to assist the other, and to assume control when needed. Therefore, there is possibility for the driver to give an input for the use case of “compute, command and execute action”, which again involves the road surface as a final actor.

The third of the use cases is of carrying out the DDT while maintaining safety for vulnerable users, as can be seen in Figure 21. First, the actors of pedestrians, motorbike users and cyclists are given as representatives of vulnerable road users in Figure 22. Since the main actor responsible for carrying out the DDT for the vehicle is undefined for the duration of this mission, the driver state monitoring as seen in the previous use case diagram is included here. Additionally, the use case of “Execute DDT that is safe for other road users” includes the driver as again the controller of the DDT is undefined. By keeping the controller undefined, this use case becomes a more general case for whenever the DDT is being carried out for the vehicle. The latter use case is included in the parent use case of “detect, monitor and avoid vulnerable road users”. The other included use case is “detect and monitor vulnerable road users”, which is associated with the vulnerable road users.

The use case analysis highlights functional needs of the ADS. In fact, there are significant overlaps between the missions regarding the realization of the stakeholder needs. The most frequently used terms of “detect and monitor” that is associated with the context of the ADS points to the important need of perception, while also specifying the direct actors that are involved that must be perceived in the key mission phases. The analysis also points to the importance of designing the computation of commands in a way that assures safety. The above two are key functional needs that will in the future require certification of safety, prior to being utilized on public roads by consumers, and prior to being released on the market as a consumer product.

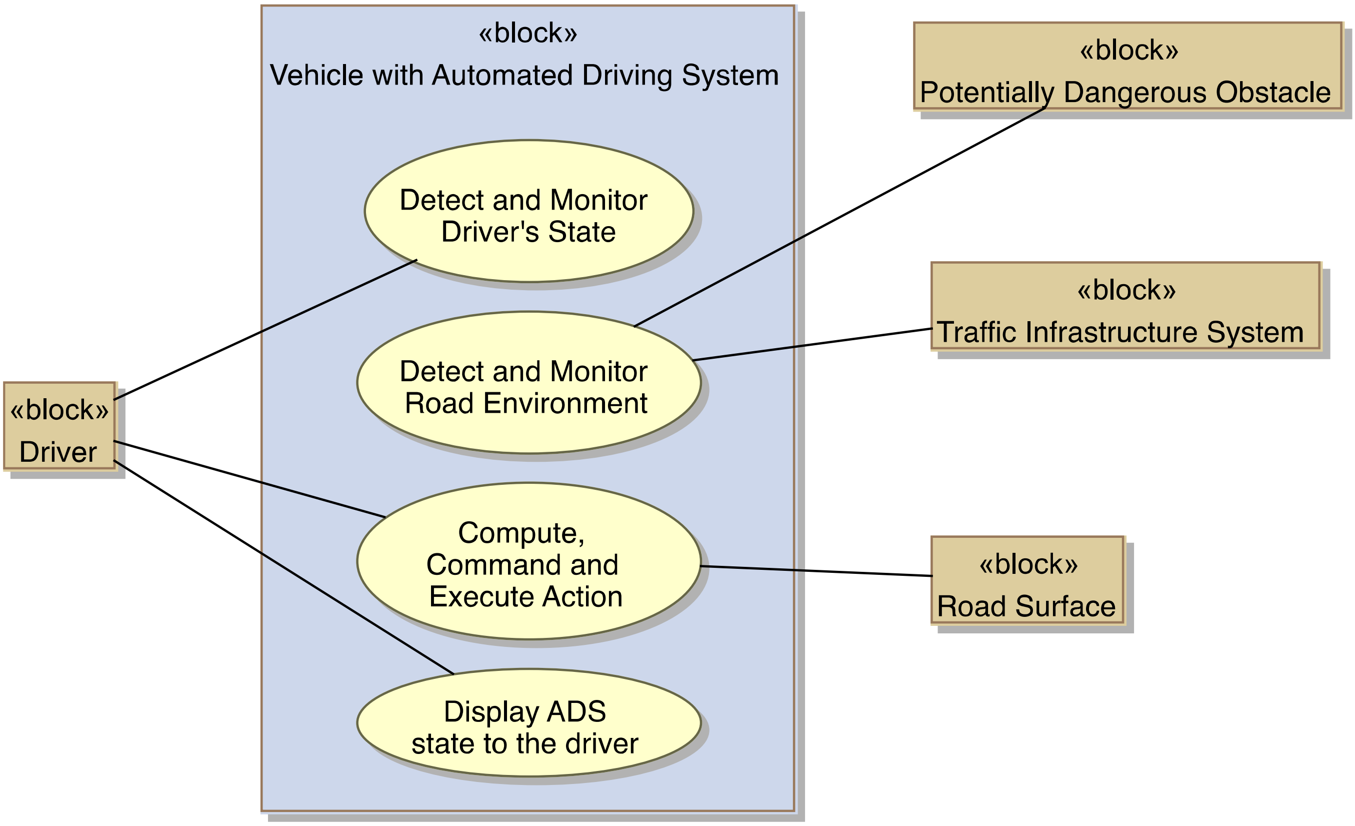


Figure 20: ADS mission use case of collaborating with the driver in order to safely carry out the DDT

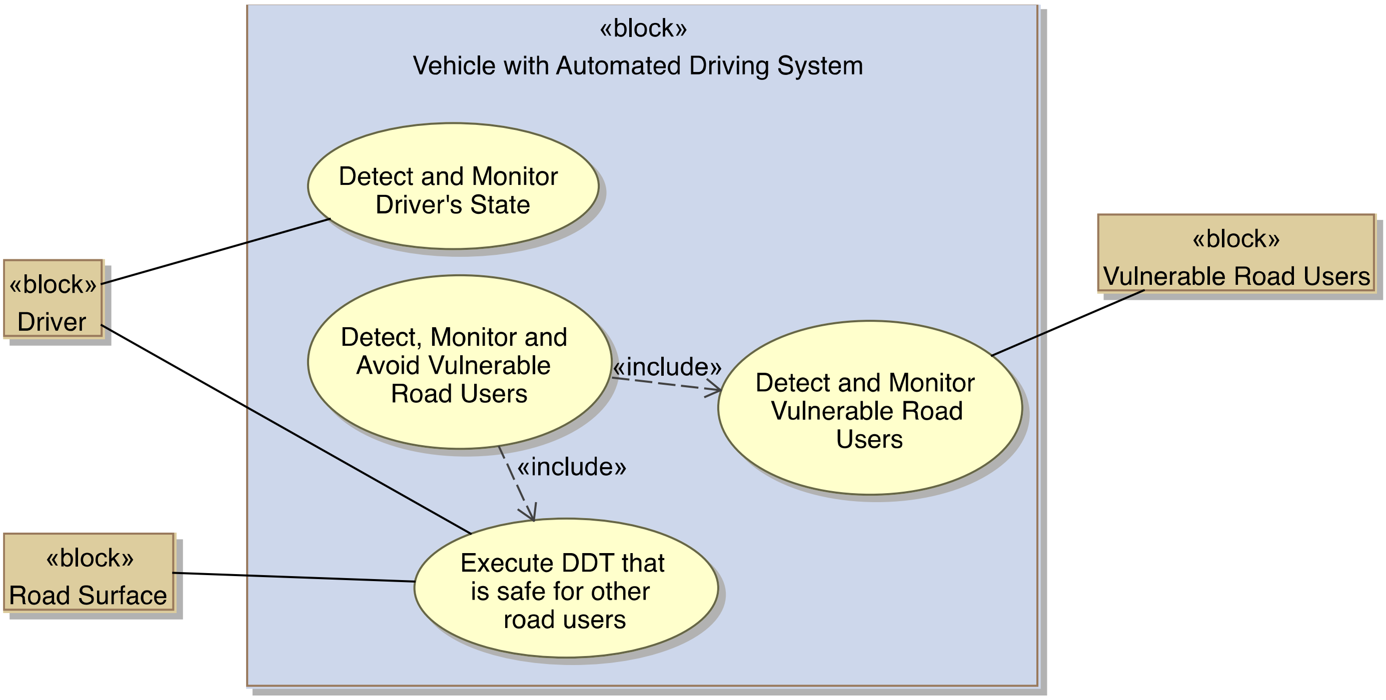


Figure 21: ADS mission use case of carrying out the DDT while maintaining safety for vulnerable road users

