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Master’s Dissertation 2021

Architecture Definition of Automated Driving System Based on Communication Problems Elicited from a Field Test Report

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Major in System Design and Management

SUMMARY OF MASTER'S DISSERTATION

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Title

Architecture Definition of Automated Driving System
Based on Communication Problems Elicited from a Field Test Report

Abstract

Autonomous vehicles, when are officially launched onto the streets and into the traffic systems, it is inevitable that the interactions between the vehicles, road users, external entities such as the pedestrians and construction site are to be established. The safety and the feeling of comfort are, at the point, the utmost importance and hence, the communication between the all units under automotive domain comes in play. To gain a comprehensive understanding of the true capacities and limitations of automated driving system in autonomous vehicle, this study assessed the progress made in the development of autonomous vehicle by reviewing and analyzing actual field test report of autonomous vehicle on public road. The use case of automated driving system disengagement events based on communication issues between automated driving system and temporary traffic control devices in construction zone obtained from a field test report was utilized to propose an architecture definition and concept proposal to tackle the existing issue discovered during the testing and development. In order to gain a better understanding in automotive development process and to verify that a systems engineering approach and architecture is necessary, the interviews and workshop sessions with professionals in automotive research and development sector were conducted, as is the validation of concept proposal and architecture definition.

Key Word

Automated Driving System, Field Test Report, Communication Problem,

Architecture Definition, Research and Development

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1. Introduction

1.1 Research Background

There has been a steady increase in public interest in automated vehicles in recent years. With the objective of improving emissions, energy efficiency, and safety, the automotive industry has transitioned away from traditional combustion engine vehicles and toward electric vehicles, and finally to the most advanced autonomous vehicles. This transition has presented a substantial challenge to automotive developers in terms of assuring user and community safety, as well as communication reliability within the automotive domain.

Fully automated vehicles have enormous potential for enhancing mobility. Many potential users, on the other hand, do not yet have the full confidence to adopt these technologies, which may take some time to mature. User perceptions and willingness to use automated driving vehicles must be understood in order to develop and improve automated driving systems (ADS) and its components that will be more widely accepted by the general public.

According to the findings of a consumer preferences study, consumers have a low willingness to use high levels of automation in vehicles, partial autonomy, and full autonomy, particularly among older adults [1](Table 1-1). According to the study, persons over the age of 45 have a willingness to use a partially or fully automated car of less than 25%, while people of all ages have a willingness of 40% or less. Passengers who took part in a study on their perceptions of autonomous vehicles said they felt more secure dealing with a human driver than they did dealing with an autonomous vehicle [2].

Table 1-1 Age differences in willingness to use automation in vehicles

Level of automation	Age						
	16-24	**24-34**	**35-44**	**45-54**	**55-64**	**65-74**	**75+**
No automation	12.4%	8.0%	9.7%	6.1%	5.0%	3.8%	3.1%
Emergency Only	18.3%	11.3%	15.7	16.0%	14.7%	12.2%	16.7%
Help Driver	26.7%	25.4%	21.1%	41.2%	44.4%	56.0%	52.2%
Partial Autonomy	16.3%	15.3%	19.0%	13.2%	17.0%	13.9%	15.4%
Full Autonomy	26.2%	40.0%	34.4%	23.4%	18.9%	14.2%	12.7%

Source: reference [1]

One of the key factor result in low willingness of using autonomous vehicle is a lack of transparency into the underlying decision-making processes can make it difficult for people to predict the autonomous vehicles behavior, diminishing trust. Hence, the improvement of effective and efficient communication between the automated driving system and external entities in automotive domain is required, that resulted in concerning how automated driving system should be developed. [3][4][5][6] The above-mentioned background can reflect that the research of improving of automated driving system based on communication problem has an importance.

1.2 Autonomous Vehicle

1.2.1 Objective of Autonomous Vehicle

According to data from the World Health Organization, approximately 3,000 people die every day as a result of road traffic accidents [7]. The study predicts that injuries sustained on the road are one of the world's top nine primary causes of sickness or injury in 1990. In 2020, it was expected that road traffic injuries will rise to the top three (Table 1-2)[8]. According to accident studies and statistics, human error is the major cause of traffic accidents, accounting for 93.5 percent of all injuries, vastly outnumbering the leading causes of environment/weather (4.6 percent), technological failures (0.7 percent), and other factors (1.2 percent)(Figure 1-1)59[9]. It is a public health emergency, and governments, developers, automotive manufacturers, and all other stakeholders must work together to find a solution that will assist in reducing human error, which will reduce traffic accidents, while also improving systems in the automotive domain to increase overall security.

Table 1-2 Burden of Disease

1990		2020	
Rank	Disease or Injury	Rank	Disease or Injury
1	Lower respiratory infections	1	Ischaemic heart disease
2	Diarrhoeal diseases	2	Unipolar major depression
3	Perinatal conditions	3	Road traffic injuries
4	Unipolar major depression	4	Cerebrovascular disease
5	Ischaemic heart disease	5	Chronic obstructive pulmonary disease
6	Cerebrovascular disease	6	Lower respiratory infections
7	Tuberculosis	7	Tuberculosis
8	Measles	8	War
9	Road traffic injuries	9	Diarrhoeal Diseases
10	Condenital abnormalities	10	HIV

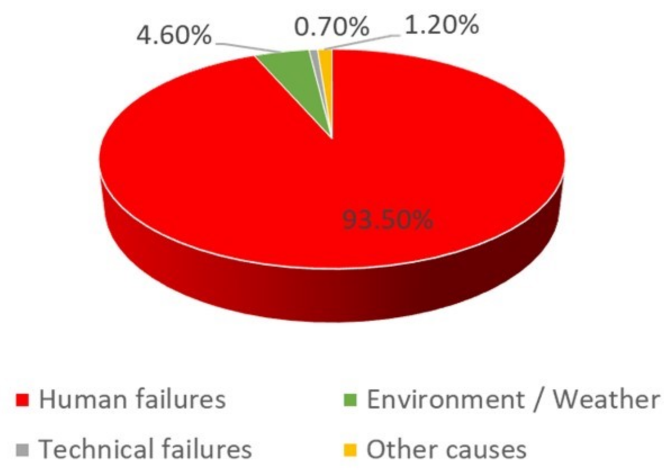

Figure 1-1 Traffic accident with personal injury

According to the above, Autonomous vehicle is designated to solve the problem of human failures, which result in a tremendous amount of deaths and injuries [10].

1.2.1 Autonomous Driving Levels

Instead of human control, the vehicle itself operates the vehicle at different levels based on autonomy of the system. Autonomous Driving levels are classified as follows: level 0 to level 5.

It is classified as driving support at levels ranging from 0 to 2, with the driver being required to perform driving operations as usual, remain engaged with driving tasks, and monitor the surrounding environment while seated in the vehicle. Additionally, the vehicle is equipped with advanced driver-assistance systems (ADAS), which assist drivers in driving and parking functions and automated functions for acceleration, steering and brake at level 1 and level 2. Range from level 3 to level 5, it is considered as autonomous driving.

At level 3, the driver is not required to perform driving tasks, remain engage with driving tasks and monitor environment. However, in some situations where the driver is required to take control of the vehicle or when the system requests it, the driver must be prepared to do so at all times. At level 4, the vehicle is capable of perform driving under certain conditions. At maximum level 5, the vehicle is capable of performing driving under all conditions (Table 1-3).

Table 1-3 Definitions of Autonomous Driving Level

Tasks	**Driving Support**			**Autonomous Driving**		
	Level 0	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Driver perform driving	Must	Must	Must	System Request	Not Required	Not Required
Driver remain engage with driving tasks	Must	Must	Must	Not Required	Not Required	Not Required
Driver monitor environment	Must	Must	Must	Not Required	Not Required	Not Required
Assist Features		ADAS	ADAS	AD	AD	AD
Automated Functions			Yes	Yes	Yes	Yes
Vehicle perform driving under certain condition					Yes	Yes
Vehicle perform driving under all conditions						Yes

1.2.3 How does Autonomous Vehicle work?

To enable the vehicle to operate at automated driving level 3 to level 5, the vehicle is equipped with technologies and components to help detect, identify, clarify, and communicate with environment, other road users, other vehicles, pedestrians and traffic. The advance systems support to locate or navigate itself through network and satellite system. The inertial measurement unit will aid in the vehicle's understanding of its inertial behavior.

A variety of sensors are used to ensure that an autonomous vehicle can be operated reliably and safely. Long-range radar is used for object detection in adverse weather conditions such as rain, fog, and dust. Signals can bounce around or below automobiles in front of the vehicle that obstruct the vehicle perception. In order to detect objects at short and long distances, a combination of cameras is used. A wide range of application scenarios is possible, ranging from distant feature perception to cross-traffic detection and road sign recognition. LIDAR is used for 3D environment mapping and object detection, as well as for other applications. Short and medium-range RADAR are utilized for object detection, as well as side and rear collision avoidance, in a variety of applications. Object detection at close range for objects approaching the vehicle's lane as well as parking are accomplished using ultrasound. [11]

To circumvent the limitations of technology and tackle challenges, vehicle makers use a combination of sensors strategically. In the Tesla Model X, for example, 3 Forward Facing Cameras (for wide, main, and narrow views), Forward Looking Side Cameras at the B-Pillar, Rear View Camera, Rearward Looking Side Cameras at the body side, Forward Facing RADAR at the bumper, and 12 Ultrasonic sensors are employed [11](Figure 1-2).

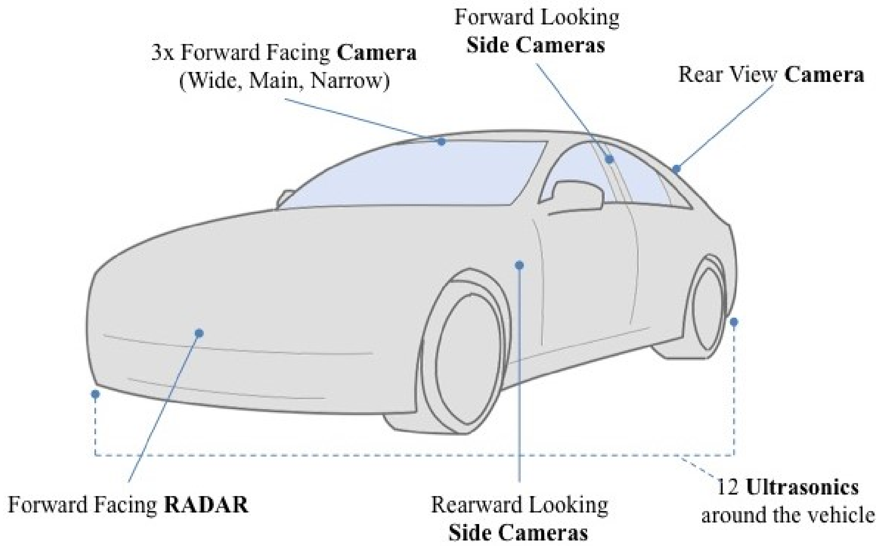

Figure 1-2 The visualization of sensors used in Tesla Model S

In another example, 4 RADARs at the rear and body sides, Long-range LIDAR, 360-degree cameras, and an audio sensor on top of the car, 2 Short-range LIDARs at the body side, and 2 Mid-range LIDARs at the front and rear bumpers are employed in the Waymo Chrysler Pacifica (Figure 1-3)[11].

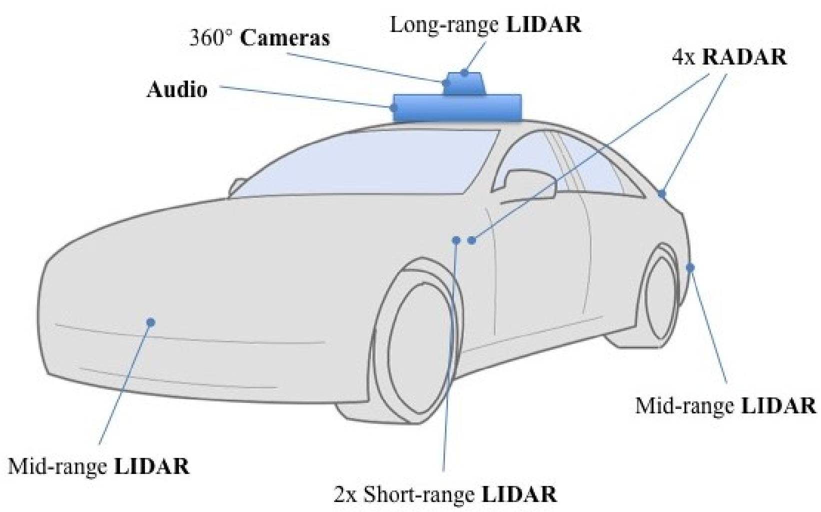

Figure 1-3 The visualization of sensors used in Waymo Chrysler Pacifica

Using V2X communication and connectivity, autonomous vehicles may exchange information and engage with other road users as well as with other vehicles, traffic and pedestrians (Vehicle-to-Everything). V2X is composed of three components: V2V (vehicle-to-vehicle), V2I (vehicle-to-infrastructure), V2N (Vehicle-to-Network) and V2P (Vehicle-to-Pedestrian). Advance technology and its applications can assist in improving prediction, planning, reducing energy consumption, increasing efficiency, increasing the level of trust and confidence among road users, pedestrians and others in the proximity of a vehicle's path, as well as increasing overall safety, which is the ultimate purpose of autonomous vehicle development. From all of input data from sensors and communication, the information will be processed by the self-driving computer, which will make proposal and command to the vehicle control unit to control acceleration, braking, and steering (Figure 1-4).

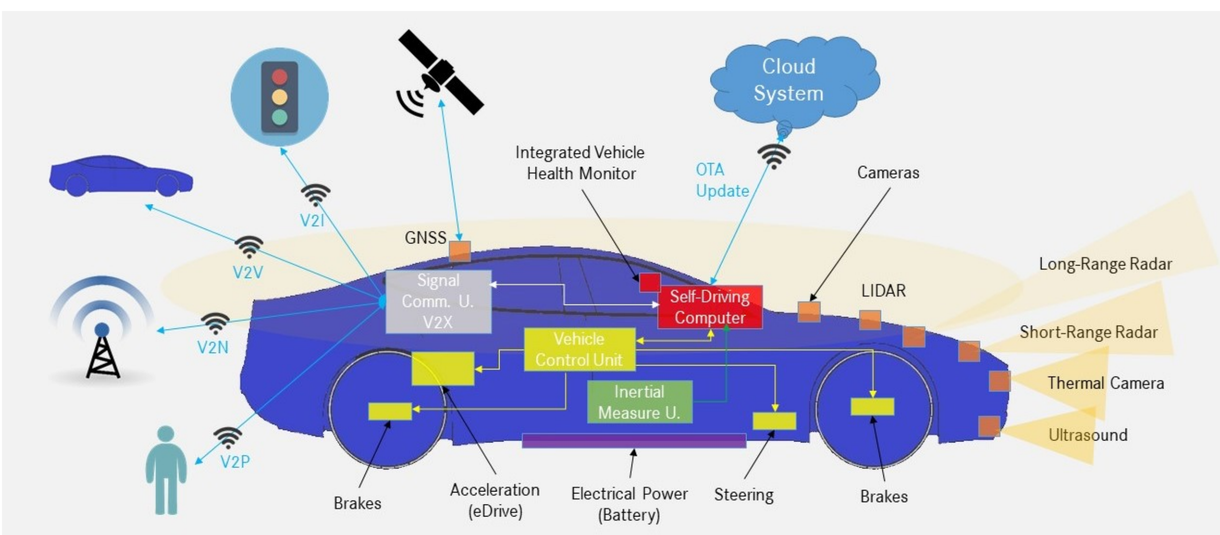

Figure 1-4 The visualization of typical elements in Autonomous Vehicle

Based on Sensing and Data Input for environmental mapping captured by sensing, communication and connectivity systems, which including Map Data, Global Navigation Satellite System (GNSS), Inertial Measurement Unit (IMU), Passive Sensors: Cameras, Active Sensors: LIDAR and RADAR, and V2X, the output information will be processed by Computation & Decision Making systems (Simultaneous Localization, Mapping and Planning). The result will give a proposal to Act & Control system to give command the steering system, accelerating system, braking system and signalling system [11] (Figure 1-5)(Figure 1-6).