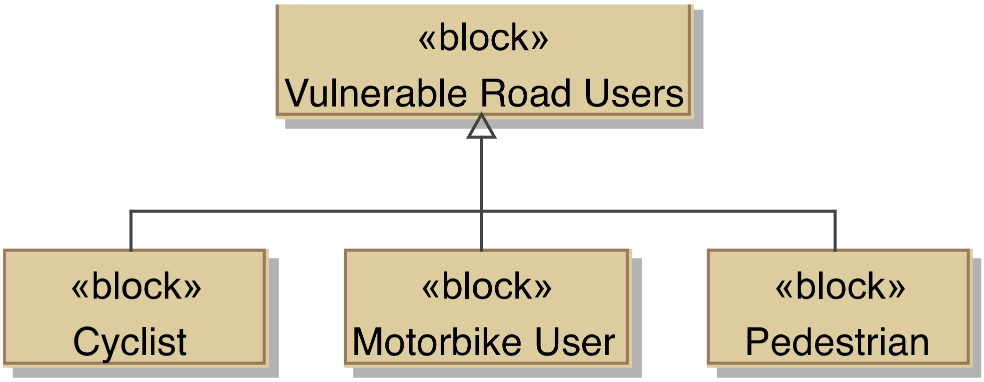


Figure 22: Description of types of vulnerable road users

4.3.2. ADS Functionality as an activity

Having identified the key functional needs of the ADS for its mission, the overall activity is gathered from the use cases. Figure 23 is a description of the activity that the ADS will undertake in order to accomplish its mission of fulfilling the stakeholder needs. Largely, the flow of activities is the following:

1. ***Initiate*** – Begin the ADS mission.
2. ***Sense*** – Receive sensory input through the onboard sensors.
3. ***Analyze (perceive)*** – Make sense, or understand the surroundings to the vehicle with ADS by analyzing the gathered sensory data, by comparing with existing knowledge of surroundings.
4. ***Compute command (plan)*** – Compute a command of best action according to the perceived surroundings. The main criteria is to prioritize safety.
5. ***Execute (act)*** – Execute the commands generated by controlling the actuation.

Now, the activities related to perception within the activity diagram is split into three main activities.

a) ***Understanding of the outside environment*** – The outside environment to be sensed includes the traffic infrastructure which provides the driving environment, the natural environmental factors such as weather and temperament, the intelligent transport system which may notify the ADS of important current updates to the infrastructure and traffic, and the obstacles that are potentially dangerous to the DDT of the vehicle with ADS.

b) ***Understanding of the driver's state*** – Simultaneously to the human driver needing to supervise the ADS activity, is the need for the ADS to itself be supervising the human driver. The driver's state should be analyzed through sensory input from the onboard sensors to determine the ability of the human driver to perform. This perception should be done at all times that the human driver is in control of the DDT, and also at any time that the human driver may take over control from the ADS, which is to say, at all times.

c) ***Understanding the state of the vehicle with ADS*** – Carrying out the DDT under the capabilities of the hardware and software that composes the ADS requires an understanding of the current behavior and performance. Both the driver and the ADS should be allowed to monitor this, to enable the determination of a best action for the vehicle.

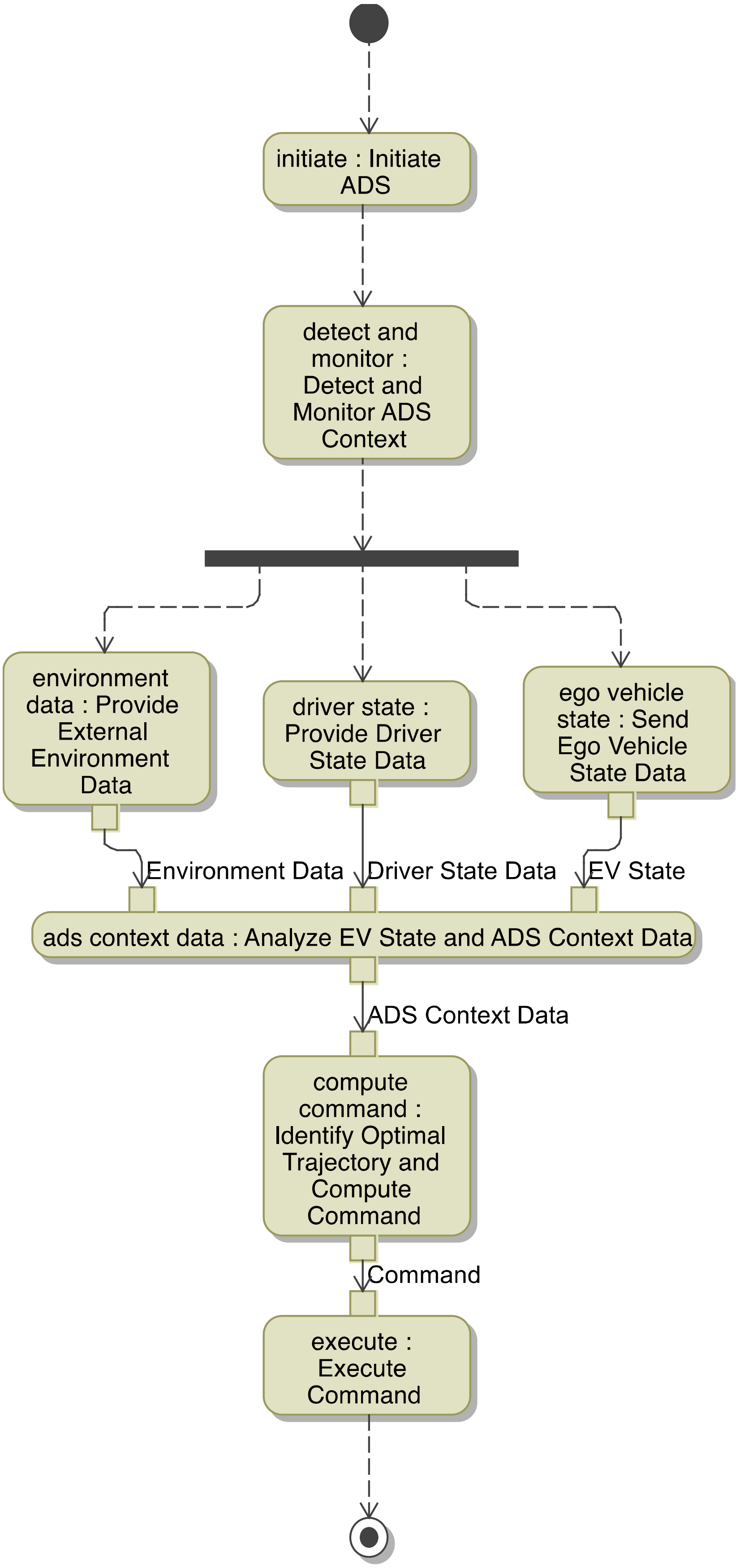


Figure 23: Activity description of the mission of a vehicle

5. Studying the Preliminary Architecture of the ADS

5.1. Preliminary Architectures of Vehicle with ADS

Building upon the activities developed in the case study of Section 4, an allocation is done to determine the feasibility of architectures for a vehicle with ADS. The co-system design that is proposed by HAVEit is first used for the allocation. Next, an alternative architecture is proposed, and a comparison is made.

5.1.1. Allocation of Activities in HAVEit Architecture

Figure 24 shows an allocation of the mission activities within the four layers proposed by the HAVEit project (driver interface layer, perception layer, command layer, and execution layer), described as subsystems that make up the ADS. On initiating the ADS mission, three layers begin their activities: the vehicle sending the vehicle state data, the perception system sensing (detecting and monitoring) the driving environment, and the human interface sensing (detecting and monitoring) the driver state. Multiple sensors may be utilized by the subsystems for sensing, therefore, on receiving the respective data, a preliminary processing is carried out to validate the data. The validated data is then sent to the co-pilot within the automated driving command system, where the context is understood, and a command for the planned action is generated. The activity flow reaches a final stage at the command execution system, where the command is executed. The processing of sensory data is carried out in a total of four subsystems in this architecture.

5.1.2. Allocation of Activities in an Alternative Architecture

Figure 25 shows an allocation of the mission activities within three subsystems: the perception system, the automated driving command system, and the command execution system. Building upon the definition of the perception capability, the perception system utilized here is the subsystem that senses and makes an understanding of the driving environment. Therefore, on initiation of the ADS mission, the perception system begins to sense the context actors of: the external driving environment, the driver state, and also the vehicle state. On gathering the data, the perception system makes an analysis to render an understanding of the surrounding context. Having understood the context, the automated driving command system takes an input of the understood environmental model. An optimal trajectory is then identified, and the output is a command to realize the selected action. The command execution receives this command, and the mission activities reaches the activity final having executed the command. Here in this architecture, the processing of sensory data is carried out in the single perception system.

5.1.3. Discussion of Allocation and Comparison of Architectures

The two architectures selected for allocation are among many possible architectures that can all carry out the ADS mission. The first was the HAVEit co-system design as an architecture. The second of the architectures was a modification, or a refinement of the HAVEit design. The main difference between the two architectures, reflected in the allocation, is the placement of the sensory data analysis. Commonly in the literature referenced in this dissertation, a sensor data fusion is relied upon to carry out validation and understanding of data.

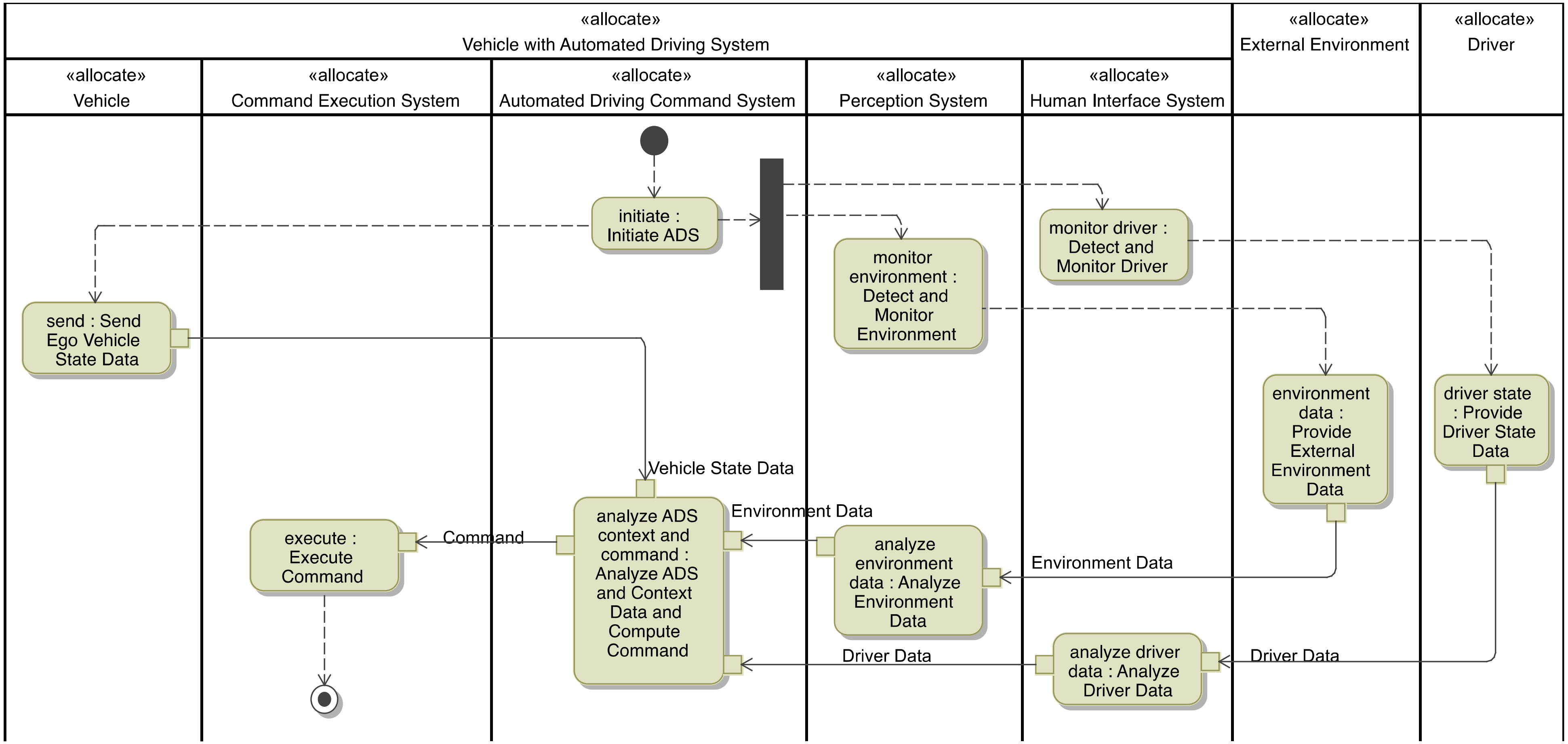


Figure 24: Allocation of ADS mission activities in the HAVEit architecture

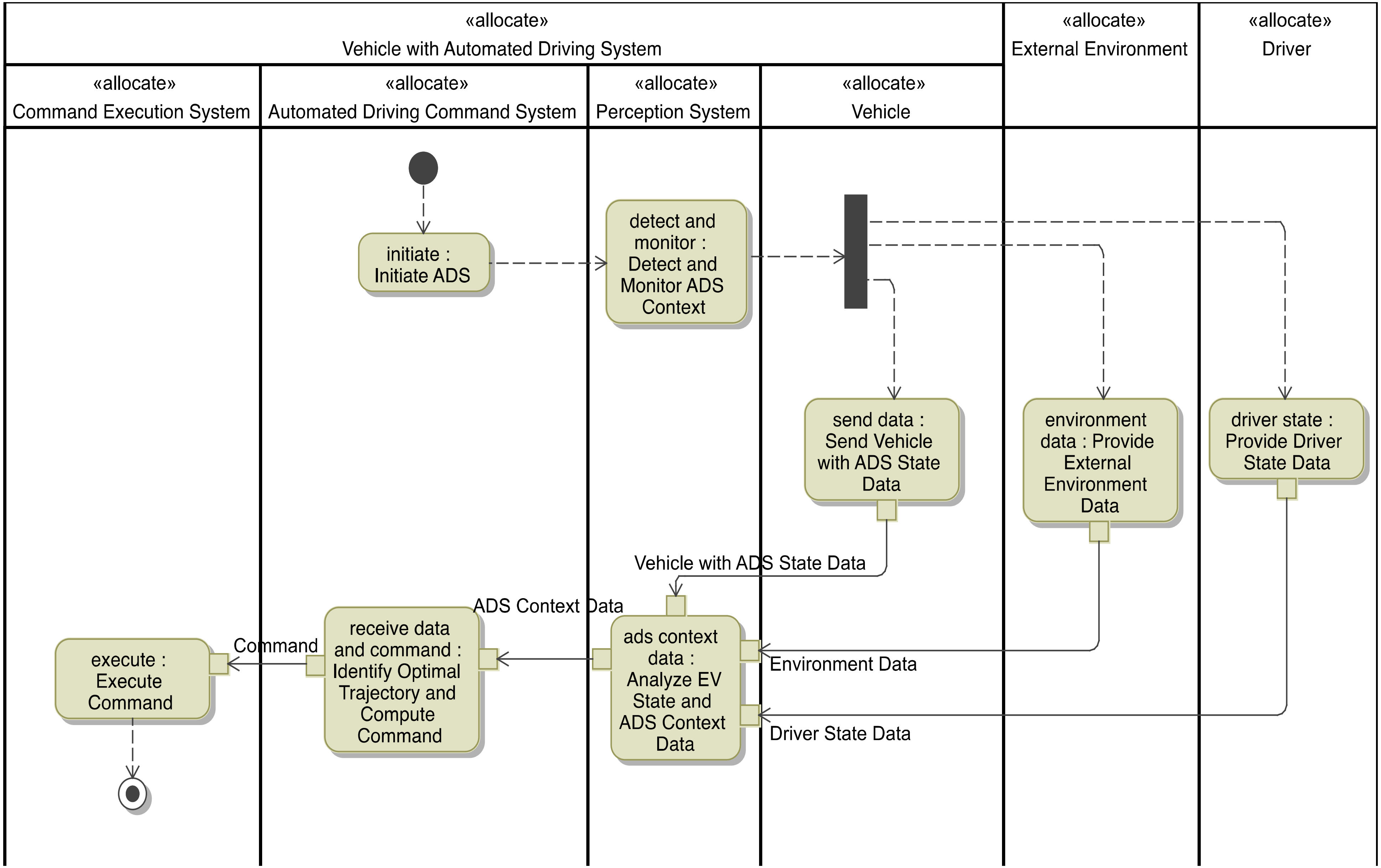


Figure 25: Allocation of ADS mission activities with perception dedicated to a single system

The differences in the placement of sensor data analysis is highlighted in Figure 26 and Figure 27. These figures represent the internal structure of the two architectures given the above allocations.

Figure 26 shows the main analysis of all sensory data taking place in the automated driving command system. In order to do this the inputs from the following are described: the processed output of the perception system on receiving inputs from the external environment, the processed output of the human interface system on receiving inputs from the driver, and the raw data from the vehicle for the vehicle state. The automated driving command system commands both the human interface system and the command execution system for interacting with the driver and also with actuation to realize the planned action. The total number of interfaces seen here is 9.

Figure 27 shows the main analysis of all sensory data taking place in the perception system. In order to do this, the raw sensory inputs from the external environment, from the driver, and from the vehicle are received. Based upon the contextual data that the perception system sends to the automated driving command system, a command is given to both the human interface system for interacting with the driver, and the command execution system for the actuation that realizes the planned action, as was seen in the previous figure. The total number of interfaces seen here is 8.

5.2. A Test Case for Perception, and Refining an Architecture

The difference in the number of subsystems carrying out the perception capability can become important for verification purposes, not only in the testing carried out by the manufacturer, but also for the certification authority. Consider the following test scenario shown in Figure 29 proposed to illustrate this purpose: observation of the ADS behavior on coming into contact with an actor that is not known.