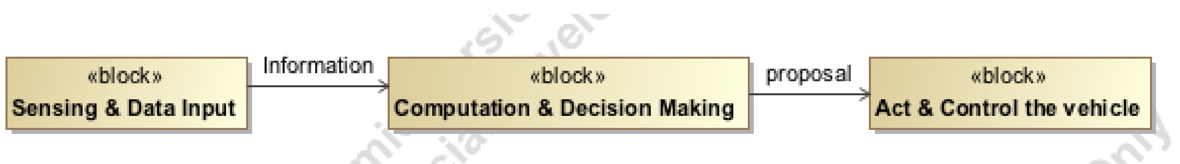

Figure 1-5 The Block definition diagram of typical Automated Driving System

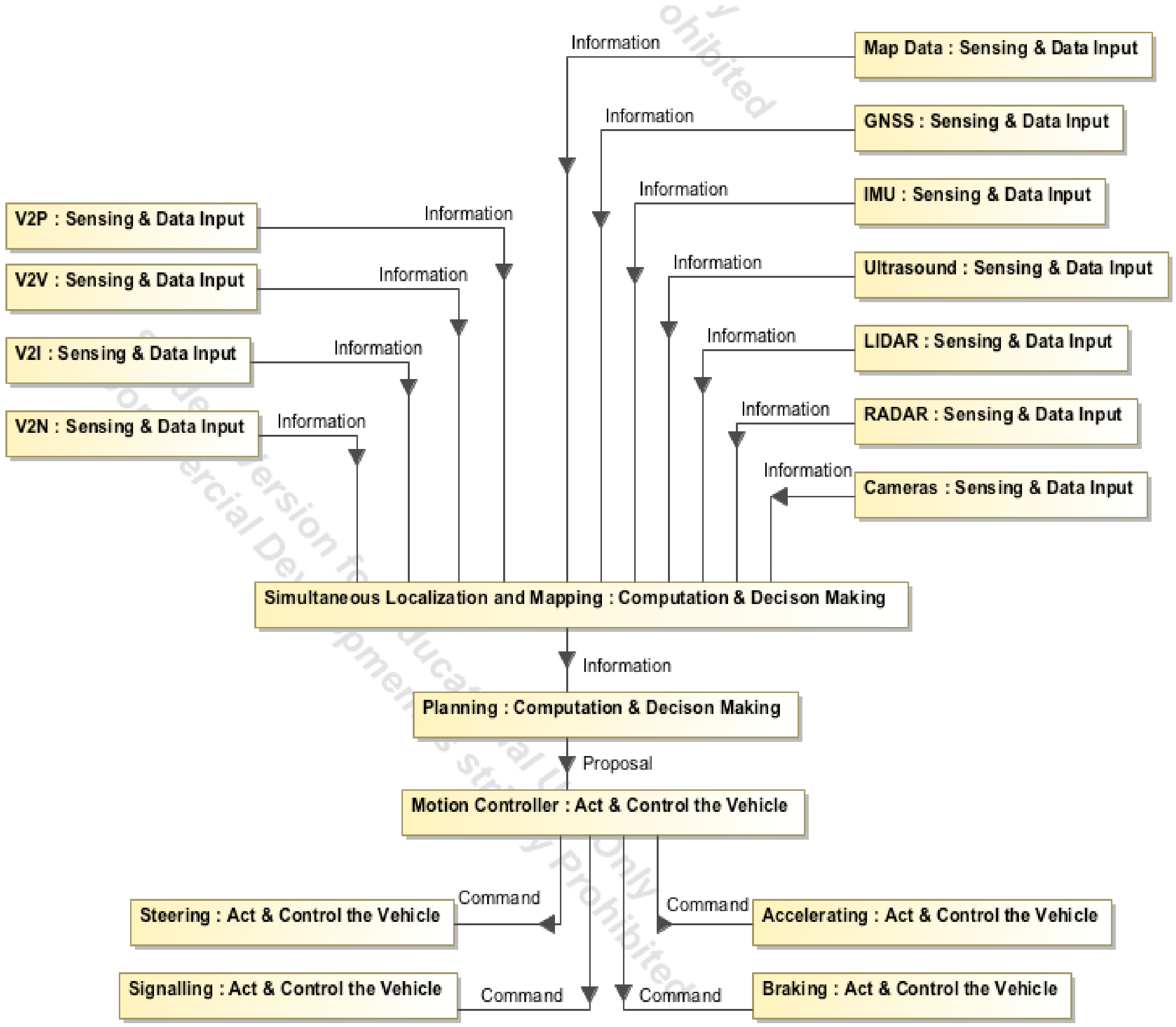

Figure 1-6 The Internal block diagram of typical Automated Driving System

1.2 Communication and Trust Issue

External human-machine interfaces for Autonomous Vehicle-to-pedestrian communication are also being developed and tested to be unambiguous, perceptible, and understandable in a variety of environments while not being distracted. Driving mode (manual, semi-automated, full automation), impending vehicle maneuvers (changing lanes, taking off, yielding), perception and acknowledgement of surroundings and environment (ex. detection of pedestrians), and cooperation abilities (communicating the vehicle's intentions) are assumed to be broken down into the contents of an effective and efficient communication. Lights and sounds are preferred over texts and spoken language in a number of experiments with physical prototypes. Pedestrians who were polled also stated that receiving pedestrian detection is more important than learning about vehicle intentions. Pedestrians, on the other hand, rely on vehicle kinematics (distance to crossing, vehicle speed) to make decisions about whether or not to cross at a distance beyond or at a time when there are no discernible 'human' cues.[12]

According to the foregoing, a crossing pedestrian may have difficulty distinguishing autonomous driving vehicles from human-driven vehicles from afar. After an autonomous vehicle is detected, which is presumably when the vehicle has approached the distance at which a driver is expected to be seen, the feeling of being unsafe is likely to be established. A dedicated lane for autonomous vehicle, on the other hand, is said to increase roadside users' trust in the technology. This means that the 'trust issues' of pedestrians cannot be solved solely through vehicle design, but rather require a more systemic approach that includes related development in automotive domain, such as innovative pedestrian crossing areas that can clearly communicate both with autonomous vehicle and pedestrians while also providing some sort of physical barrier as a backup in the event that an autonomous vehicle communication system fails. The feeling of being protected, as well as becoming more familiar with the existence of autonomous vehicle, should lead to an increase in trust not only in pedestrians, but also in autonomous vehicle users.

Taking into account not only pedestrians but also other physical environments in the automotive domain, external entities such as events on the roadside have the ability to change and move in a dynamic manner, which has an impact on the activity of autonomous vehicles. In order to successfully develop an automated driving system, it is necessary to take into account a variety of use cases and perspectives in order to cover all possible scenarios. In this research, the use cases and perspectives are identified and introduced later in chapter 2.

1.3 Motivation of Proposing Architecture Definition

A series of interviews and workshops with professionals in the automotive research & development (R&D) sector were undertaken to gain knowledge of the challenges in development of products for the future and insights were gathered to give an understanding of automotive development process and necessity of systems engineering approach in Original Equipment Manufacturers (OEM). In order to propose a practical solution idea, it is also vital to verify whether systems engineering and architecture definition are required while developing and designing automated driving systems.

In traditional approach, the vehicle requirements are broken down directly into component requirements. The components are then integrated to create features and functionalities (Figure 1-7). Following component development, this strategy can be seen in the establishment of Research and Development (R&D) organizations, divisions, and workforces in general. In various product developments, vehicles are developed to meet complex and new standards, which can result in communication across departments, on the other hand, becoming increasingly crucial, as modern vehicle development gets more complicated. Collaboration and Communication are becoming increasingly important.

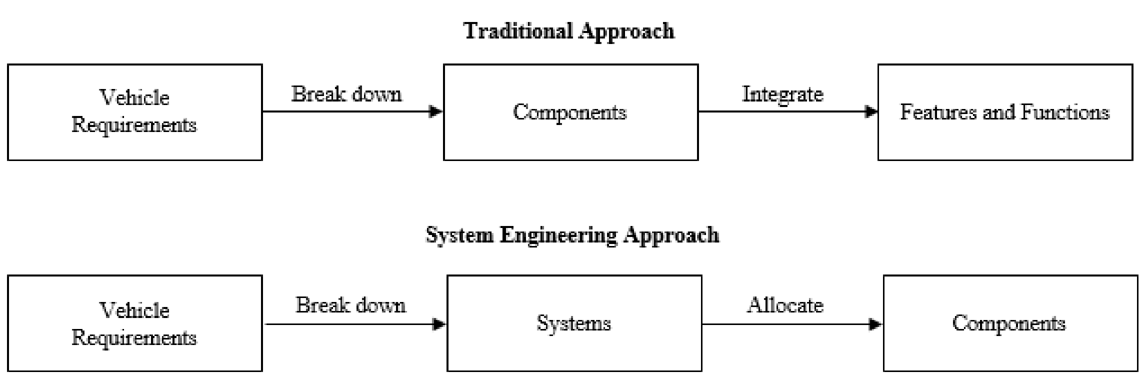

Figure 1-7 Comparison of traditional approach and Systems Engineering approach from workshops

Following the workshops, it was determined that systems engineering methods should be implemented in order to provide proper development methods and workflows that are appropriate for the organization and business, and to ensure that the product and completed system meets the needs of stakeholders and customers. It is critical to do a thorough analysis of the requirements for a system of interest and to build the architecture while taking into account all of the system's life cycle stages. The architecture definition is one of the variables that contribute to the success of product and system development in high complexity development project. Several work packages, including training and a deployment plan, are being discussed as part of the organization's effort to incorporate systems engineering including architecture definition process in the organization workflow for vehicle development in the near future.

From the result of workshop, it was verified that the approach of proposing architecture definition will contribute to solve the unsolved problem from defined use case in ADS development and other problems in developing systems in automotive industry.

1.4 Research Purpose

To gain a comprehensive understanding of the true capabilities and limitations of an automated driving system and issues in communication with external entities, it is necessary to examine the advancement and progress of automated driving technology. It is also necessary to take into account a variety of use cases and perspectives in order to cover possible scenarios. In this research, the use cases and potential issues caused by technological flaws and other factors were identified in order to determine the risk or pain points associated with the system. To improve safety, communication effectiveness and trust, the understanding of issues in development should be realized not only on a single autonomous vehicle, but throughout the automotive domain as a whole. Software and hardware in the automated driving system, as well as communication and safety protocols, must be dependable in accordance with technology acceptance research and models, according to the requirements. With finding from architecture definition, this research aims to propose the solution ideas to overcome the issues associated with the automated driving system from the use case captured in the study of progress of automated driving technology.

The result of this research is aimed to be a reference for improvement and development in both automated driving system and other developments in automotive domain.

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1.5 Research Framework

Following **Figure 1-8**, the research framework was developed to provide the underlying structure for implementing the research plan and steps followed throughout the research process. Figure1: Research Framework was also used as a reference to determine the scope of research to be conducted and the focus topics to be addressed.

Aiming to clarify the goal of autonomous vehicle (Figure 1-8, Objective of AV), observations are made regarding the impact of human error on road traffic accidents, as well as the classification of autonomous driving levels, objective of autonomous vehicle (Figure 1-8, What is AV?) and its operation (Figure 1-8, How AV work?). This study aims to better grasp the necessity, motivation, and pain points associated with development in order to suggest a solution to an existing problem. To better understand the true capacity, the limitation and the advancement of automated driving technology, the study of progress in autonomous vehicle development, and the review and analysis of disengagement events from actual autonomous vehicle testing in the field are conducted (Figure 1-8, What are they doing in the industry) (Figure 1-8, AV development Progress). The result from the analysis of disengagement report was reflected into the problem (Figure 1-8, Problem).

In order to solve an existing problem and improve automated driving system for autonomous vehicle, this research proposes an architecture definition and a solution idea based on defined use case focused on communication related problems elicited from the actual field test report (Figure 1-8, Systems Engineering & Architecture Definition)(Figure 1-8, Proposal to solve problem). For this reason, it is also vital to investigate the logical and practical development approach in automotive research and development sector to verify whether systems engineering approach and architecture definition is necessary, interviews and workshops with professionals in the automotive development sector were conducted (Figure 1-8, Automotive Development Process)(Figure 1-8, Problems in Development Process).

To validate the proposed concept and architecture definition and gather feedback for further study, the interview with professionals in advanced driver-assistance systems and automated driving system sectors is undertaken (Figure 1-8, Validation). Finally, the research is concluded, and recommendations are made to communicate the findings of the study (Figure 1-8, Summary & Recommendation.