There are many combinations possible for placement of data fusion for sensor data analysis, not all are shown in this work. Since the task of detecting and monitoring the driver requires sensors, the gathered information, analysis, and cross validation, while also being part of the ADS context, arguably this would be better assigned to a layer dedicated to perception with the additional benefit of being testable as a standalone subsystem.

Inclusion of the perception capability also introduces a knowledge base that is referenced. The relationship types of dynamic and complex as described by the IIC reference architecture [54] mention a dynamic composition and automated interoperability of models. Further definition of a “knowledge base” will be required in future. Future work should consider the exact placement of such a system, and the need for it to be continuously updated should also be discussed among the stakeholders.

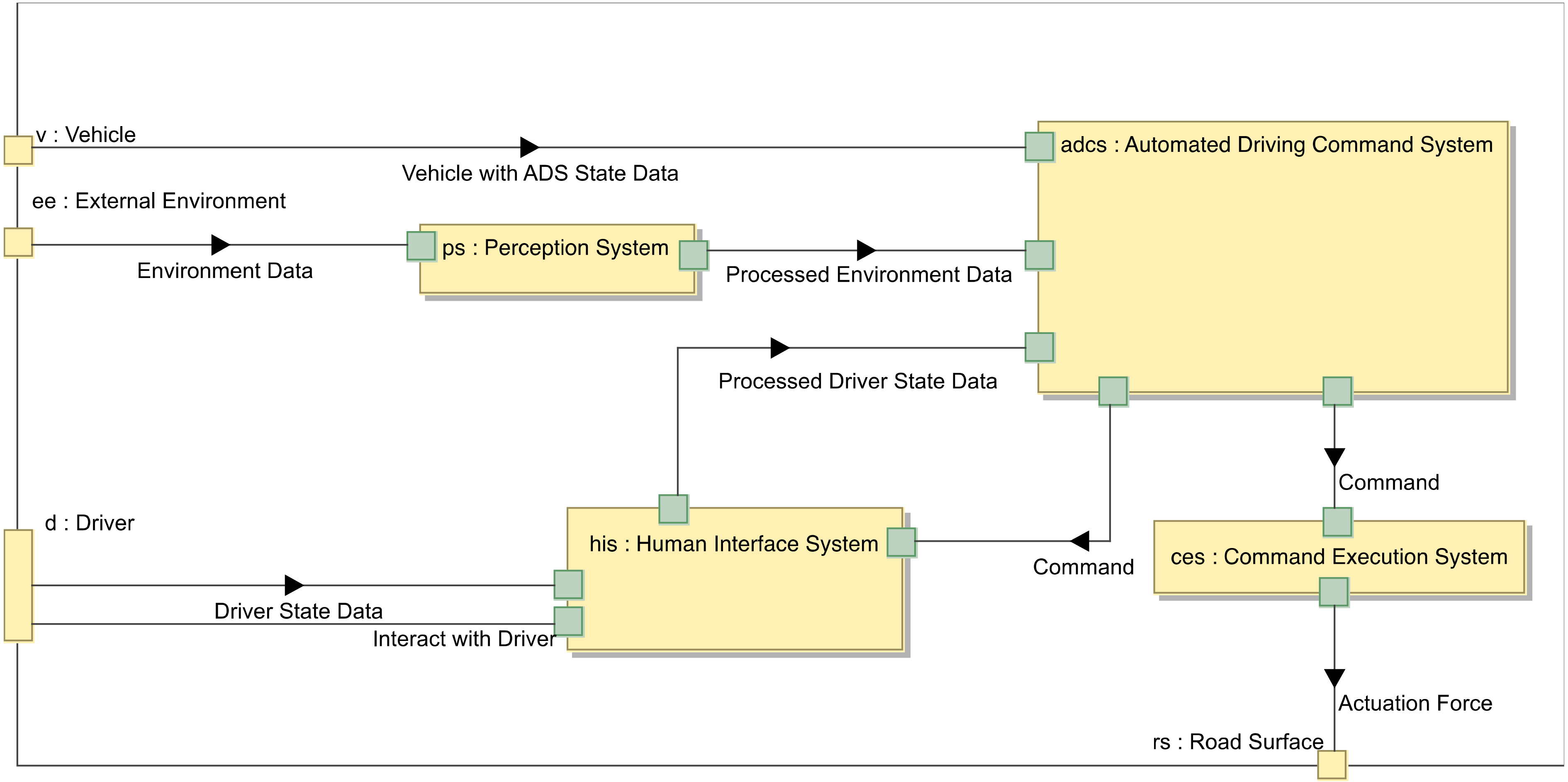


Figure 26: Description of internal interaction of HAVEit architecture after allocation of activities

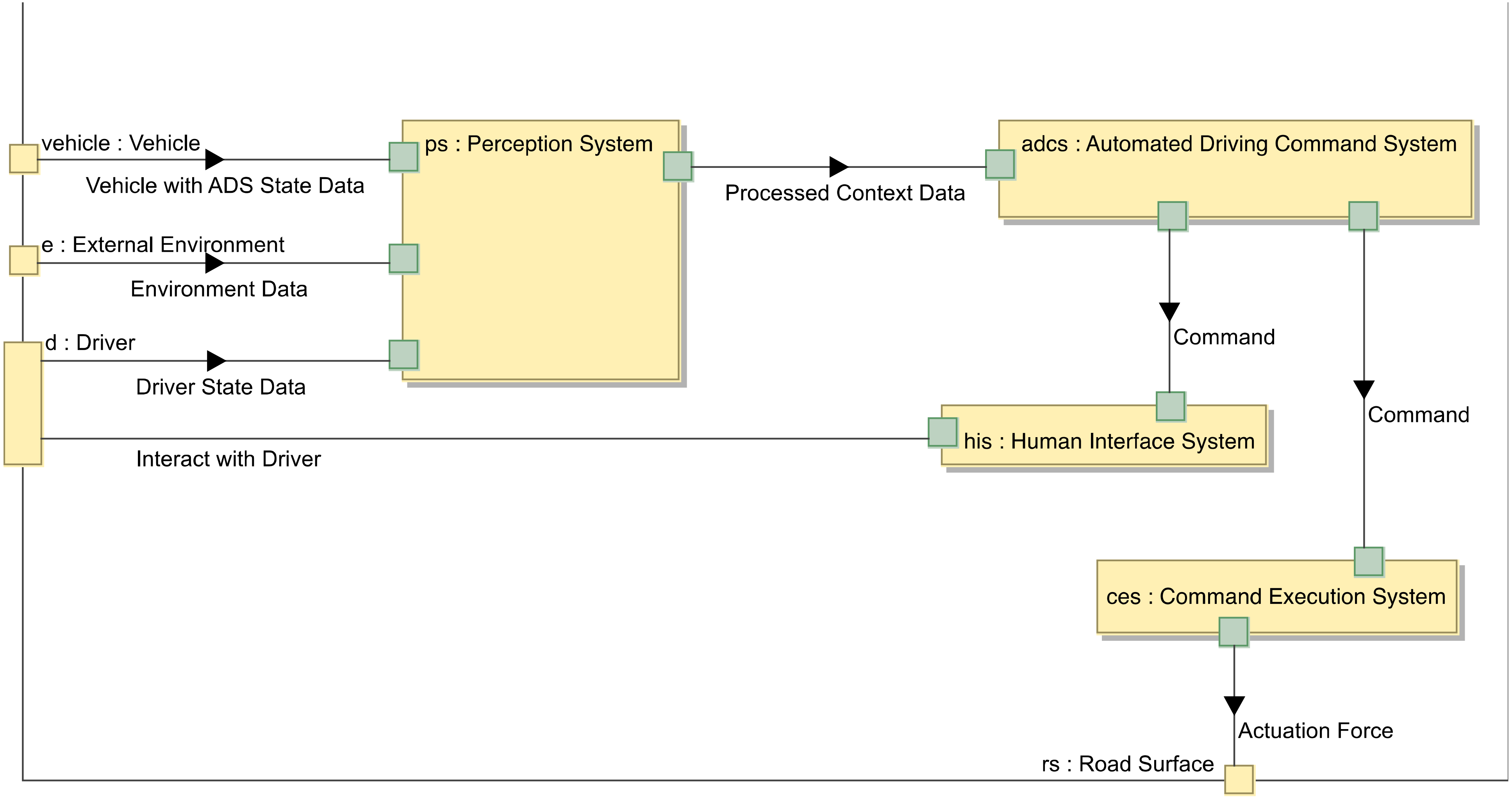


Figure 27: Description of internal interaction of the ADS when the perception system is dedicated to the context after allocation

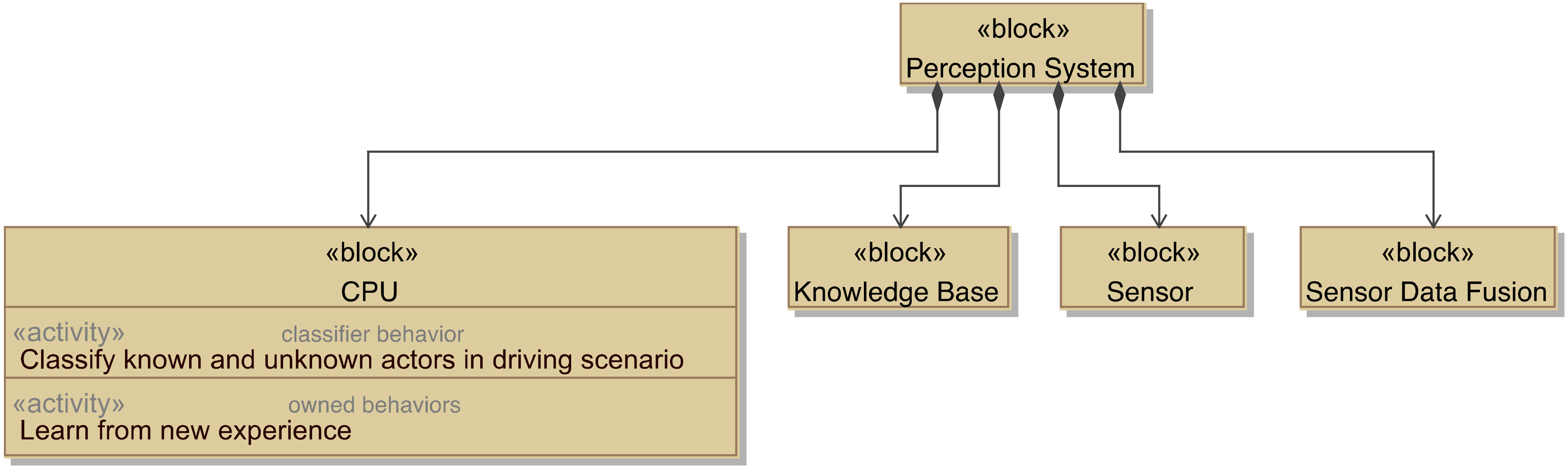


Figure 28: Description of a proposed architecture for the perception system of an ADS

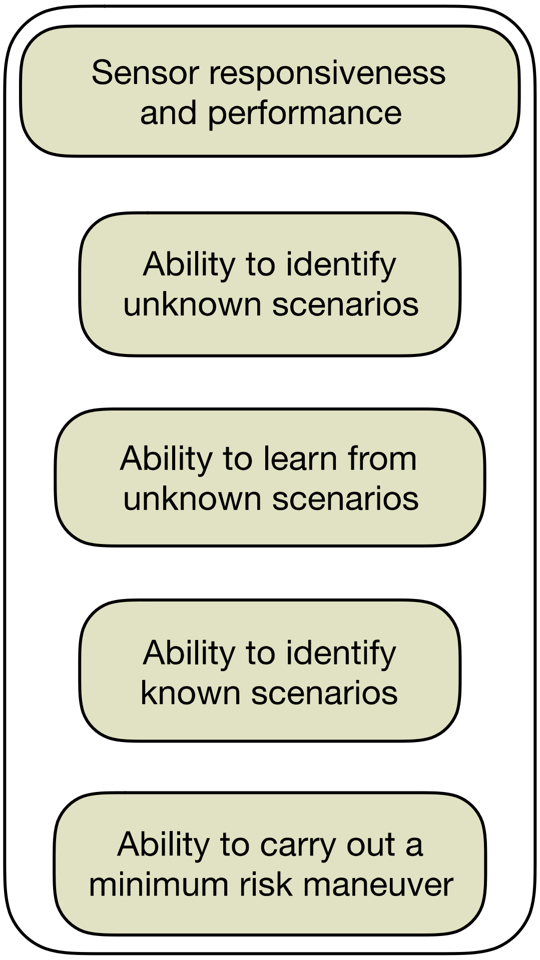


Figure 29: Description of considered preliminary test cases for the perception capability for safety certification

6. Driver Interaction with the ADS

6.1. Human Behavior Monitoring and Human-Machine Interface

Designing an ADS to drive in a complicated environment that even a human driver finds to be difficult at times, is an unprecedented control task. An actor just being present on the road presents a potential danger to the ADS. On top of this, in the case of a vehicle with ADS, the fallback and driving delegation is a key interaction that the system must have. Therefore, the driver is a key composition of the operational context of ADS, and an interaction to smoothly transition between the controller of dynamic driving tasks must be made to maintain and improve road safety of vehicles.

6.2. Human-Machine Interface for an ADS

ADS technology requires a refined design to facilitate the interaction between the ADS and the human driver, to achieve the goal of improving safety on the road. The need for a drastic increase in information exchange, or dialogue, between the two actors to perform the dynamic driving task requires testing of the human-machine interface, particularly in hazardous situations such as the delegation of driving control.

The above two capabilities in a vehicle with ADS can be realized by technologies developed for the human-machine interface. Several projects and studies exist in the field of monitoring driver attentiveness, many of which focus on trials of eye motion tracking, and also gaze direction tracking[55]–[58]. In the area of information relay, König[53] in a guideline for user-centered development of Driver Assistance Systems (DAS) describes three channels for interaction: visual, acoustic, and haptic. Interestingly, however, the receiving of external stimulus can act as stressors to an operator, and as Wickens[59] describes, external stressors influence the quality of information received by the operator's receptors or the precision of the response. With the rapidly increasing flood of information projected being made available to the ADS and to the human driver, a key challenge will be, as Bruder and Didier[60] mention, in what information must be conveyed, how this information should be transmitted, and where the information should be presented.

6.3. Prototype Design of a Visual Interface

Consideration of the visual interface for the ADS was done by building a prototype in a software (SCADE). This tool provides the necessary environment to draw objects that can be exported as simulations; both interactive and behavioral aspects of the objects can be defined. Figure 30 shows a still shot of the prototyped graphical cluster unit for an ADS. A classical speedometer dominates the center of the unit, with a digital number display for information such as speed, braking force, and steering angle. The information was chosen to represent the ADS state. Improvements should be made in the type of information and the location of information displayed within the unit. Additionally, there are a series of messages for the driver located in the top of the unit. The messages on the left and in the center are are displayed according to the commands of the ADS. This section was assigned to be the port of dialogue between the ADS and the driver.