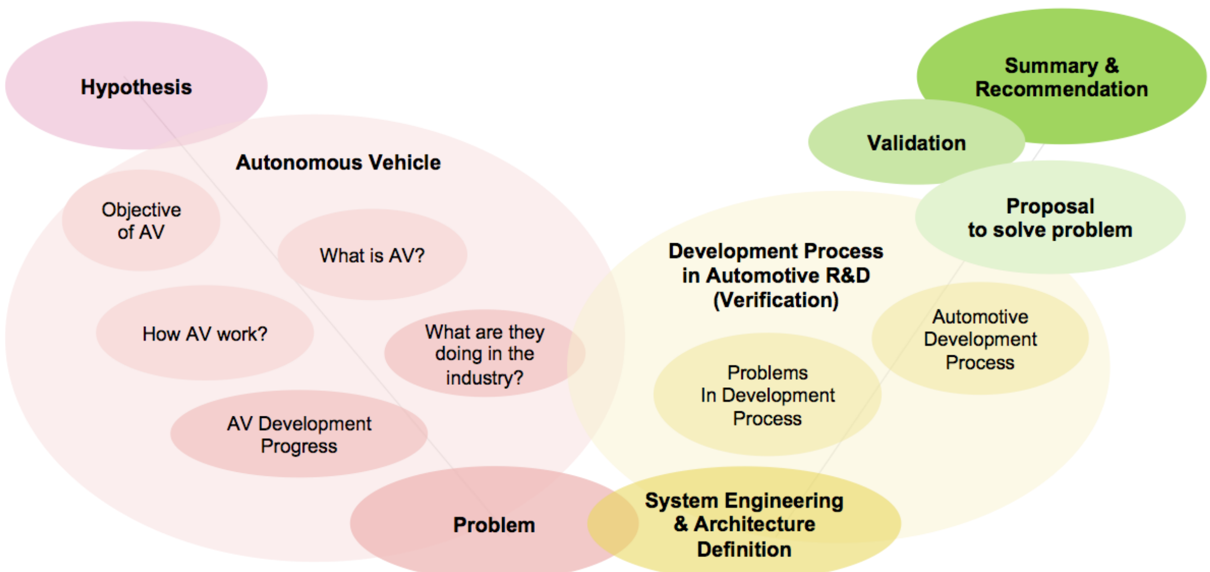

Figure 1-8 Research Framework

2. Problems Elicited from a Field Test Report

This chapter describes the problems and use case selection elicited from an actual field test report of autonomous vehicle on public road. For proper verification and validation of systems and product, testing and evaluation and in testing facilities, as well as vehicle testing on the road, are required. This is necessary in order to accurately analyze the performance and true capabilities of the autonomous vehicle under development to ensure that it meets all requirements. It is necessary for the developer to examine a range of use cases, issues, actual problems and potential problems in order to establish where the system's risk or pain points may be. This research aims to analyze the field test report by analyzing the progress made by developer to verify the need of research, analyzing to find potential use case for further study to propose the solution to unsolved problem.

2.1 Field Test and Field Test Report

To encourage innovation and promote road safety, a vast set of standardized rules and regulations has been put in place at various places to allow for autonomous vehicle testing on the road to be carried out safely. The Autonomous Vehicles branch of the California Department of Motor Vehicles (DMV) established regulations governing autonomous vehicle (level 3 to level 5) testing and deployment on California roads, where some of the state's most innovative technology companies and startups have established headquarters. The regulations were put in place to spur innovation while also promoting road safety. 2nd March 2018, DMV posted a public notice and approved regulations allowing for the testing and deployment of autonomous vehicles (passenger car). 16th December 2019, DMV approved revised regulations allowing for the testing and deployment of autonomous motor trucks (delivery vehicles) weighing less than 10,001 pounds on California's public roads. Self-driving vehicle manufacturers that are participating in the program and performing safety tests in the autonomous vehicle tester (AVT) are required to submit annual reports on how often their vehicles disengaged from autonomous mode while being tested (whether due to technical failure or situations that required the test driver or operator to take manual control of the vehicle to operate safely) and on any accidents they have encountered [13].

In this research, the field test report is consisted of the 2020 Autonomous Mileage Reports and 2020 Autonomous Vehicle Disengagement Reports from DMV.

2.2 Progress in Autonomous Vehicle Development

From autonomous vehicle tests conducted on California's public road, the result in 2020 showed that 25 companies registered 650 autonomous vehicles. In total, 497 vehicles were tested and run on actual road. With 1,955,202 mileages combined, the vehicles disengaged from autonomous mode during tests due to technology failure or situations requiring the test driver or operator to take manual control of the vehicle to operate safely 3,695 times (Table 2-1)[14]. Among participants, 3 companies registered with one test vehicle, which is capable of operating without a driver. However, operator was inside the vehicles to be able to stop or intervene when needed for safety reason.

The table of autonomous vehicle testing results in 2020 (Table 2-1) was analyzed and constructed from the actual raw data of the 2020 Autonomous Mileage Reports from DMV, which consists of the information of manufacturers, test vehicle permit numbers, test vehicle identification number (VIN), annual total of disengagement, monthly testing mileage and annual total mileage, in order to explain the progress of autonomous vehicle development in 2020. Miles/Disengagement and Average Mileage/Test were defined as figures of merit. A map of the progress of autonomous vehicle development is depicted in the graphic below, and it was discovered that four companies had a significant lead over the remaining participants/developers (Figure 2-1). Nevertheless, given the reliability mileage target that is prevalent in the automobile development, it is unlikely that autonomous vehicle development will be completed any time soon, and this will persist as a major challenge to find a solution for disengagement events, use cases elicited from the test result and all possible use cases [15].

Table 2-1 Autonomous Vehicle Testing Result 2020

Company	Tested Vehicle Quantity (Mileage > 0) [a]	2020 Annual Total Mileage [b]	2020 Annual Total of Disengagements [c]	Miles/ Disengagement [b/c]	Average Mileage/ Test Vehicle [b/a]
AImotive Inc.	3	2,987	113	26	996
Apple Inc.	29	18,805	130	145	648
Aurora Innovation, Inc.	12	12,201	37	330	1,017
AutoX Technologies, Inc.	**6**	**40,734**	**2**	**20,367**	**6,789**
BMW of North America *1	1	122	3	41	122
CRUISE LLC	**137**	**770,049**	**27**	**28,520**	**5,621**
DiDi Research America LLC	12	10,401	2	5,201	867
EasyMile	1	424	128	3	424
Gatik AI Inc.	1	2,352	11	214	2,352
Lyft	19	32,731	123	266	1,723
Mercedes Benz R&D North America, Inc.	10	29,984	1,167	26	2,998
Nissan North America, Inc.	2	395	4	99	197
Nuro, Inc.	20	55,370	11	5,034	2,768
NVIDIA	7	3,033	125	24	433
PONY.AI, Inc.	**24**	**225,496**	**21**	**10,738**	**9,396**
QUALCOMM Technologies, Inc.	3	1,727	90	19	576
Ridecell Inc.	1	148	189	1	148
SF Motors, Inc.	2	875	61	14	437
Telenav, Inc. *1	1	4	2	2	4
Toyota Research Institute	7	2,875	1,215	2	411
Udelv, Inc. *1	1	66	49	1	66
Valeo North America Inc.	1	49	99	0	49
Waymo LLC	**145**	**628,839**	**21**	**29,945**	**4,337**
WeRide Corp.	7	13,014	2	6,507	1,859
Zoox, Inc.	45	102,521	63	1,627	2,278

*1 Test Vehicle is capable of operating without a driver.

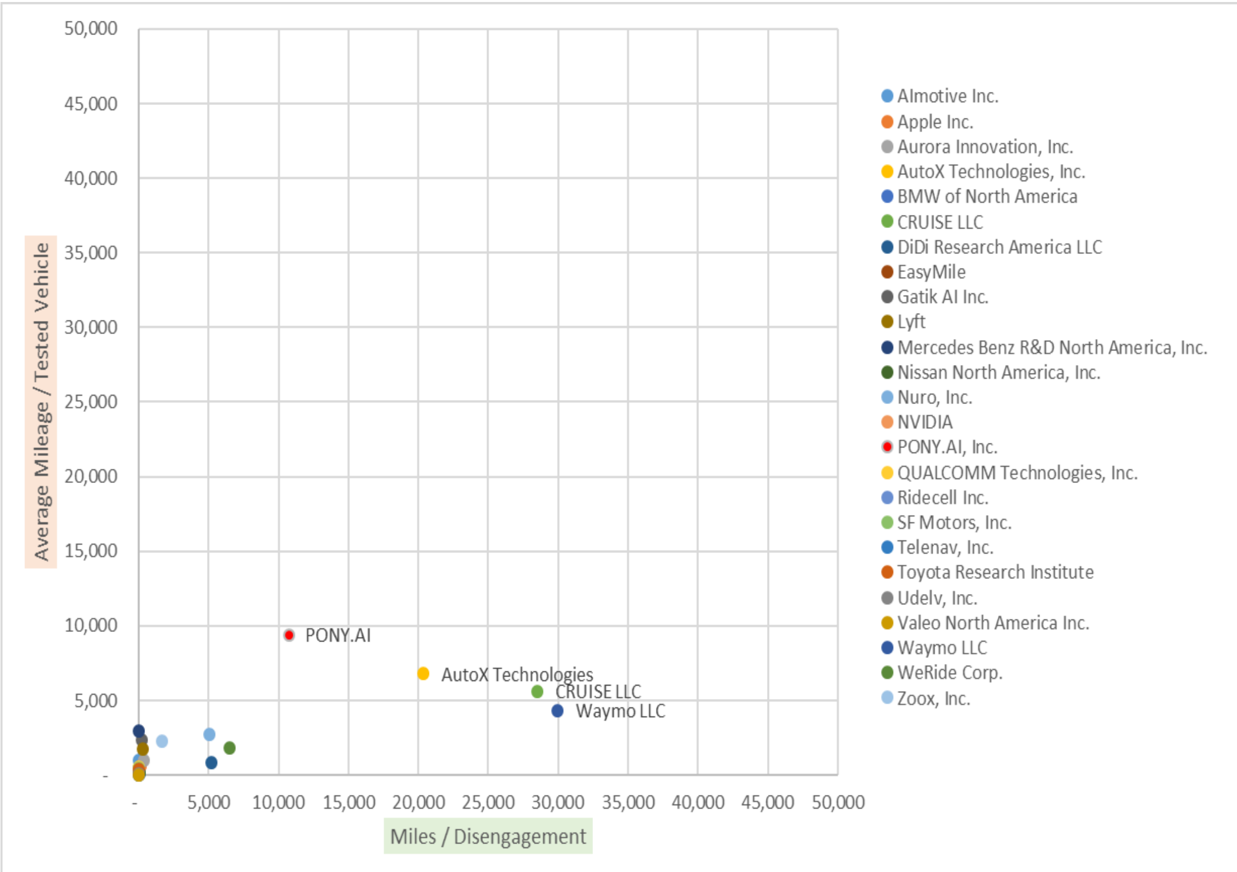

Figure 2-1 Autonomous Vehicle Development Progress until January 2021

2.3 Disengagement Cases

Disengagement is the behavior that the vehicle disengaged from autonomous mode during tests due to technology failure or situations requiring the test driver or operator to take manual control of the vehicle to operate safely. The disengagement can be initiated by ADS, driver, tester, safety officer or passenger inside the vehicle.

By categorizing autonomous vehicle manufacturers, locations of testing and disengagement initiation responsible for understanding the fact and all engagement situations from actual field tests in 2020, the table of description of facts causing disengagement and disengagement cases (Appendix A: Disengagement Cases in 2020) were constructed and analyzed from the actual raw data of 2020 Autonomous Vehicle Disengagement Reports from DMV, which consists of the information of manufacturer, test vehicle permit number, date of disengagement, vehicle identification number, information of vehicle that capable of operating without a driver, driver presence in the vehicle, disengagement initiation responsible (AV system, test driver, passenger, safety driver and vehicle operator), disengagement location (freeway, highway, parking, facility and street) and description of facts causing disengagement.

2.4 Disengagement Related to Communication Problems

From the table of description of facts causing disengagement and disengagement cases (Appendix A: Disengagement Cases in 2020), disengagement categories were reviewed and analyzed based on architectural composition of a typical autonomous vehicle system (Figure 1-5)(Figure 1-6), which was organized into three categories, Sensing & Data Input, Computation & Decision Making and Act & Control the Vehicle, as well as other disengagement categories (General Error and Driver Intervene & Safety Precaution) (Table 2-2) (Figure 2-2).

Table 2-2 Disengagement Category Cases

Disengagement Category	Cases	Cases Related to Communication
Sensing & Data Input	545	111
Computation & Decision Making	1,481	-
Act & Control the Vehicle	1,064	-
General Error	65	-
Driver Intervene & Safety Precaution	540	366

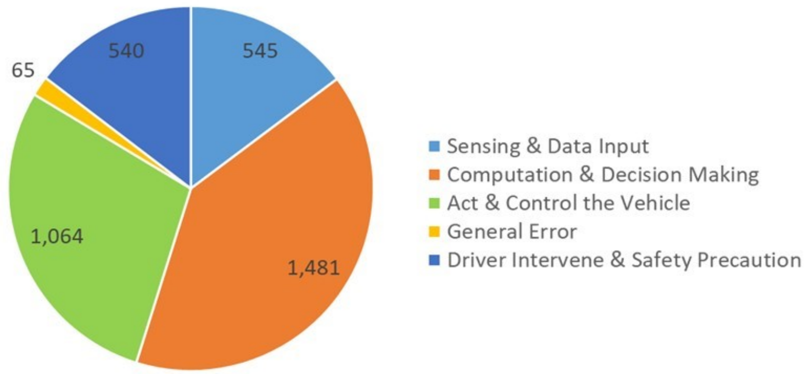

Figure 2-2 Disengagement category cases

Following The block definition diagram of typical Automated Driving System (Figure 1-5) and the internal block diagram of typical Automated Driving System (Figure 1-6), Disengagement related to Communication was realized (366 cases in Driver Intervene & Safety Precaution and 111 cases in Sensing & Data Input) (Figure 2-3). In conclusion, analysis of total 3,695 disengagement cases can identified 82 potential use cases for Model-based Systems Engineering activity and Architecture Definition (Appendix B: Disengagement Related to Communication).

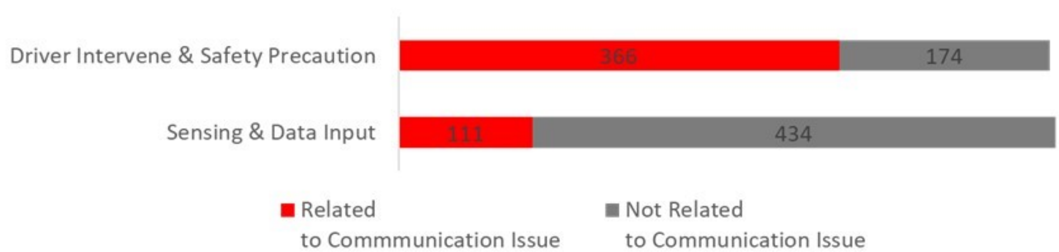

Figure 2-3 Disengagement related to communication

2.5 Use Case Selection

From defined potential use cases, use case No.48 “AV turning right. Construction warning signs on the side of the turn not detected by AV. Driver takes over to avoid AV getting close to the construction zone.” (Appendix B) which contains 25 instances of disengagement during the testing of automated vehicle on a public road in the state of California, was selected for an Architecture Definition study using Model-Based Systems Engineering from among the defined potential use cases due to potential scalable in future study, potential highest degree of communication, highest complexity among use cases, dynamic change of situation, different local rules and most importantly no solution has been released yet.