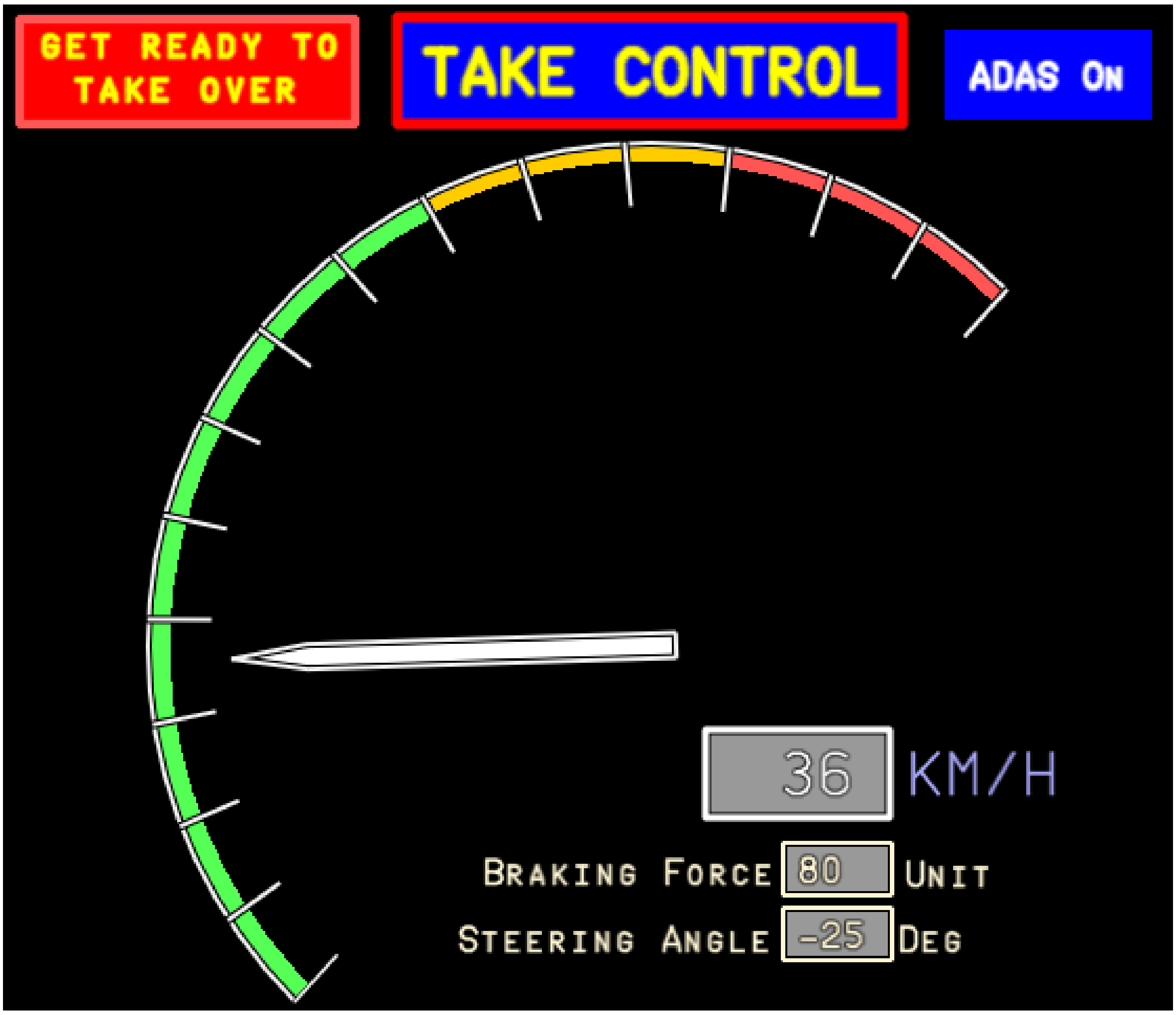


Figure 30: A prototype of the graphic cluster unit

7. Sensors

Following the discussion on the sensor selection problem, the following is presented in this section: a list of currently used and available sensors, and a comparison with the human driver's senses.

7.1. Available Sensors

Developments in sensor technology over the years has seen the introduction of new dominant players. As a prominent example is the lidar, which is gradually becoming the most widely used among research teams, which has replaced in some cases the radar that had previously been installed. Each of the new sensors provides advantages over another, yet paradoxically has disadvantages in certain scenarios. Lidar is notably quicker in surveying the surrounding environment, and in generating a very precise 3D map, however, it has a major performance disadvantage in certain weathers due to its use of laser light. Table 1-5 summarize gathered information on the commonly used sensors.

In Table 6, a comparison is made of the sensors on parameters of cost, information type, and in range of detection. One can observe and conclude that not a single sensor is capable of being the sole detector of the entirety of the ADS context, but a combination of these must be utilized for reliability. Some of the major (and conflicting) needs of the sensor selection are the following:

- The different types of objects within the ADS context points to the need of identifying through visual image processing for color and shape
- The accuracy and speed of detecting relative/absolute velocity and the distance to the object is vital to quick response
- The variety of natural conditions that are present for the road environments must be accounted for, and performance in these guaranteed
- The ADS as a consumer product should not utilize overly expensive sensors

A requirements specification of the perception system for the sensors is offered in Figure 31. One can observe the work necessary to further improve the specifications to allow for parameters and constraints to be chosen for an optimization problem to be defined. Another observation is the necessity of further sensor development to be completed in this area, perhaps tailored especially for ADS use, that can become the next dominant player out of the selection of available sensors.

Video Camera

Uses:	Visible Light
Analysis:	Imaging, classification, texture
Cost:	Very low
Cycle time:	60 ms
Pros:	Object classification
Cons:	Heavy data processing
	Needs clean lens
	Affected by lighting and shadows

Table 1: Analysis of video camera usages for the ADS

Radar

Uses:	Radio Waves (24 GHz or 77 kHz)
Measures:	Range, angle, velocity
Cost:	Low
Cycle time:	66 ms
Pros:	Computationally light
	Tolerant to all weather conditions
	Can see behind obstacles

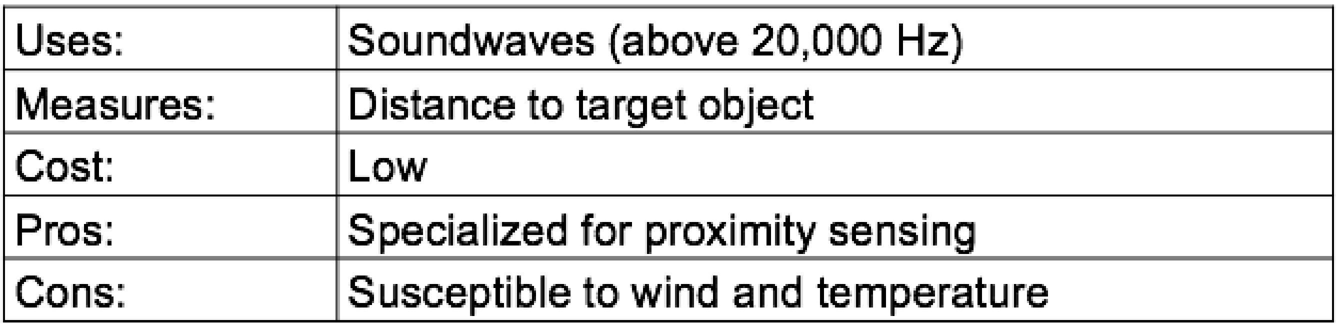
Table 2: Analysis of radar sensor usages for the ADS

Lidar

Uses:	Ultraviolet, Visible, Infrared light
Measures:	Precise 3D map of radius 100m
Cost:	Very high
Update rate:	12.5– 50 Hz
Pros:	Near real-time static slice of environment
	Very high precision (2-5 cm)
	Unavailable in some weather conditions

Table 3: Analysis of lidar sensor usages for the ADS

Ultrasonic



Uses:	Soundwaves (above 20,000 Hz)
Measures:	Distance to target object
Cost:	Low
Pros:	Specialized for proximity sensing
Cons:	Susceptible to wind and temperature

Table 4: Analysis of ultrasonic sensor usages for the ADS

Infrared

Uses:	Infrared Light
Measures:	Thermal radiation
Cost:	Low
Refresh rate:	30 Hz
Pros:	Can detect thermal radiation

Table 5: Analysis of infrared sensor usages for the ADS

Name	Near	Medium	Distant	Information	Cost ($)
Radar	○		○	Active scanning for obstacle position and relative speed (weather independent)	50-150
Ultrasonic	○			Detect distance to target (works on translucents, but susceptible to temp and wind)	15-20
Video camera	○	○		Digital imaging for feature extraction and detection in conjunction to recording	125-200
Night vision		○	○	Digital imaging in the dark while also capturing temperature differences between objects	
LIDAR laser scanner			○	Dynamic scan detecting and tracking objects in near real time	90-8000
V2V	-	-	-	Provides information to improve car safety	
eHorizon or V2I	-	-	-	Provides information such as map, route, speed limit, 3D landscape, positioning and navigation	80-6000

Table 6: Comparative analysis of commonly used sensor for the ADS with information from [18]

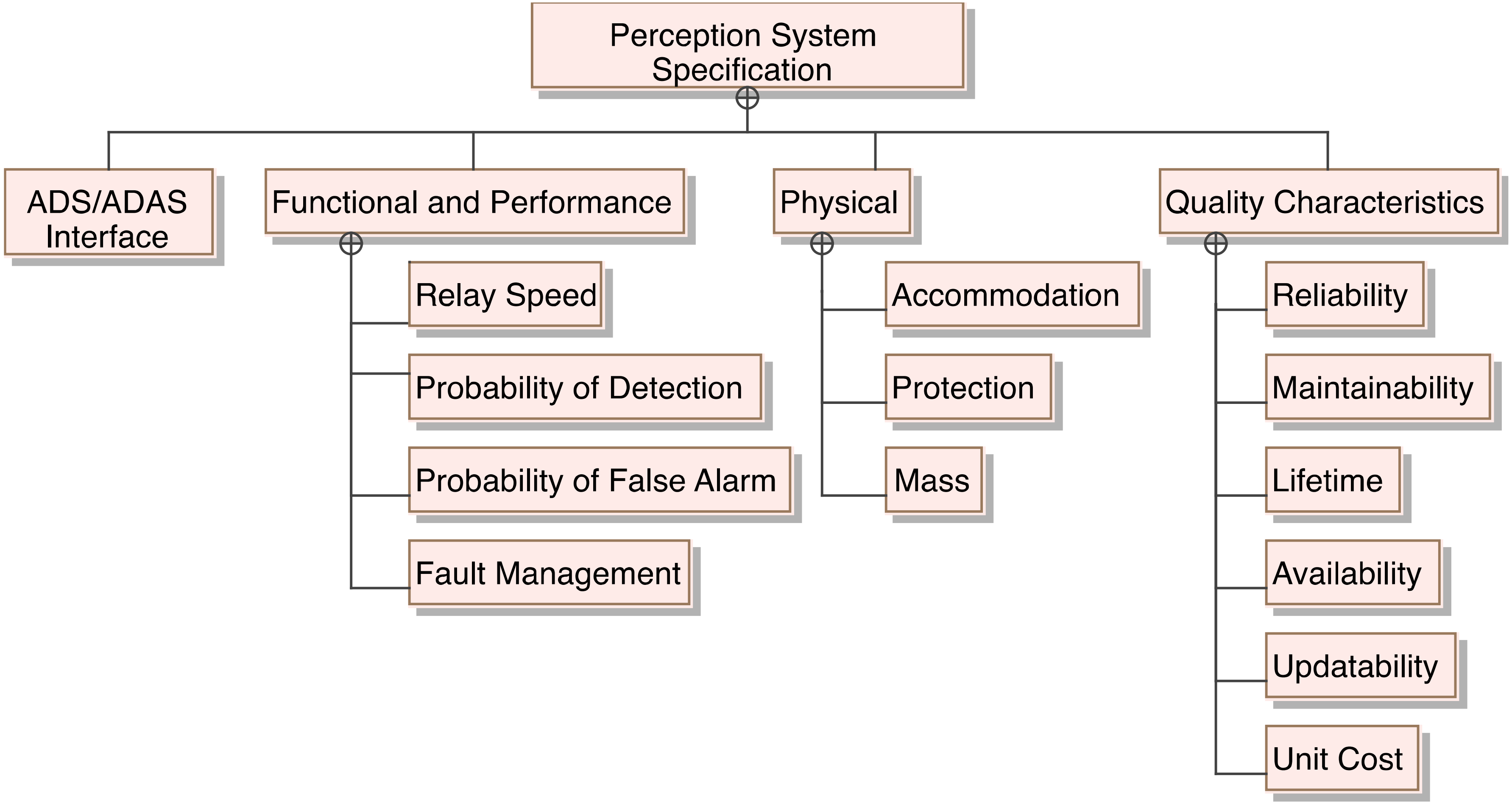


Figure 31: Description of a preliminary requirement specification for the sensors of the perception system

7.2. Human Senses

Keeley [61] in a discussion of the senses of humans and non-human animals begins with the ealiest systemic accounts from Aristotle's De Anima and De Sensu (350 B.C.). The human senses are described in this account as being: sight, hearing, smell, taste, and touch. More recently, he remarks, the commonly proposed set of senses for humans has changed within the field of psychology. Some of the newer senses proposed are the following:

- Vestibular balance
- Proprioception (position of limbs)
- Touch (temperature, pain, pressure, etc.)

Next, the various animal senses that differ to the human senses are given as examples:

- Electrical
- Magnetic
- Ultrasound
- Infrared

Many of the nonhuman senses are difficult to understand fully due to limitations in experimentation. One may only experiment and observe the observations or perceptions carried out by the animal. It is interesting to note, however, that the classical categorization of the five senses (shown in Figure 32) is yet a debatable topic.

The human senses were explored for the reason of understanding further the human driver's perception capability. Sivak [62] explores a regularly claimed percentage of 90% of the driving-relevant information being attributed to being visual. The literature, he observes, commonly mentions numbers of "90%", "95%", "over 95%", or "about 100%" while not providing supported evidence for these. An exhaustive tracing of references of the percentages is described in an attempt to find the source. However, the importance of vision providing driving-relevant information for the human driver is apparent, and alternative methods of providing a perceptage of attribution is offered. The following are the alternatives:

1) Out of 601 items dealing with senses and behavior at the library of the University of Michigan Transportation Research Institute (excluding nonroad transportation), 83% involve vision
2) Only two states in the USA require a hearing test, while all require a standard of vision in order to obtain a driving license

Further work is necessary in this area of understanding human driver perception. This section of research for the purposes of this dissertation concludes with the classification of the commonly used sensors into the categories of the classically described set of human senses, as can be observed in Figure 33.

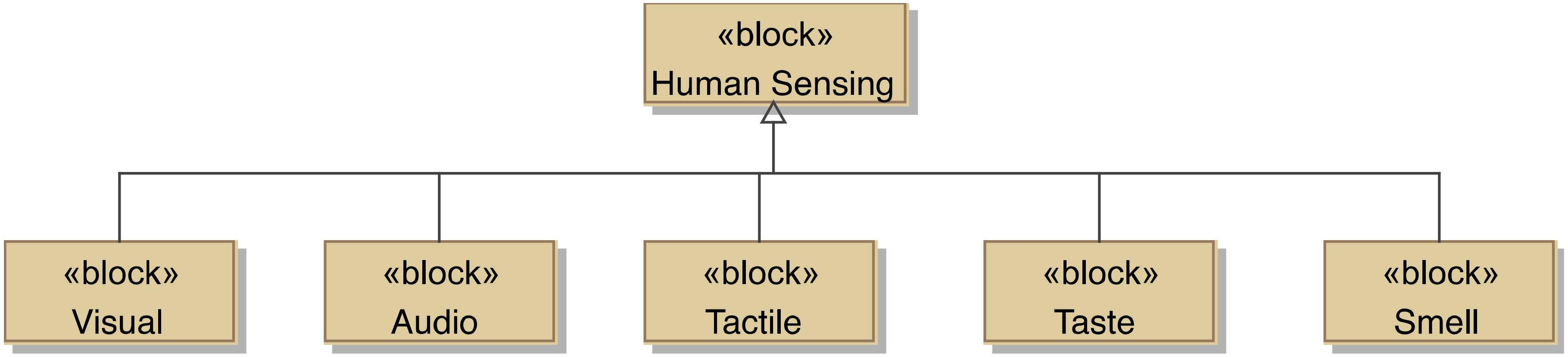


Figure 32: Description of the types of human senses

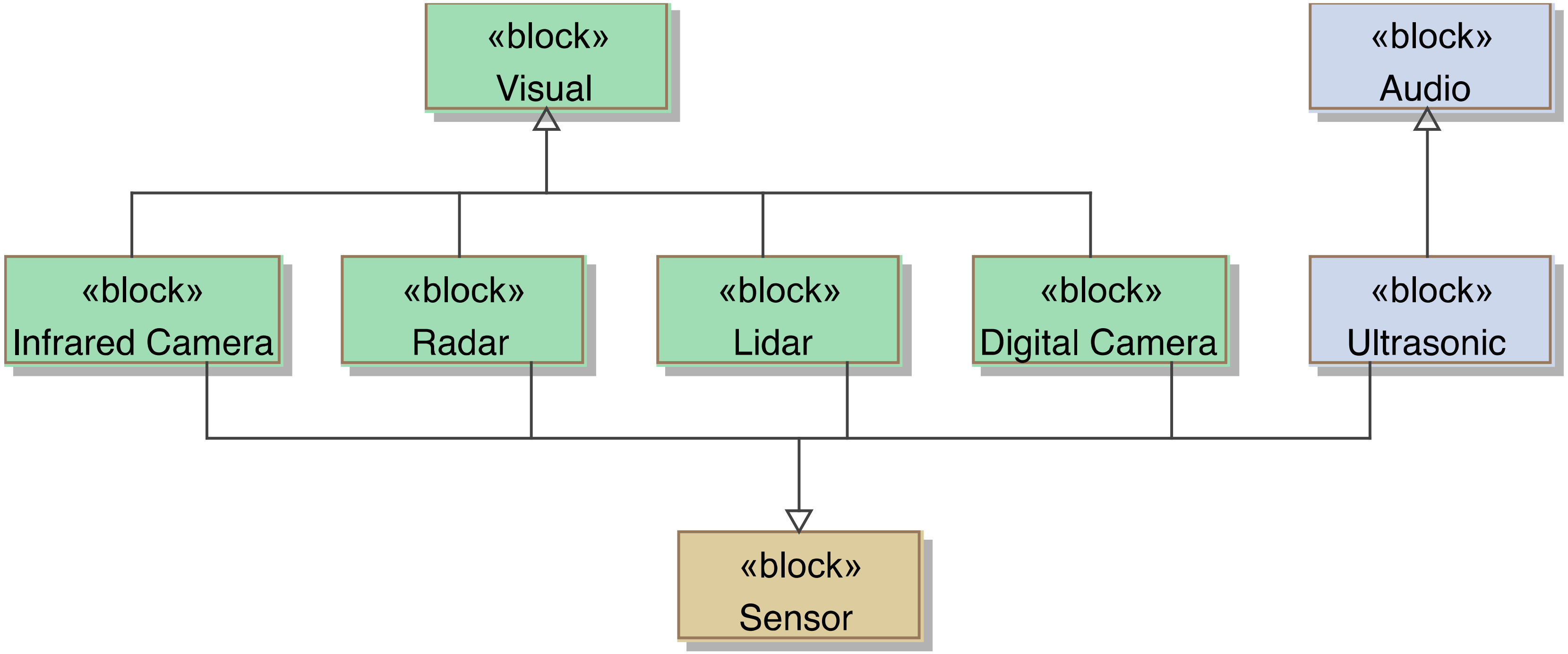


Figure 33: Description of available sensors for the ADS as types of visual and audio sensing

8. Conclusion and Discussion for Future Work

8.1. Conclusions

Having relied on manually driven personal transportation methods, the research and development by auto-manufacturers, the debates and analysis by governmental departments, and the reformulation of key traffic codes by law-makers are gradually bringing a future of automated driving modes of personal transport closer to realization. Amid a background of a need to increase traffic safety by reducing the risk of human errors that are a major contribution towards traffic accident fatalities, and the classic desire of more automation to decrease the manual load of the human operator, the investment towards realization is rapidly increasing. However, the complexities posed by the large-scale and intertwining stakeholder concerns, and the technology itself provide many challenges. The challenge posed by regulation of safety is one of these. The results of this study are detailed below:

8.1.1. Perception Capability of the ADS

Following the literature review on perception across several fields, and the need for standardization on functionality for increased confidence in liability issues, the following extracted definition was found to be applicable to ADS:

The ability to gather sensory input, to compare with relevant experience and knowledge, and to gain new knowledge through previously unencountered experiences.