Considering the methods of transmitting information about ongoing construction or special events occurring in the path of an autonomous vehicle, depending on the circumstances, this use case has the potential to transmit information to drivers or autonomous vehicles using the highest degree of communication method available. Furthermore, the occurring event has a dynamic shift in state that changes depending on the situation day by day, which is difficult to solve with specific solution. It also contains diverse methods of transmitting information in different areas or countries, which are governed by their rules, laws, and regulations, as well as, distinct types of information and different languages or symbols (Figure 2-4). In some countries, the contractor also needs to dispatch an officer or worker to communicate with approaching vehicle. For example, in Japan, the contractor must dispatch a signalman who is responsible for using specified signals and communicating signals in a clear and understandable manner. The signalman must be stationed close to work areas in order to ensure that the work is carried out in a safe and secure manner [16]. In some construction areas, the using of temporary traffic control robot or mechanical human dummy waving pole, flag or light was observed (Figure 2-5). Temporary traffic control devices are complex and differences in various countries or areas. Hence, It is important to consider these complexity and challenges in design and development in order to achieve the goal of communication in automotive domain.

Figure 2-4 Example of temporary traffic control signs in Thailand

Source: Creative Commons, © CEphoto, Uwe Aranas
https://commons.wikimedia.org/wiki/File:Thailand_Traffic-signs_Working-sites-02.jpg

Figure 2-5 Example of temporary traffic control robot in Japan

Source: Creative Commons

The use of temporary traffic control devices and construction signs is vitally important during construction to ensure the safe and efficient passage of people and goods through the work zone and to prevent accidents. The use of temporary traffic control devices on construction sites serves to improve communication between people and vehicles, avoid accidents and traffic congestion, and provide the safety of drivers, construction workers and activities on the construction site. Despite the fact that the United States Department of Transportation (DOT) and the California Department of Transportation (Caltrans) have established a standard for sign information that includes specified patterns, dimensions, wordings, and colors, the specifics of the sign can be changed or updated as necessary [17]. The additional signs can be incorporated into the standard as well. To be able to perceive all of the warning signs, an automated driving vehicle must also react to changes in the environment as soon as they are noticed.

By construction manual of California Department of Transportation, temporary traffic control signs (Figure 2-6) and devices are consisted of several standardized devices such as Traffic Cones, Plastic Traffic Drums which should use the same type and brand of retrorefective sheeting, Channelizers, which is predominantly orange, Barricades, Telescoping Flag Trees, Temporary Railing, Object Markers, Temporary Traffic Screens, Temporary Crash Cushion Module, Impact Attenuator Vehicles, Flashing Arrow Signs, Portable Flashing Beacons, Portable Changeable Message Signs, Construction Area Signs, which required the contractor to keep signs clean and clearly visible, and repair them if damaged, and etc. More detailed information can be referred to the construction manual from the United States Department of Transportation, which contains all of the necessary information and minimum specifications [17].

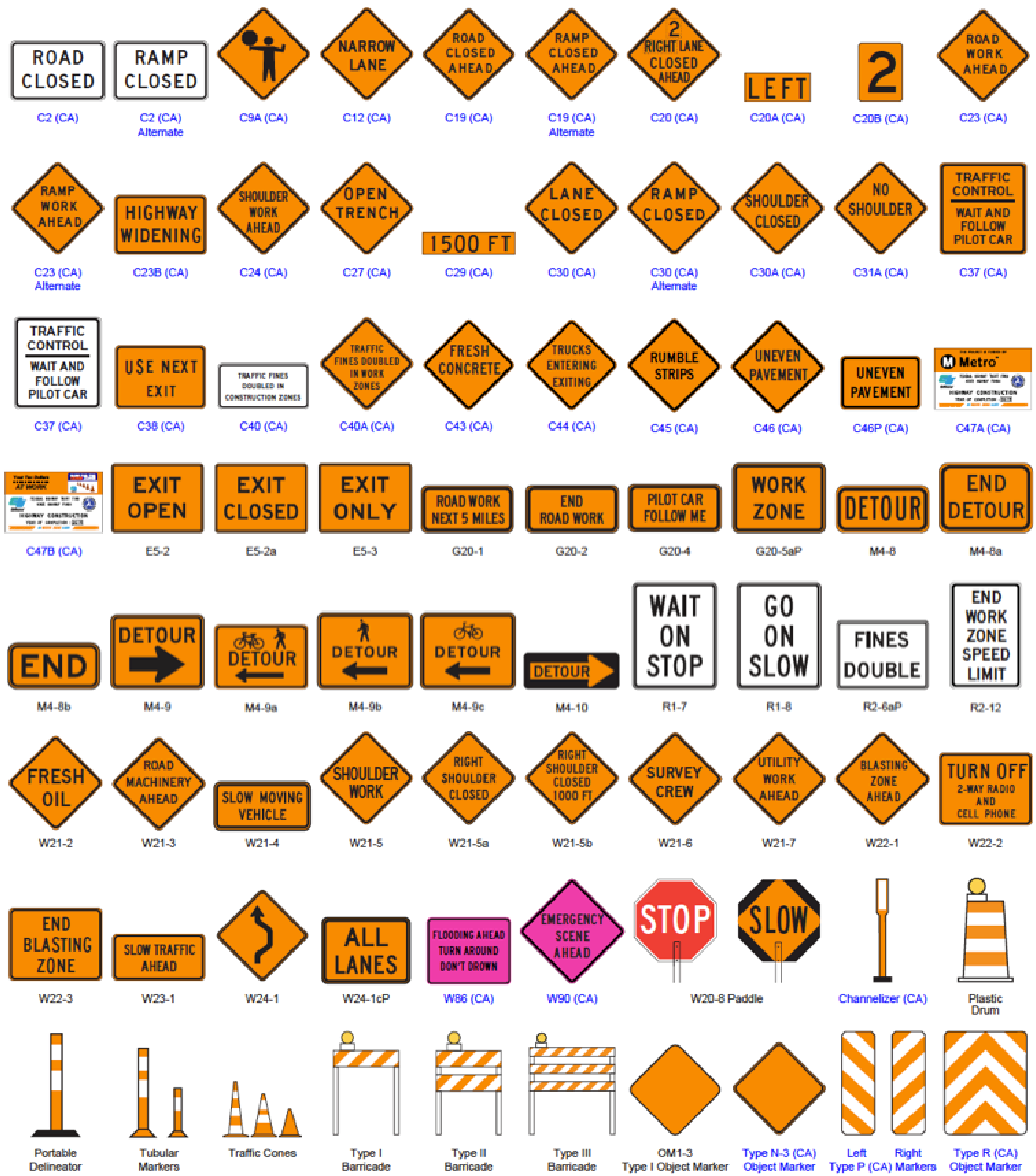

Figure 2-6 Example of temporary traffic control signs in California

Source: California Department of Transportation

According to the described use case No.48, during the testing on public road, the automated driving system was disengaged from autonomous mode, which allowed the tester to take control of the vehicle in order to prevent the automated vehicle from straying too close to the construction zone, which was a safety concern. When approaching a construction zone, an automated driving system for testing an automated vehicle on a real road is presented with an unsolved challenge, which is to detect and recognize standardized temporary traffic control signs. It will continue to be a problem in future development to recognize all events occurring in close proximity to the vehicle path. Furthermore, due to the fact that there are so many different rules, laws, and regulations in different areas and countries, as well as unstandardized temporary traffic control patterns, it will present a variety of challenges to developers who are working on improving the sensing system in automated driving systems in order to ensure that the communication purpose is achieved while also providing safety to passenger and automotive domain.

By using systems engineering method and model-based systems engineering, the conceptual model that defines the structure, behavior, and activity from use case No.48 was studied in order to provide a solution idea for the problem that caused the disengagement event in the field test of an automated vehicle in the state of California, as well as for any other similar problems that the developer may encounter in the future from diverse methods of traffic control and its communication in different areas and countries. In order to improve automated driving systems and autonomous vehicles while also increasing safety, the findings can also serve as a baseline for further research, such as integration and implementation of sensing system and control system for complex communication in automotive domain.

3. Architecture of ADS Based on Communication Problems Elicited from a Field Test Report

Based on the study and selection of use case in Chapter 2, this chapter describes the use case diagram, the activities of ADS while performing actions following selected use case, the proposal of architecture definition of ADS and solution ideas from the findings of study.

The activities of system architecture and design in automotive development allow for the development of a global solution based on logically compatible principles, concepts, and attributes, which necessitated alignment among essential stakeholders. Architecture and design are two distinct tasks that are carried out at different stages of development. In contrast to the traditional approach, which focuses solely on component design, development and integration, system architecture is more abstract, conceptual, high-level, and global, with the goal of realizing the system's mission and operation concept. Using different viewpoints and models, the architecture definition process is used to develop and establish alternative architectures, evaluate their properties, and select appropriate system configuration [26][27]. In this research, the architecture definition is proposed to explain the solution concept for defined use case described in Chapter 2(Table 3-1).

Table 3-1 Diagrams Used in Architecture Definition

Figure	Diagram Kind	Diagram Name
Figure **3-1**	Requirement diagram	Requirement diagram for *Automated Driving System Specification*
Figure **3-2**	Block definition diagram	Block definition diagram of the *Automotive Domain*
Figure **3-3**	Use case diagram	Use case diagram of use case no.48 from the analysis of DMV test report
Figure **3-4**	Sequence diagram	Sequence diagram of *Act and Control the vehicle*
Figure **3-5**	Activity diagram	Activity diagram of *Act and Control the vehicle*
Figure **3-6**	Requirement diagram	Block definition diagram of *Automated Driving System*

3.1 Requirement diagram for ADS

Figure 3-1 depicts the Automated Driving Specification requirement diagram, which shows the fundamental requirements of the system. Sensing & Data Input, Computation & Decision Making, Act & Control the Vehicle, Integration, Development Cost, Production Cost, Security, Reliability, Safety, Energy Efficiency, and Regulations requirements are all represented in the diagram. Infrastructure, Pedestrians, Vehicles, and External Entities requirements are all part of the Sensing & Data Input requirement. Steering, Accelerating, Braking, and Signaling are all included under the Act & Control the Vehicle section.

Beyond the functional requirements for Sensing & Data Input, Computation & Decision Making and Act & Control the Vehicle in the Automated Driving System Specification, Integration requirements should be considered, such as the ability to integrate the system into the vehicle in terms of dimension, compatibility, and so on. The Development Cost and the Production Cost should be within acceptable bounds in the development business case. Following ISO21434, Security is a requirement, which states that the system should be secured from attack and that communication networks, software, and data should be safeguarded from harm. Reliability requirement reflects system and its components reliability to perform under system lifetime and target mileage. Safety is a requirement following ISO26262, which the system must comply with the standard of functional safety features in the system to address possible hazards caused by the malfunctioning behavior of system. Energy Efficiency represents the requirement that the system should consume the energy within a certain range in order to meet the energy efficiency target. Regulation refers to the requirement that the system and complete vehicle should meet all regulations and standards in the vehicle class.

These fundamental requirements should be considered when defining architecture and designing the system and its components. It was also used as a baseline in discussing with professional in automotive industry to validate the architecture definition proposal.

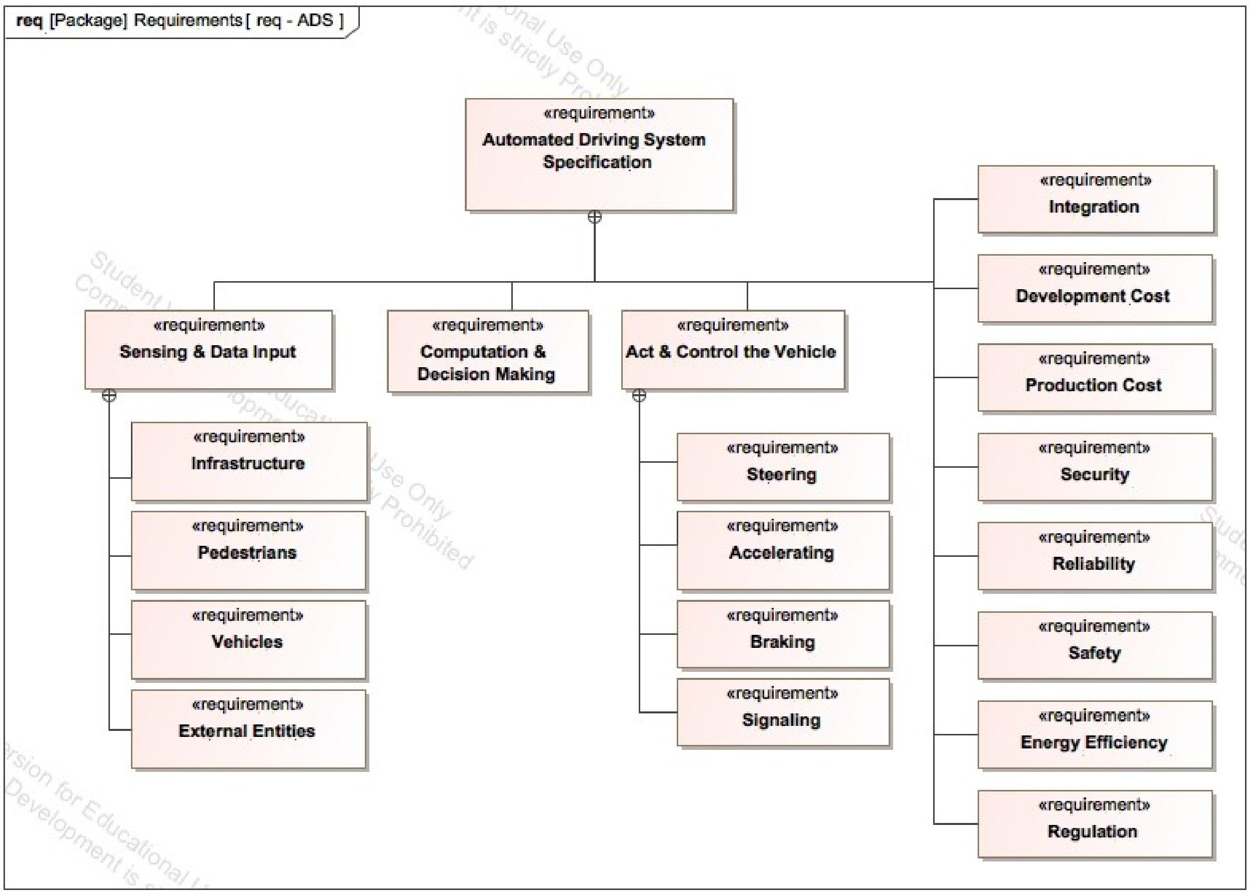

Figure 3-1 Requirement diagram for *Automated Driving System Specification*

3.2 Structure of Automotive Domain

From selected use case No.48 "AV turning right. Construction warning signs on the side of the turn not detected by AV. Driver takes over to avoid AV getting close to the construction zone.". The block definition diagram (bdd) was created to realize the structure of automotive domain, relationship and identify what is external to the system (Figure 3-2). The automotive domain is the top-level block in the block definition diagram. It is composed of several blocks, including the automated vehicle block, as well as other blocks that are external to the automated vehicle. Other blocks include the Driver, Passenger, Baggage & cargo and Physical Environment. Driver block represents tester or driver who conducts testing of automated vehicle on public road. Passenger block represents co-tester or assistant who sit in the automated driving vehicle with tester. Baggage & Cargo represents their instruments, belonging or any physical object external to automated vehicle system.

Physical Environment is composed of Infrastructure, External Entities, and Atmosphere. Infrastructure block represent road, fixed installations and other foundational structures or systems for transporting people and goods. External Entities block represents any objects on-road, other vehicles, other road users, pedestrians, construction zone, warning sign and any physical object that may locate close to the vehicle' path. From use case No.48, External Entity represents Construction Zone, Construction Zone is composed of Construction Site, Construction Sign and Construction Officer. Construction Zone represents an area where roadwork or construction works is being carried out, and which may result in lane closures, detours and moving of equipment and materials. Construction site represents a location where construction operations take place and which is located within a construction zone. Construction Sign represents construction signs, temporary traffic control devices and warning signs.

Automated vehicle block consists of Automated Driving System, Body, Chassis, Power, Steering, Acceleration, Brake and Signalling. The Automated Driving System is designated as the system of interest in this diagram. Body refers to the whole body system of a vehicle, encompassing both the interior and the exterior. Chassis is the frame or primary structural system that supports the vehicle. For the vast majority of systems, including Body, it acts as the principal mounting point for the systems. Steering refers to the steering system that directs and allows a vehicle to travel down a specific course or path. Acceleration is the system that is in charge of generating the vehicle's speed and acceleration as it travels down the road. Braking is assigned for the brake system, which is designed to slow, halt, or completely stops the motion of a vehicle. Signaling represents a signal system that sends signals to external entities with the objective of allowing those entities to better comprehend a behavior of a vehicle.

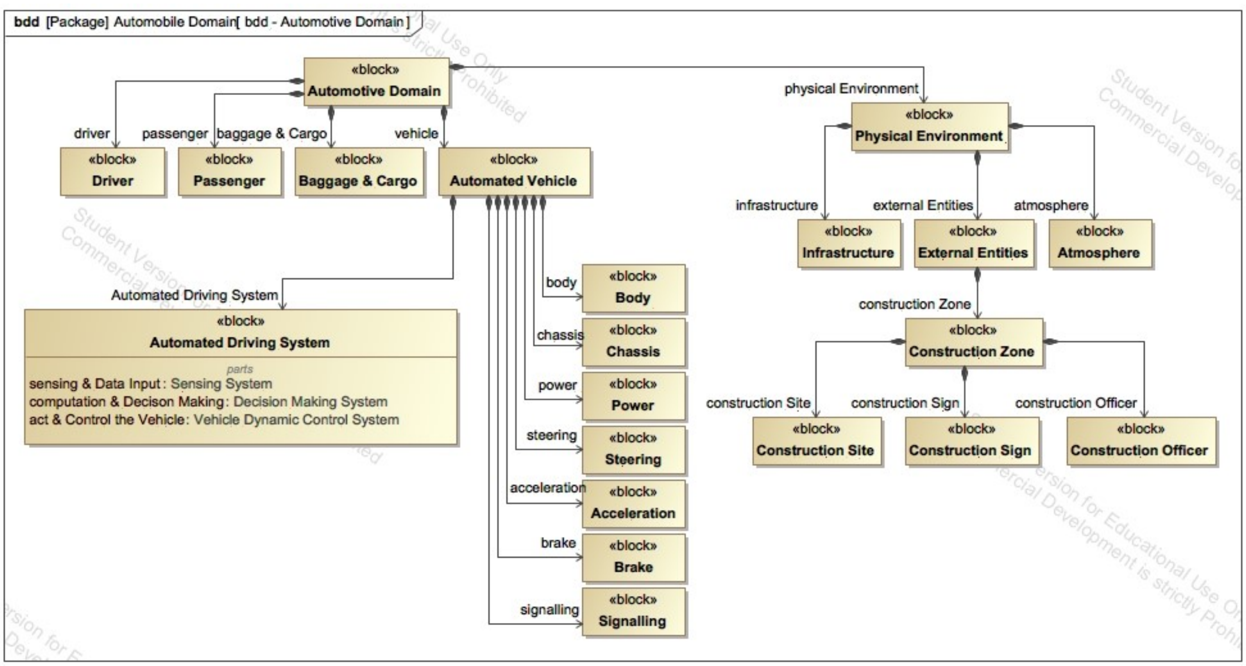

Figure 3-2 Block definition diagram of the *Automotive Domain*

3.3 Use Case

The disengagement occurrences, represented by use case No.48 “AV turning right. Construction warning signs on the side of the turn not detected by AV. Driver takes over to avoid AV getting close to the construction zone.” is presented in the use case diagram (Figure 3-3). It depicts the Automated Driving System' high-level functionality during the disengagement occurrence in order to provide a better understanding of the situation. In the use case diagram, the system of interest, Automated Driving System is portrayed as a rectangle, which represents the subject of the use case.

The Construction Zone is an actor that is external to the system of interest. Construction Zone is generalized to Construction Sign, Construction Officer and Construction Site. The actors are allocated to the blocks with the same name in Automotive Domain block definition diagram (bdd) in Figure 3-2.

The use case "Act and Control the vehicle" has been established as the base use case (Figure 3-3). It has common functionality and relationship, which includes the Compute and Make decision use case and Sense & Input data use case. The Delegate control use case (extension points) extends the Act and Control the vehicle base use case that the delegation of controlling the vehicle happens in the situation that Vehicle getting close to construction zone and unable to detect construction sign. As a result of the use cases that have been identified, the goal for architectural definition was established. It also reflects one of the objectives of the automated driving system, which is to provide safety to the automotive domain by avoiding the vehicle from getting too close to the construction zone.

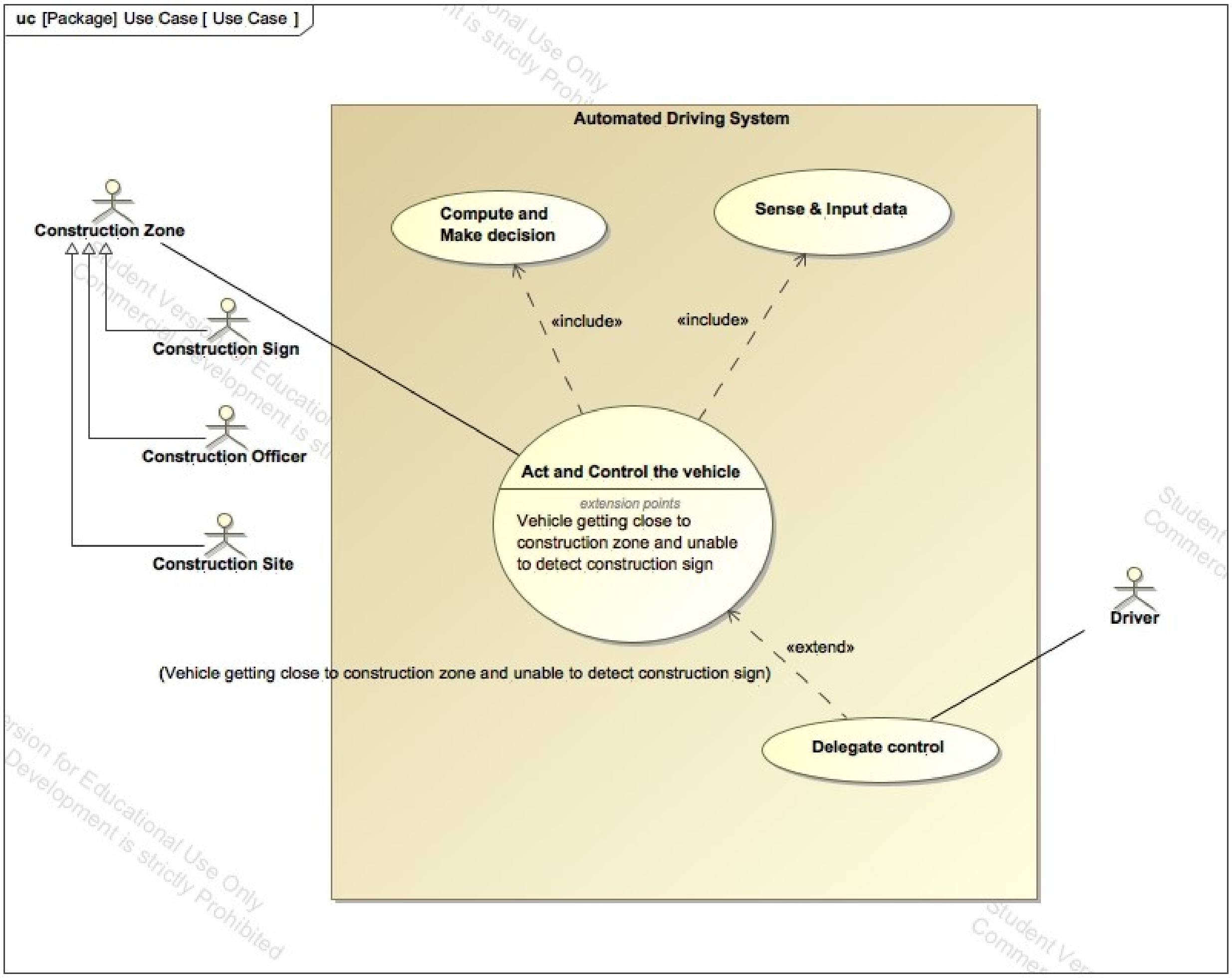

Figure 3-3 Use Case diagram of Use Case No.48 from the analysis of field test report

3.4 Activity and Actions of ADS communicates with Construction Zone

Following the Act and Control the vehicle use case in Figure 3-3, the sequence diagram is shown in Figure 3-4. The sequence diagram specifies the high-level interaction between Automotive Driving System and Construction Zone as indicated at the top of the lifelines to realize Act and Control the vehicle use case. The events in the diagram are ordered in a vertical sequence down the diagram. The first interaction is 1: Approach construction zone, which occurs when an automated vehicle controlled by Automotive Driving System approaches the construction zone. Secondly, 2: Send warning information, in which construction zone sends a warning information about on-going construction nearby or communicates warning information back to automated driving system using temporary traffic control devices or construction signs. Lastly, Automated driving system responses as 3: Response to construction zone information, which describes the activity of Act and Control the vehicle.

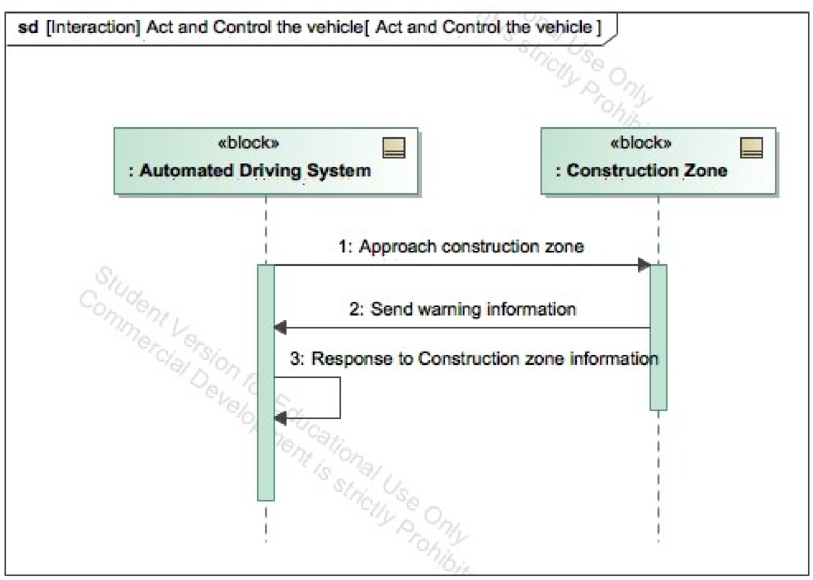

Figure 3-4 Sequence diagram of *Act and Control the vehicle*

To solve the problem, the activity diagram in Figure 3-5 was proposed and used to explain the specifics of interaction in the sequence diagram that follows the use case, Act and Control the vehicle, as shown in Figure 3-3. This activity diagram depicts the actions required by the Construction Sign and Automated Driving System, which are further subdivided into the Sensing System, the Decision Making System, and the Vehicle Dynamic Control System in order to solve disengagement problem from the use case. The activity partitions or swim lanes correspond to the Construction Sign, the Sensing System, which includes the Camera, the Sensing Control, and the Scanning in the inner swim lanes, the Decision Making System, and the Vehicle Dynamic Control System. The actions contained within the activity partitions establish the functional requirements that the systems must meet in order to function properly.

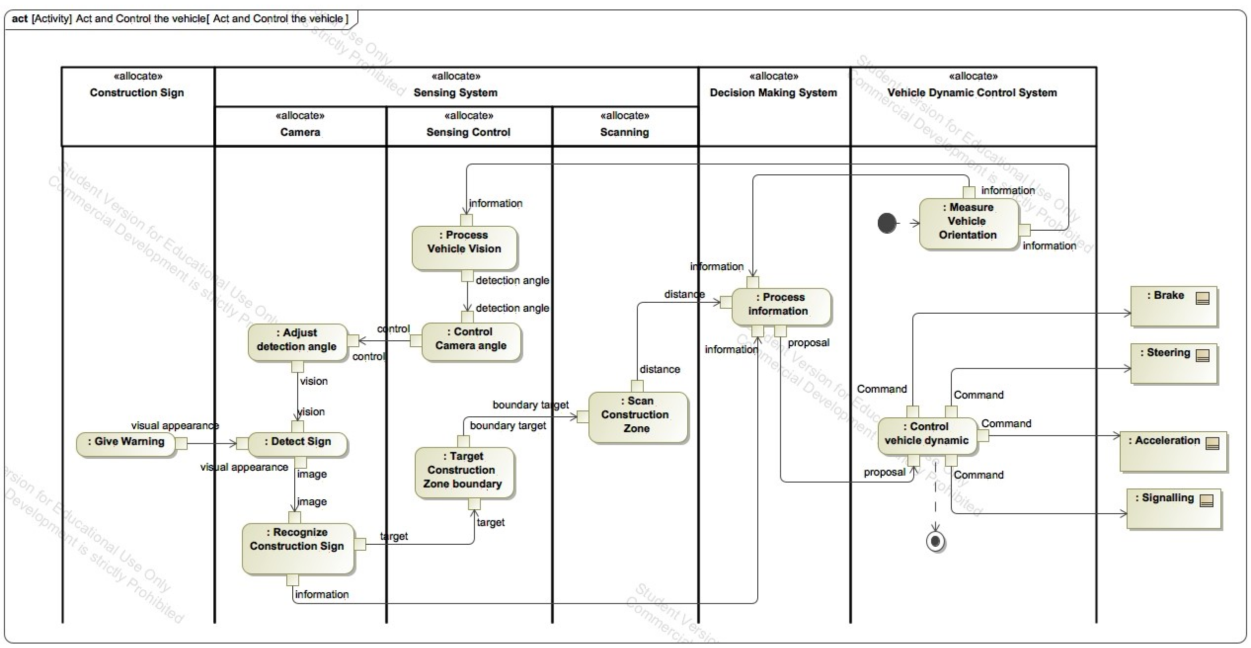

Figure 3-5 Activity diagram of *Act and Control the vehicle*

According to the proposed activity diagram, the activity begins execution at the initial node (filled black circle) when the automated vehicle approaches the construction zone or corner to enable Measure Vehicle Orientation action in the Vehicle Dynamic Control System. The vehicle's orientation information will be measured by the Vehicle Dynamic Control System and sent to the Sensing Control system and Decision Making System. The Sensing Control system will examine the output information of the vehicle orientation to determine the proper detection angle of the Sensing System in relation to the vehicle orientation and send detection angle to Control Camera angle action. Then, the Sensing Control system will send control signal to Camera system to Adjust detection angle action in order to adjust the angle of Camera and provide the appropriate vision to the system.