8.1.2. Potentially Dangerous Obstacles to the Vehicle with ADS

The technological goal and expectation of autonomy that an ADS carries, to be achieved through the architecture and design of a system that can perform DDT in a manner that is as safe, if not safer, than a human driver, requires a system context analysis to accurately define the surrounding environment to the system of interest. The MBSE approach provided the insights into defining the potentially dangerous obstacles to the vehicle with ADS. This categorization of obstacles to detect and respond to, combined with the defined perception ability will perhaps enable the creation of feasible test cases for the safety certification by regulators.

8.1.3. Human Driver Interaction

The need for effective perception of the human driver was also discussed, and a state transition of the ADS interacting with the human driver was proposed. Surrounding the ADS is a vast environment to perceive, and a perception system was also proposed to singularly carry out the task of perception as a subsystem. An architecture comparison shows the introduction of the subsystem to decrease the number of interfaces after allocation of mission functions. This grouping of perception functions into a single subsystem may also aid in the above-mentioned creation of feasible test cases for the safety certification by regulators.

This dissertation presented a study which was focused on characterizing the solution space and thus defining an operational concept for the ADS. The key issue of standardization of terminology, both descriptive of the context and descriptive of the functionality are reiterated as enablers to solving the complexity of the issues towards realizing the ADS.

8.2. Discussions for Future Work

From a technological point of view, the variety of selections of sensors within readiness for inclusion in the ADS forms the foundations for sensory detection. The variety of the selections, combined with the variety of makers of ADS developers also means that validation of the emergent performance of combined sensors and subsystems is beyond existing capabilities. The graphical processing methods of digital images presents promising developments that mimic a human driver's ability of perception.

However, there remains a significantly large amount of work to do towards the certifying of safety for the ADS, to realizing the potential benefits of a conceptualized system. Firstly, the definition of a standardized certification environment must be agreed upon, and operational behaviors defined from conceptual modeling should be reformulated into methods of testing. In order to do this, the operational behaviors that pose difficulties in definition must be adequately, appropriately, and perhaps creatively translated into the models.

The significant new architectural issues presented by ADS are driven by the intermediate automation required; neither fully driver controlled nor fully automated. As the study is limited to the utilization stage in conceptual modeling, further work should consider other life cycle concepts. The stages of maintenance, support and retirement in particular will refine the specification requirements of updatability and maintainability, developing a more complete set of evaluation criteria for design trades.

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11. Glossary

1. ACTIVE SAFETY SYSTEM

Active safety systems are vehicle systems that sense and monitor conditions inside and outside the vehicle for the purpose of identifying perceived present and potential dangers to the vehicle, occupants, and/or other road users, and automatically intervene to help avoid or mitigate potential collisions via various methods, including alerts to the driver, vehicle system adjustments, and/or active control of the vehicle subsystems (brakes, throttle, suspension, etc.).

2. AUTOMATED DRIVING SYSTEM (ADS)

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

3. ADS-DEDICATED VEHICLE (ADS-DV)

A vehicle designed to be operated exclusively by a level 4 or level 5 ADS for all trips.

4. DRIVING AUTOMATION

The performance of part or all of the DDT on a sustained basis.

5. DRIVING AUTOMATION SYSTEM or TECHNOLOGY

The hardware and software that are collectively capable of performing part or all of the DDT on a sustained basis; this term is used generically to describe any system capable of level 1-5 driving automation.

6. [DRIVING AUTOMATION SYSTEM] FEATURE or APPLICATION

A driving automation system’s design-specific functionality at a specific level of driving automation within a particular ODD.

7. DRIVING MODE

A type of vehicle operation with characteristic DDT requirements (e.g., expressway merging, high-speed cruising, low- speed traffic jam, etc.).

8. DYNAMIC DRIVING TASK (DDT)

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

- Lateral vehicle motion control via steering (operational);
- Longitudinal vehicle motion control via acceleration and deceleration (operational);
- Monitoring the driving environment via object and event detection, recognition,

classification, and response preparation (operational and tactical)

- Object and event response execution (operational and tactical);
- Maneuver planning (tactical); and
- Enhancing conspicuity via lighting, signaling and gesturing, etc. (tactical).

9. [DYNAMIC DRIVING TASK (DDT)] FALLBACK

The response by the user or by an ADS to either perform the DDT or achieve a minimal risk condition after occurrence of a DDT performance-relevant system failure(s) or upon ODD exit.

10. LATERAL VEHICLE MOTION CONTROL

The DDT subtask comprising the activities necessary for the real-time, sustained regulation of the y-axis component of vehicle motion.

11. LONGITUDINAL VEHICLE MOTION CONTROL

The DDT subtask comprising the activities necessary for the real-time, sustained regulation of the x-axis component of vehicle motion.

12. MINIMAL RISK CONDITION

A condition to which a user or an ADS may bring a vehicle after performing the DDT fallback in order to reduce the risk of a crash when a given trip cannot or should not be completed.

13. MONITOR

A general term referencing a range of functions involving real-time human or machine sensing and processing of data used to operate a vehicle, or to support its operation.

13.1. MONITOR THE USER

The activities and/or automated routines designed to assess whether and to what degree the user is performing the role specified for him/her.

13.2. MONITOR THE DRIVING ENVIRONMENT

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

13.3. MONITOR VEHICLE PERFORMANCE (FOR DDT PERFORMANCE-RELEVANT SYSTEM FAILURES)

The activities and/or automated routines that accomplish real-time evaluation of the vehicle performance, and response preparation, as needed to operate a vehicle.

13.4. MONITOR DRIVING AUTOMATION SYSTEM PERFORMANCE

The activities and/or automated routines for evaluating whether the driving automation system is performing part or all of the DDT appropriately.

14. OBJECT AND EVENT DETECTION AND RESPONSE (OEDR)

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

15. OPERATE [A MOTOR VEHICLE]

Collectively, the activities performed by a (human) driver (with or without support from one or more level 1 or 2 driving automation features) or by an ADS (level 3-5) to perform the entire DDT for a given vehicle during a trip.

16. OPERATIONAL DESIGN DOMAIN (ODD)

The specific conditions under which a given driving automation system or feature thereof is designed to function, including, but not limited to, driving modes.

17. RECEPTIVITY (OF THE USER)

An aspect of consciousness characterized by a person’s ability to reliably and appropriately focus his/her attention in response to a stimulus.

18. REQUEST TO INTERVENE

Notification by an ADS to a driver indicating that s/he should promptly perform the DDT fallback.

19. SUPERVISE (DRIVING AUTOMATION SYSTEM PERFORMANCE)

The driver activities, performed while operating a vehicle with an engaged level 1 or 2 driving automation system, to monitor the driving automation system’s performance, respond to inappropriate actions taken by that system, and to otherwise complete the DDT.

20. SUSTAINED (OPERATION OF A VEHICLE)

Performance of part or all of the DDT both between and across external events, including responding to external events and continuing performance of part or all of the DDT in the absence of external events.

21. TRIP

The traversal of an entire travel pathway by a vehicle from the point of origin to a destination.

22. USAGE SPECIFICATION

A particular level of driving automation within a particular ODD.

23. (HUMAN) USER

A general term referencing the human role in driving automation.

24. DRIVER

A user who performs in real-time part or all of the DDT and/or DDT fallback for a particular vehicle.

24.1.1. (CONVENTIONAL) DRIVER

A driver who manually exercises in-vehicle braking, accelerating, steering, and transmission gear selection input devices in order to operate a vehicle.

24.1.2. REMOTE DRIVER

A driver who is not seated in a position to manually exercise in-vehicle braking, accelerating, steering, and transmission gear selection input devices (if any) but is able to operate the vehicle.

24.2. PASSENGER

A user in a vehicle who has no role in the operation of that vehicle.

24.3. FALLBACK-READY USER

The user of a vehicle equipped with an engaged level 3 ADS feature who is able to operate the vehicle and is receptive to ADS-issued requests to intervene and to evident DDT performance-relevant system failures in the vehicle compelling him or her to perform the DDT fallback.

24.4. (ADS-EQUIPPED VEHICLE) DISPATCHER

A user(s) who verifies the operational readiness of the vehicle and ADS and engages or disengages the ADS.

25. VEHICLE

A machine designed to provide conveyance on public streets, roads, and highways.