After vision adjustment, the Camera, Detect Sign action, will be able to detect a visual appearance from the Give Warning action of the Construction Sign. Because the system's vision is automatically adjusted based on vehicle orientation, it will be able to detect a construction sign from any angle. The picture information from the detected construction sign will be transmitted to the Recognize Construction Sign action, which will aid in the recognition of various traffic control devices and signs using advance image recognition technology. The output from recognition will be delivered to the Decision Making System directly in case the recognition result required immediate action, such as a stop sign, and to the Sensing Control system, where it will be processed to target a construction zone boundary, in the Target Construction Zone boundary action, in order to set a boundary target area to scan a construction zone. The idea of creating a boundary target for scanning the construction zone is to provide a rational perspective of the development in order to reduce the size of the environment scanning system as much as possible while the system is still capable of perceiving the target by operating on-demand. From Scan Construction Zone action, the output of distance or range between vehicle and construction zone will be given to Process Information action in Decision Making System where the system will plan and give a proposal to control the vehicle in Control vehicle dynamic action, the final activity, in vehicle Dynamic Control System, which will give a command to control Brake system, Steering system, Acceleration system and Signalling system.

3.5 Components of ADS

Following actions in activity diagram, the Automated Driving System depicted in Figure 3-6 is a block definition diagram that illustrates the breakdown of the Automated Driving System into its components. The Sensing System, the Decision Making System, and the Vehicle Dynamic Control System are the three components of the Automated Driving System. The Sensing System is decomposed into Camera, Sensing Control, Scanning, V2X and Infrastructure Input. The Vehicle Dynamic Control System is decomposed into Accelerating Control System, Braking Control System, Signalling Control System and Steering Control System. The Steering Control System has Inertial Measurement as its component that intended to have signal flow directly from Vehicle Dynamic Control System to Process Information action following the activity diagram.

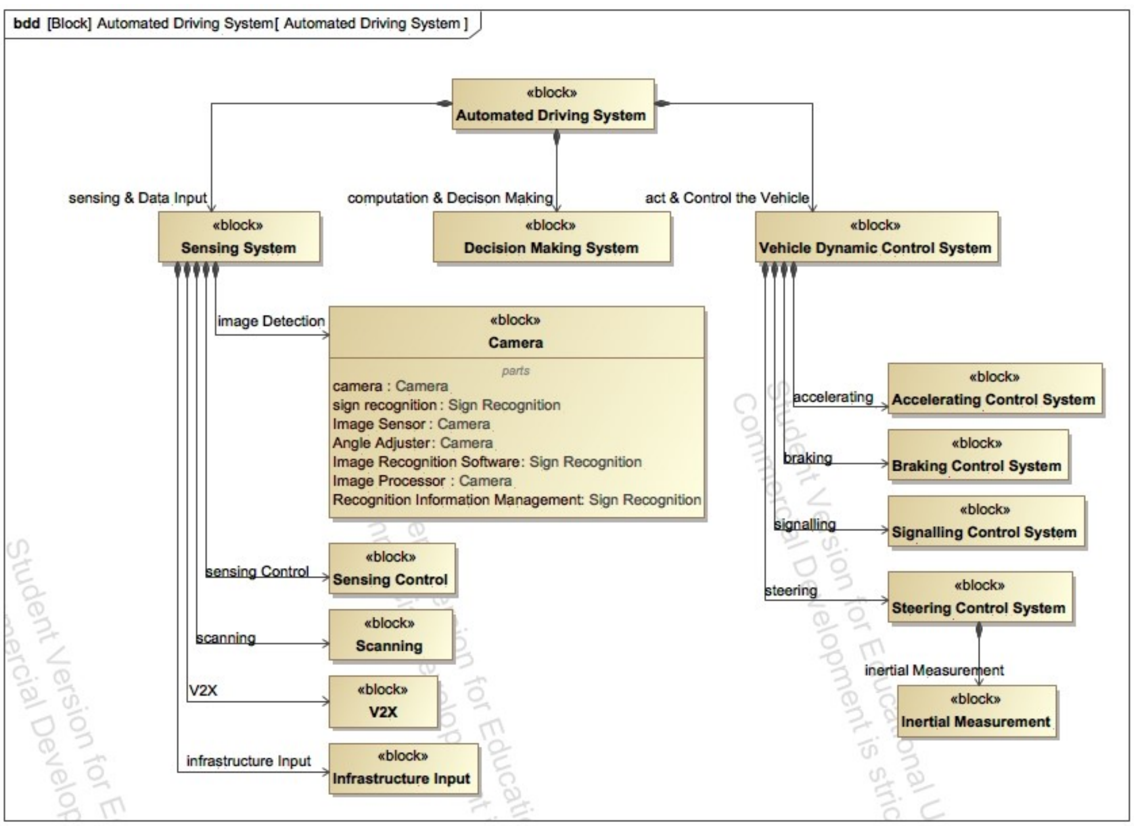

Figure 3-6 Block definition diagram of Automated Driving System

3.6 Key Findings and Solutions Concept from Architecture Definition

The important findings were taken from the proposed architecture description and activity diagram to present an idea to solve the problem from a selected use case (Table 3-2). The precise steering angle information can be measured in the Vehicle Dynamic Control System, and vehicle orientation information can be generated based on vehicle geometry. After receiving vehicle orientation information and processing a vehicle vision in the Sensing System, the Camera System can change the direction of vision or adjustable by rotating the components and adjusting the detection angle to capture objects in blind spots in order to cover the vision in all blind areas and capture all information from temporary traffic control devices such as roadside traffic control signs. With this notion, it may be possible to reduce the number of essential sensors in the vehicle. The Camera System can deliver information to the Scanning System on-demand after detecting and recognizing temporary traffic control devices, reducing the scanning system's size and scanning effort.

Table 3-2 List of Key Findings and Solution Ideas from Proposed Architecture Definition

No.	Key findings	System
1	Vehicle orientation measurement from Steering	Vehicle Dynamic Control System
2	Camera system can change direction to cover blind-spot (Adjustable Camera vision)	Sensing System, Camera System
3	Temporary Traffic Signs recognition to trigger scanning system	Sensing System, Camera System
4	On-demand scanning to reduce system size	Sensing System, Scanning System

The integration of systems and applications with existing systems and components in the vehicle is essential, based on the solution concepts given in each system. Validating the concept is vital in order to identify improvement areas and design a feasible solution that can solve the challenges posed by the specified use case.

4. Validation of Solution Concept

This chapter describes the validation of solution concept following the proposed architecture definition and solution concept in Chapter 3. The interview meeting with automotive industry professionals was held to obtain comments, make suggestions based on the essential needs, and validate the concept proposal.

4.1 Participants

For the interview, a group of professionals working on ADAS (Advanced Driver-Assistance Systems), advanced features in automated driving systems, and project manager from automotive Original Equipment Manufacturers (OEM) has been assembled (Table 4-1).

Table 4-1 List of Participants in the Concept Proposal Validation Interview

Interviewee	**Description of professional role**
Interviewee A	Engineer/Developer in Mechatronics development department who managing and developing ADAS (Advanced Driver-Assistance Systems), advanced features in ADS and general safety regulation applications
Interviewee B	Engineer/Developer in Mechatronics development department who managing and developing ADAS (Advanced Driver-Assistance Systems) and general safety regulation applications
Interviewee C	Project Manager in Product Engineering department who managing entire vehicle development projects

4.2 Interview Method

The research background, objective of the activity, motivation of proposing architecture definition, research framework, structure, how to elicit the problem and use case from field test report and use case selection were briefed to the participants. After that, problem, proposed models and diagrams of architecture definition, Use case diagram, Activity diagram and Block definition diagrams, were explained to the participants. The architecture definition and diagrams achieved its goal of providing good understanding of proposed idea and concept to the participants. After explanation, the proposal concept was discussed to get feedback and comments from participants following requirements structured from requirement diagram (Figure 3-1).

4.3 Interview Results

From the participants' point of view, the solution concept and ideas appear to be promising. According to participants, the concept is feasible, well structured and has the potential to solve the problem from defined use case and extend to cover other use cases in different countries or areas, which follow different rules and regulations. However, there are a few areas that have a concern and need be investigated further (Table 4-2).

Table 4-2 Summary of Validation Interview

Discussion Points	**Summary of comments from participants**
Function	Interviewee A: The proposed concept has potential to improve vision, recognition and communication but need to avoid the same mistakes that human made Interviewee A&B: The proposed concept has potential for city and urban application but not for highway or long-haul application
Integration	All participants: The concept is feasible for integration to the vehicle but has more complexity and may have more challenges in development
Development Cost	Interviewee A&B: Trade-off study of benefit and development cost should be carefully investigated comparing to the using of several cameras and sensors
Production Cost	Interviewee A&C: The proposed concept has potential to reduce production cost and components cost
Security	No particular concern or comment
Reliability	Interviewee B: Reliability and functional testing in local must be conducted due to different rules, requirements and traffic control method.
Functional Safety	No particular concern or comment
Energy Efficiency	Interviewee A: The proposed concept has potential to improve energy efficiency but power consumption has to be investigated further.
Regulation	All participants: The proposed concept must comply with the upcoming general safety regulation and other regulations. The change of regulations must be monitored.

According to Interviewee A, in functional requirement of sensing, The concept has the potential to improve vision of the vehicle, recognition to temporary traffic control devices, and communication, but it must avoid making the same mistakes that human drivers have made, which was the original goal of developing automated driving system: to solve the problem of human error, which results in accidents when looking in different directions. When the Camera rotated and aimed to capture temporary traffic control devices, it is necessary for the system to ensure that the rest of view can also be covered by substitute system or by other cameras, if several cameras are planned in system design phase. The detection angle should be calibrated to match the system specification, as well as vehicle dimensions and field of view.

According to Interviewee A and B, when considering the proposal's utility in a variety of situations, it is particularly advantageous when traveling in cities or urban regions, where there are more traffic intersections, which provide more targets to observe, as well as more events occurring near the vehicle path. The concept may be more appropriate for uses such as passenger cars, motorcycles, and light duty trucks than for long-haul medium or heavy-duty trucks, which are typically driven on highways.

The concept of a rotating camera and on-demand scanning, according to Interviewees A, B, and C, is practical in terms of vehicle integration. It is a new solution that has yet to be released on the market. The rotational camera from proposed concept may has a vision advantage over the fixed camera, but it is more complex, posing a greater challenge to developers and necessitating more thorough calibration of systems during vehicle integration. When comparing the use of many cameras and sensors for the same purpose, the benefit-cost trade-off for rotating the camera system and the business case should be thoroughly evaluated.

According to Interviewees A and C, if the proposed idea is successful, the concept of on-demand scanning could help lower production costs and component costs because the suggested system has the potential to be more compact than the current always-on scanning system on the market, which is large and expensive. The concept has the potential to save cost by lowering the size of the complete system. According to Interviewees A and B, the development cost and business case are disputed due to the system's complexity.

According to Interviewee B, the reliability test and functional test must be conduct locally due to different rules, requirements and traffic control method. The interviewee also gave the example of Intelligent Speed Assistance (ISA) in the EU's new General Safety Regulation for motor vehicles (GSR), which all new vehicle types will be required to comply by 2022, and all new vehicles will be required to comply by 2024 [28]. When operating on a public road or street within the European Union, the vehicle must comply with the regulation to provide speed limited assistance by detecting speed limited signs and give warning to the driver (Figure 4-1). It is necessary for developer to conduct a functional test and reliability locally to validate the system. Hence, it is necessary to do the same in developing proposed solution.

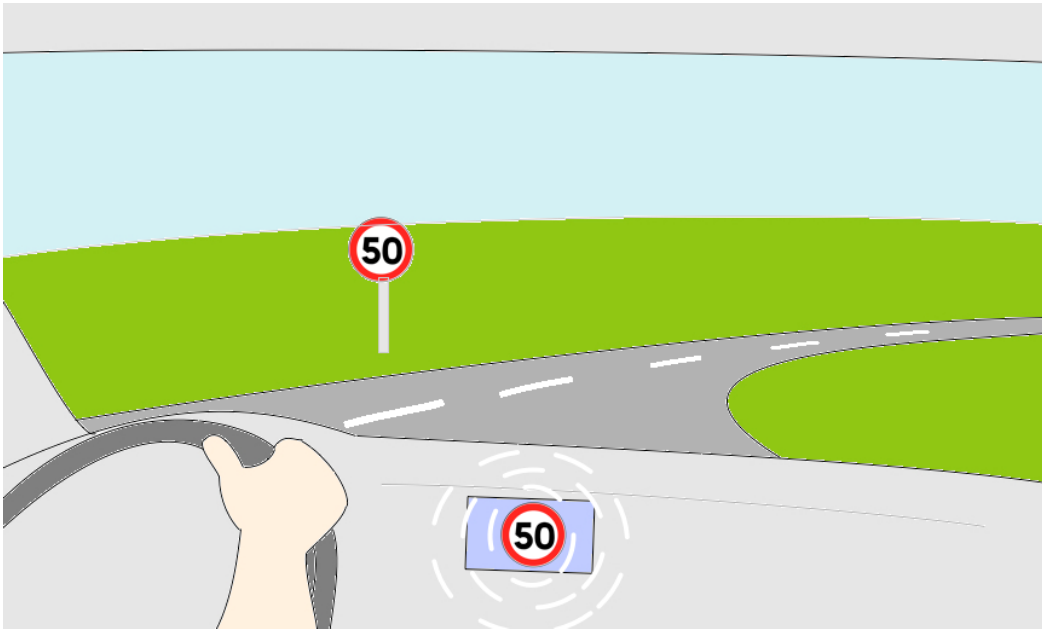

Figure 4-1 Intelligent Speed Assistance (ISA)

On-demand scanning, according to Interviewee A, may aid in enhancing the energy efficiency of the sensor system and the vehicle. Each component's and system's power usage must be explored in greater depth. All participants did not have particular concern or comment regarding security and functional safety. All of the participants agreed that the proposed concept must comply with the impending general safety regulation as well as other rules. The regulatory change must be closely observed because it will have an impact on the scope of system development. Finally, patients expressed that the concept and architectural specification have the potential to solve problems and can turn into a useful and meaningful system if further developed, expanded and enhanced.

5. Conclusion

From study of progress in autonomous vehicle development, and the review and analysis of the field test report, the 2020 autonomous mileage report and 2020 autonomous vehicle disengagement report, from DMV, the results provided a comprehensive knowledge of the progress in automated driving technology development, and showed that the development of automated driving systems remains a challenge due to unsolved disengagement events. By the review of disengagement events, various problems happened in actual field test on the public road of the state of California were examined, which can be scalable as a reference for further development in different areas and countries.

In order to solve existing problem from actual testing result, the communication problems elicited from the test report, in this case the communication between temporary traffic control devices and automated driving system, were defined as use cases for the architecture definition.

To gain a better understanding of the present development process in traditional organizations, interviews and workshops with automotive research and development specialists were undertaken. The findings verified that a systems engineering methodology and architecture definition are required when working on a high-complexity vehicle development project or an advanced system. However, in order to develop and solve challenging problems successfully with systems engineering in the organization, it is required to construct an appropriate method and process from the conceptual stage to design in the development life cycle, as well as deployment and training of systems engineering.

The architecture definition process is recommended for generating system architecture alternatives from stakeholders' concerns, captured insights, and use cases. The process of defining architecture should be iterative. The involvement of systems engineers, architects, as well as relevant designers, specialists and various perspectives from different functions in the automotive domain is required for this iterative process. According to the workshop results, it is expected that the approach of proposing architecture design can contribute to solving the unsolved problem from the identified use case of disengagement generated from the field test report.

Based on defined use case, the proposal of architecture definition and the solution concept of adjustable camera vision, temporary traffic control devices recognition and on-demand scanning were validated by the interview meeting with professionals, who developing Advanced driver-assistance systems, advanced features in automated driving systems, and project manager from automotive Original Equipment Manufacturers. The proposed concept showed potential to overcome the communication problem between automated driving system and temporary traffic control devices or construction zone. Despite the fact that several suggestions and feedback were captured, the overall outcome was positive as the concept has potential to improve. Importantly, the system should not repeat human errors or the same mistake that human did, which is the ultimate goal of developing automated driving system and autonomous vehicle. This concept can be further developed into useful and meaningful system if further developed, expanded and enhanced.

This research, as well as the result of architecture definition, can be used as a guideline for those who studying and developing an automated driving system. The proposed architecture definition can be served as a starting point for further research and in-depth investigation. It is recommended to explore more use cases and consider different scenarios in different circumstances or locations with various perspectives to solve the problem as a whole.

6. Reference

[1] Abraham, Hillary & Lee, Chaiwoo & Brady, Samantha & Fitzgerald, Craig & Mehler, Bruce & Reimer, Bryan & Coughlin, Joseph. (2017). Autonomous Vehicles and Alternatives to Driving: Trust, Preferences, and Effects of Age.

[2] Hulse, Lynn & Xie, Hui & Galea, E.R.. (2018). Perceptions of autonomous vehicles: Relationships with road users, risk, gender and age. Safety Science. 102. 1-13. 10.1016/j.ssci.2017.10.001.

[3] Shariff, Azim & Bonnefon, Jean-François & Rahwan, Iyad. (2017). Psychological roadblocks to the adoption of self-driving vehicles. Nature Human Behaviour. 1. 10.1038/s41562-017-0202-6.

[4] Pedestrian and Bicycle Information Center, Automated and Connected Vehicles, Pedestrians, and Bicycle, Bicyclists, PBIC (2017)

[5] Barabas, Istvan & Todoruţ, A & Nicolae, Cordos & Molea, Andreia. (2017). Current challenges in autonomous driving. IOP Conference Series: Materials Science and Engineering. 252. 012096. 10.1088/1757-899X/252/1/012096.

[6] Souza, Allan & Brennand, Celso & Yokoyama, Roberto & Donato, Erick & Madeira, Edmundo & Villas, Leandro. (2017). Traffic management systems: A classification, review, challenges, and future perspectives. International Journal of Distributed Sensor Networks. 13. 155014771668361. 10.1177/1550147716683612.

[7] Peden, Margaret. (2004). World Report on Road Traffic Injury Prevention.

[8] Murray, Christopher J. L, Lopez, Alan D, World Health Organization, World Bank& Harvard School of Public Health. (1996). The Global burden of disease : a comprehensive assessment of mortality and disability from diseases, injuries, and risk

factors in 1990 and projected to 2020 : summary / edited by Christopher J. L. Murray, Alan D. Lopez. World Health Organization. https://apps.who.int/iris/handle/10665/41864

[9] Winkle T. (2016) Safety Benefits of Automated Vehicles: Extended Findings from Accident Research for Development, Validation and Testing. In: Maurer M., Gerdes J., Lenz B., Winner H. (eds) Autonomous Driving. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-48847-8_17

[10] Bagloee, S.A., Tavana, M., Asadi, M. et al. Autonomous vehicles: challenges, opportunities, and future implications for transportation policies. J. Mod. Transport. 24, 284–303 (2016). https://doi.org/10.1007/s40534-016-0117-3

[11] Wevolver, 2020 Autonomous Vehicle Technology Report

[12] Rouchitsas, Alexandros & Alm, Håkan. (2020). Corrigendum: External Human–Machine Interfaces for Autonomous Vehicle-to-Pedestrian Communication: A Review of Empirical Work. Frontiers in Psychology. 11. 10.3389/fpsyg.2020.575151.

[13] DMV (Department of Motor Vehicles, State of California). https://www.dmv.ca.gov

[14] DMV (Department of Motor Vehicles, State of California). Disengagement Reports 2020

[15] Kalra, Nidhi & Paddock, Susan. (2016). Driving to safety: How many miles of driving would it take to demonstrate autonomous vehicle reliability?. Transportation Research Part A: Policy and Practice. 94. 182-193. 10.1016/j.tra.2016.09.010.

[16] Japan International Cooperation Agency (JICA), The Guidance for the Management of Safety for Construction Works in Japanese ODA Projects

[17] California Department of Transportation (Caltrans), Construction Manual

[18] Tova Rosenbloom, Yuval Wolf. Sensation seeking and detection of risky road signals: a developmental perspective, Safety Science, Accident Analysis & Prevention, Volume 34, Issue 5, September 2002, Pages 569-580

[19] Maurer, Markus & Gerdes, J. & Lenz, Barbara & Winner, Hermann. (2016). Autonomous Driving. Technical, Legal and Social Aspects. 10.1007/978-3-662-48847-8.

[20] Sergiu C. Stanciu, David W. Eby, Lisa J. Molnar, Renee M. St. Louis, & Nicole Zanier.

[21] Interpersonal Communication and Issues for Autonomous Vehicles, Report: ATLAS-2017-20

[22] I. H. Zohdy, R. K. Kamalanathsharma and H. Rakha, "Intersection management for autonomous vehicles using iCACC," 2012 15th International IEEE Conference on Intelligent Transportation Systems, 2012, pp. 1109-1114, doi: 10.1109/ITSC.2012.6338827.

[23] Liu, Zongwei & Jiang, Hao & Tan, Hong & Zhao, Fuquan. (2020). An Overview of the Latest Progress and Core Challenge of Autonomous Vehicle Technologies. MATEC Web of Conferences. 308. 06002. 10.1051/matecconf/202030806002.

[24] Basic of Autonomous Driving, Article: Intelligent Mobility Xperience

[25] 5G: a key requirement for autonomous driving—really?, Article: Kearney

[26] (2015). INCOSE Systems Engineering Handbook A Guide for System Life Cycle Processes and Activities. INCOSE Systems Engineering Handbook. https://nbn-resolving.org/urn:nbn:de:101:1-20150805943.

[27] FRIEDENTHAL, S., MOORE, A., STEINER, R., & ROGERS, M. (2015). A practical guide to sysml: the systems modeling language. Waltham, Massachusetts, Morgan Kaufmann.

[28] European Transport Safety Council

[29] JEITA 技術戦略部会 センシング技術専門委員会，自動運転と協調センシング ～都市 IoT センサの活用に向けて～，講演，2021 年 7 月.

Appendix A: Disengagement Cases in 2020

Table A1 List of Disengagement Cases of AImotive Inc.

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
AImotive Inc.	113
Freeway	113
Test Driver	113
During a lane change, the test vehicle oscillates from left to right in the lane. Conditions: Non-inclement weather, dry roads, no other factors involved	1
During a merge, the test vehicle failed to keep an appropriate distance between a merging car or the merging car failed to yield to us. Conditions: Non-inclement weather, dry roads, no other factors involved	56
During an exit/merge the test vehicle was going the "correct" speed as posted by road signs, but was going too slow or too fast given the traffic and road conditions. Conditions: Non-inclement weather, dry roads, no other factors involved	13
The test vehicle makes a lane change at an improper speed, e.g.: slow acceleration. Conditions: Non-inclement weather, dry roads, no other factors involved	14
The test vehicle's software recommended an incorrect lane change to the software operator. Conditions: Non-inclement weather, dry roads, no other factors involved	12
The test vehicle's software recommended an incorrect lane to move into during an upcoming exit on the freeway.	12

Conditions: Non-inclement weather, dry roads, no other factors involved	
This occurs when the test vehicle is making an autonomous lane change and it cuts across the lane marker into another lane. Conditions: Non-inclement weather, dry roads, no other factors involved	5

Table A2 List of Disengagement Cases of Apple Inc.

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Apple Inc.	130
Freeway	2
AV System	1
Hardware diagnostic caused software kick out	1
Test Driver	1
Safety driver discomfort due to selected motion plan	1
Highway	3
AV System	3
Motion control health check caused software kick out	3
Street	125
AV System	77
Hardware diagnostic caused software kick out	15
Hardware diagnostic detected hardware health issue	1
Incorrect prediction lead to undesirable motion plan	1
Incorrect prediction lead to undesirable motion plan	1
Motion control health check caused software kick out	43
Motion planning unable to produce valid trajectory	1
Sensor data mismatch caused software kick out	15
Test Driver	48
Hardware diagnostic caused software kick out	9
Hardware diagnostic detected hardware health issue	2
Incorrect map encoding lead to undesirable motion plan	1
Incorrect perception lead to undesirable motion plan	1
Incorrect perception of traffic signal lead to undesirable motion plan	4
Incorrect prediction lead to undesirable motion plan	9

Incorrect prediction lead to undesirable motion plan violating keep clear zone	2
Incorrect prediction lead to undesirable motion plan	7
Incorrect prediction of parked vehicle caused undesirable motion plan	1
Incorrect prediction of vehicle caused undesirable motion plan	2
Motion plan exceeded speed limit	1
Reduced visibility of a vehicle due to occlusions resulted in an undesirable motion plan	1
Safety driver performed improper robotic mode engagement	1
Sensor/Perception discrepancy resulted in incorrect predictions for motion planning	2
System issue interrupted driving algorithm	2
Undesirable motion plan violating keep clear zone	1
Undesirable motion plan violating traffic signal	2

Table A3 List of Disengagement Cases of Aurora Innovation, Inc.

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Aurora Innovation, Inc.	37
Freeway	1
Unknown ("Yes" was described)	1
Planning Discrepancy: AV reacted poorly for merging vehicle	1
Highway	1
Unknown ("Yes" was described)	1
Planning Discrepancy: Poor lane change in contested target lane	1
Street	35
Unknown ("Yes" was described)	35
Perception Discrepancy: Lost track of open door of parked vehicle	1
Planning Discrepancy: Poor lane change in contested target lane	1
Planning Discrepancy: AV reacted poorly for merging vehicle	1
Planning Discrepancy: Failure to yield to other actors	13
Planning Discrepancy: Incorrect behavior at traffic light	2
Planning Discrepancy: Incorrect behavior while following a vehicle	1
Planning Discrepancy: Poor trajectory across lanes	1
Planning Module Failure due to mapping issue	5
Planning Module Failure due to software issue	9
Unexpected or reckless behavior of other road user	1

Table A4 List of Disengagement Cases of AutoX Technologies, Inc

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
AutoX Technologies, Inc	2
Street	2
Test Driver	2
Disengagement for a perception discrepancy false positive which impacted the vehicle to react and make unwanted maneuver	1
Disengagement for unwanted maneuver of the vehicle in merging situation with consecutive aggressive cut-ins in front of the vehicle in down town San Jose.	1

Table A5 List of Disengagement Cases of BMW of North America

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
BMW of North America	3
Street	3
Passenger	2
Clear weather, good surface conditions. Disengagement was the result of a planned test of the autonomous technology. Driver assumed control in less than 1 second.	2
Test Driver	1
Clear weather, good surface conditions. Trajectory message timeout: Took too long to plan trajectory. Driver assumed control in less than 1 second of system alert. Clarification: The autonomous vehicle has a safety mechanism to alert the driver if the trajectory calculations are not completed within a margin of safety and this system notified the driver to be prepared to take over. The driver took over within 1 second and the autonomous feature was disengaged. The root cause was identified and rectified on the 1/14 to be retested successfully on the 15th Jan.	1

Table A6 List of Disengagement Cases of CRUISE LLC

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
CRUISE LLC	27
Street	27
Test Driver	27
Precautionary takeover to address controls, AV lane encroachment	1
Precautionary takeover to address controls, other road user behaving poorly	4
Precautionary takeover to address perception, AV lane encroachment	1
Precautionary takeover to address perception, other road user behaving poorly	7
Precautionary takeover to address planning, AV attempted unsuccessful lane change	1
Precautionary takeover to address planning, AV attempted unsuccessful left turn	2
Precautionary takeover to address planning, other road user behaving poorly	4
Precautionary takeover to address planning, third party lane encroachment	4
Precautionary takeover to address planning, third party lane obstruction	1
Precautionary takeover to address prediction, other road user behaving poorly	2

Table A7 List of Disengagement Cases of DiDi Research America LLC

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
DiDi Research America LLC	2
Street	2
Test Driver	2
Disengage for a late detection of a pedestrian riding a scooter.	1
Disengage for unwanted vehicle maneuver due to perception of a parked vehicles	1

Table A8 List of Disengagement Cases of EasyMile

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
EasyMile	128
Street	128
AV System - Emergency Stop	43
A collision hazard in the environment ahead was detected by the software, which triggered an Estop	20
The software detected a pedestrian in the AV's path and triggered an Estop	2
The software detected an inanimate object in the AV's path and triggered an Estop	18
The software detected another vehicle in the AV's path and triggered an Estop	2
The weather caused a Lidar impact that the software interpreted as an obstacle and caused an Estop	1
Test Driver - Soft Stop	85
The Test Driver chose to stop preemptively to let a cyclist clear from the AV's path	1
The Test Driver chose to stop preemptively to let a pedestrian clear from the AV's path	8
The Test Driver chose to stop preemptively to let another vehicle clear from the AV's path	31
The Test Driver saw an inanimate obstacle ahead and preemptively triggered a soft stop	45

Table A9 List of Disengagement Cases of Gatik AI Inc.

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Gatik AI Inc.	11
Street	11
AV System	5
Hardware discrepancy or system fault; On city road in moderate traffic with clear sky during night	1
Motion/Behavior planning discrepancy; On city road in heavy traffic with clear sky during day	1
Motion/Behavior planning discrepancy; On city road in heavy traffic with cloudy sky during dusk	1
Perception discrepancy; On city road in heavy traffic with cloudy sky during night	1
Perception discrepancy; On city road in moderate traffic with clear sky during dusk	1
Test Driver	6
Motion/Behavior planning discrepancy; On city road in heavy traffic with cloudy sky during day	1
Motion/Behavior planning discrepancy; On city road in moderate traffic with clear sky during night	1
Motion/Behavior planning discrepancy; On city road in moderate traffic with cloudy sky during dusk	1
Perception discrepancy; On city road in moderate traffic in light rain during dusk	1
Perception discrepancy; On city road in moderate traffic with cloudy sky during night	1
Reckless Agent/Road User; Prediction discrepancy; On city road in heavy traffic with cloudy sky during dusk	1

Table A10 List of Disengagement Cases of Lyft

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Lyft	123
Street	123
Test Driver	123
Disengage for a perception discrepancy for which a component of the vehicle's perception system failed to detect an object correctly	9
Disengage for a software fault due to a potential performance issue with a software component of the self-driving system (including third party software components)	2
Disengage for unwanted maneuver of the vehicle caused by a control discrepancy in delivering the planned trajectory to the vehicle's controls system	6
Disengage for unwanted maneuver of the vehicle caused by a planning discrepancy while generating an appropriate trajectory	85
Disengage for unwanted maneuver of the vehicle caused by map discrepancy	21

Table A11 List of Disengagement Cases of Mercedes Benz Research & Development North America, Inc

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Mercedes Benz Research & Development North America, Inc	1167
Freeway	45
AV System	45
A general error caused the system to stop the engaged status. Vehicle not in an active construction zone. No emergency vehicles or collisions present in the vicinity. Weather and/or road conditions dry in the area.	12
Driver performed steering maneuver because the vehicle did not drive on the expected path. Vehicle not in an active construction zone. No emergency vehicles or collisions present in the vicinity. Weather and/or road conditions dry in the area.	27
Driver pressed the accelerator pedal because the vehicle was driving slower than driver expected. Vehicle not in an active construction zone. No emergency vehicles or collisions present in the vicinity. Weather and/or road conditions dry in the area.	1
Driver pressed the brake pedal because the vehicle was driving faster than driver expected. Vehicle not in an active construction zone. No emergency vehicles or collisions present in the vicinity. Weather and/or road conditions dry in the area.	2
Invalid control unit operation. Vehicle not in an active construction zone. No emergency vehicles or collisions present in the vicinity. Weather and/or road conditions dry in the area.	1
Quality of generated trajectory did not meet the system's expectation. Vehicle not in an active construction zone. No emergency vehicles or	1

collisions present in the vicinity. Weather and/or road conditions dry in the area.	
System detects driver override due to significant one-sided road bump. Vehicle not in an active construction zone. No emergency vehicles or collisions present in the vicinity. Weather and/or road conditions dry in the area.	1
Street	1122
AV System	567
A middleware component was offline, leading to the system disengagement. The system asked the operator to take control of the vehicle.	2
An issue with environment model caused the system to disengage. The system asked the operator to take control of the vehicle.	7
An issue with localization component caused the system to disengage. The system asked the operator to take control of the vehicle.	20
An issue with motion control system caused the system to disengage. The system asked the operator to take control of the vehicle.	18
An issue with pedestrian detection caused the system to disengage. The system asked the operator to take control of the vehicle.	1
The planner was not able to generate a valid trajectory. The system asked the operator to take control of the vehicle.	2
The planner was not able to generate a valid trajectory. The system asked the operator to take control of the vehicle.	470
The system disengaged because of an error with the fusion component. The system asked the operator to take control of the vehicle.	12
The system disengaged because of an error with the maps component. The system asked the operator to take control of the vehicle.	6
The system disengaged because of an error with the maps component. The system asked the operator to take control of the vehicle.	29

Test Driver	555
An issue with motion control system caused the system to disengage. The system asked the operator to take control of the vehicle.	2
The operator disengaged the system manually to remain in the operational design domain. The driver performed a steering maneuver to correct the trajectory of the vehicle.	156
The operator disengaged the system manually to remain in the operational design domain. This was accomplished by pressing the brake pedal to reduce the velocity of the vehicle.	389
The planner was not able to generate a valid trajectory. The system asked the operator to take control of the vehicle. The operator disengaged the system manually to remain in the operational design domain. The driver performed a steering maneuver to correct the trajectory of the vehicle.	3
The planner was not able to generate a valid trajectory. The system asked the operator to take control of the vehicle. The operator disengaged the system manually to remain in the operational design domain. This was accomplished by pressing the brake pedal to reduce the velocity of the vehicle.	2
The system disengaged because of an error with the maps component. The system asked the operator to take control of the vehicle.	3

Table A12 List of Disengagement Cases of Nissan North America, INC

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Nissan North America, INC	4
Street	4
AV System	1
The AV controller unexpectedly stopped running and AV operation was disengaged. The driver safely took over control of the vehicle shortly after the disengagement.	1
Test Driver	3
Comparing map files and an offset was noticed by the safety driver as a result the safety driver disengaged and resumed manual control.	1
The AV was Breaking incorrectly. As a result the safety driver disengaged and resumed manual control.	1
When the AV was making a lane change, too much acceleration was observed despite the existence of lead vehicle on the target lane. The driver safely disengaged and resumed manual control shortly after the unexpected acceleration.	1

Table A13 List of Disengagement Cases of Nuro, Inc

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Nuro, Inc	11
Street	11
Test Driver	11
Object Perception: late perception of in-road crosswalk sign	1
Object Perception: late perception of ripped tire in planner's path	1
Object Perception: late perception of rock in planner's path	1
Object Perception: late perception of small box in planner's path	3
Object Perception: late perception of trash bag in planner's path	1
Planning Logic: following conservative yield, vehicle behind made contact. No reportable damage of property or bodily injury	1
Planning Logic: incorrect behavior prediction for vehicle at roundabout results in a planned trajectory that overlaps with the vehicle	1
Planning Logic: planner inadequately yields to lead vehicle coming to a stop	1
Planning Logic: planner inadequately yields to vehicle turning into our lane	1

Table A14 List of Disengagement Cases of NVIDIA

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
NVIDIA	125
Freeway	75
Test Driver	75
Disengage due to operating outside ODD (road condition, weather, traffic)	3
Disengage due to operator discomfort	65
Disengage due to perception mismatch	7
Highway	18
Test Driver	18
Disengage due to operator discomfort	14
Disengage due to perception mismatch	4
Street	32
Test Driver	32
Disengage due to operator discomfort	28
Disengage due to perception mismatch	4

Table A15 List of Disengagement Cases of PONY.AI, INC.

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
PONY.AI, INC.	21
Street	21
Test Driver	21
Driver precautionary intervened for a reckless cutting in vehicle	1
Mapping, driver precautionary intervened before vehicle runs to curb	1
Mapping, unable to detect oncoming vehicle due to missing road graph	1
Mapping, Driver precautionary intervened for mis-detected leading vehicle due to incorrect map information	2
Perception, driver took over to avoid hitting a gate which is accidently closed by a community safety guard	1
Planning, driver precautionary intervened for a bus drives crossing its lane boundary	1
Planning, driver precautionary intervened for a cyclist proceeding to us in high speed	1
Planning, driver precautionary intervened for a reckless left vehicle makes a right turn from a go straight lane	1
Planning, driver precautionary intervened for a reckless neighbor vehicle cuts in our lane	1
Planning, driver precautionary intervened for a vehicle cuts in ADV's lane suddenly	1
Planning, driver precautionary intervened for insufficient yielding to a vehicle going straight	6
Planning, driver precautionary intervened for reckless behind vehicle rushing to enter zigzag (Single lane to two lanes split)	2
Prediction, driver precautionary intervened for a cyclist in bike lane before ADV enters zigzag (Single lane to two lanes split)	1

Prediction, driver precautionary intervened for a vehicle lane change without looking	1

Table A16 List of Disengagement Cases of QUALCOMM TECHNOLOGIES, INC.

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
QUALCOMM TECHNOLOGIES, INC.	90
Freeway	64
Test Driver	64
Driver disengagement due to control discrepancy to maintain minimum follow distance	1
Driver disengagement due to perception discrepancy in the detection of merging vehicle	3
Driver disengagement due to planning discrepancy in the determination of autonomous vehicle speed	3
Driver disengagement due to planning discrepancy in the execution of mandatory lane change	3
Driver disengagement due to planning discrepancy in yielding to merging vehicle	2
Driver disengagement due to positioning discrepancy of the autonomous vehicle	1
Driver disengagement due to safety monitor notification of general system discrepancy	18
Driver disengagement due to safety monitor notification of planning discrepancy in the determination of vehicle trajectory	21
Driver disengagement due to safety monitor notification of planning discrepancy in the planning of lane change	3
Driver disengagement due to safety monitor notification of positioning discrepancy of autonomous vehicle	4
Driver precautionary disengagement due to aggressive cut-in by other vehicle	1

Driver precautionary disengagement due to aggressive driver passing during lane change	1
Driver precautionary disengagement due to aggressive driver passing in lane merge zone	2
Driver precautionary disengagement due to aggressive maneuver by vehicle in the adjacent lane	1
Highway	26
Test Driver	26
Driver disengagement due to control discrepancy resulting in undesired lateral movement in the lane	2
Driver disengagement due to perception discrepancy in the detection of vehicle in adjacent lane	1
Driver disengagement due to planning discrepancy in the determination of autonomous vehicle speed	4
Driver disengagement due to planning discrepancy in the execution of mandatory lane change	3
Driver disengagement due to planning discrepancy in the recommendation of lane change	3
Driver disengagement due to planning discrepancy in yielding to merging vehicle	1
Driver disengagement due to safety monitor notification of general system discrepancy	7
Driver disengagement due to safety monitor notification of planning discrepancy in the determination of vehicle trajectory	2
Driver disengagement due to safety monitor notification of positioning discrepancy of autonomous vehicle	1
Driver precautionary disengagement due to aggressive cut-in by other vehicle	2

Table A17 List of Disengagement Cases of Ridecell Inc

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Ridecell Inc	189
Street	189
Safety Driver	8
AV drives close to a parked car with an open door, on a narrow street. Safety drive makes a preventive intervention to avoid any close encounters.	1
AV fails to make a right turn on a tight corner with parked vehicles on either side and slows down. Safety Driver takes over.	1
AV gets closer to a parked vehicle on a narrow street. Driver takes over to avoid any unsafe situation.	1
AV maneuvering around a parked car on a narrow street. Driver takes over as AV gets closer to the parked car.	1
AV takes a wide turn at a stop sign intersection, resulting in the AV stepping on the opposite lane boundary. Driver takes over. Cause: Error in Lidar-vehicle calibration resulted in a high cross track error in lateral controller causing the wide turn.	1
AV takes a wide turn at an intersection of a narrow street, resulting in AV getting close to parked vehicle on right. Cause: Error in Lidar-vehicle calibration resulted in a high cross error in lateral controller causing the wide turn.	1
AV (Autonomous Vehicle) taking a left turn on a narrow street and got close to a parked car on the street. Safety Driver makes a preventive intervention to avoid AV getting too close to the parked car.	1
Parker cars on both sides of a narrow street, with another vehicle approaching from oncoming lane. AV yields to the oncoming vehicle	1

and starts coming to a stop. Driver takes over to ensure encounter is safe.	
Test Driver	181
Autonomous mode initiated in a narrow path. Motion planner commands to maneuver around a parked vehicle to the right. Instability in localization heading angle cause small oscillations in controller action. Safety driver initiates a take over to avoid any possible unsafe situation.	1
AV at a 4-way stop sign intersection with other vehicles. The current AV version takes a cautious stop-creep action at a stop sign junction, which is slower than a typical human driver. Safety driver took over to avoid any inconvenience to other vehicles.	2
AV at a busy 4-way stop sign intersection. The current AV version takes a cautious stop-creep action at a stop sign junction, which is slower than a typical human driver. Safety driver took over to avoid any inconvenience to other vehicles.	3
AV at a busy stop sign intersection. AV starts to move after the first cross vehicle turns in, however it comes to a stop when another vehicle approaches the cross stop sign. The second vehicle also turns in ahead of AV, as the AV response is slow and conservative. Safety driver intervenes once the 2nd vehicle took AV's right of way.	1
AV at a busy stop sign intersection. The current AV version takes a cautious stop-creep action at a stop sign junction, which is slower than a typical human driver. Safety driver took over to avoid any honking response from other vehicles.	2
AV at a busy stop sign intersection. The current AV version takes a cautious stop-creep action at a stop sign junction, which is slower than a typical human driver. Safety driver took over to avoid any inconvenience to other crossing vehicles at the intersection.	1
AV at a junction where AV has the right of way to move forward. Oncoming car cutting across does not come to a complete stop.	1

Prediction module appears to cause AV to stop. Safety driver does a preventive intervention to continue flow of traffic.	
AV at a stop sign intersection with one other trailing vehicle. The current AV version takes a cautious stop-creep action at a stop sign junction, which is slower & conservative than a typical human driver. Safety driver took over to avoid any inconvenience to the other vehicle	16
AV at a stop sign intersection with one other vehicle. The current AV version takes a cautious stop-creep action at a stop sign junction, which is slower & conservative than a typical human driver. Safety driver took over to avoid any inconvenience to the other vehicle	1
AV at a stop sign intersection with one other vehicle. The current AV version takes a cautious stop-creep action at a stop sign junction, which is slower & conservative than a typical human driver. Safety driver took over to avoid any inconvenience to the other vehicle. No AV system fault.	1
AV at a stop sign intersection with one other vehicle. The current AV version takes a cautious stop-creep action at a stop sign junction, which is slower than a typical human driver. Safety driver took over to avoid any inconvenience to the other vehicle	1
AV at a stop sign intersection with two other trailing vehicles. The current AV version takes a cautious stop-creep action at a stop sign junction, which is slower & conservative than a typical human driver. Safety driver took over to avoid any inconvenience to the other vehicles	1
AV at stop sign intersection with vehicles turning in to the AV lane of travel. Safety driver takes over once the AV misses its right of way.	1
AV creeps cautiously after stopping at a stop sign intersection, watching out for other crossing vehicles. Oncoming traffic on the cross street. Safety driver initiates the take over to avoid possible	2

honking response from other vehicle to the AV interaction at stop sign, which is slower & conservative than a typical driver.	
AV decides to stop for an on-coming vehicle, even though there is enough room for both vehicles in their respective lanes. Safety driver takes over so that the AV does not come to an unexpected stop on the street.	1
AV decides to stop for an on-coming vehicle, even though there is enough room for both vehicles in their respective lanes. Safety driver takes over so that the AV does not come to an unexpected stop on the street. Cause: Wrong prediction of oncoming vehicle movement.	1
AV did not detect construction ditch on side of the road. Safety driver took over as a precaution.	2
AV falsely detects a pedestrian yield sign as a pedestrian, causing the AV to come to a stop. Safety driver initiates take over to maintain smooth traffic flow.	15
AV falsely detects a pedestrian yield sign as a pedestrian, causing the AV to come to a stop. Safety driver initiates take over to maintain smooth traffic flow. No AV system fault detected.	1
AV going straight with no other vehicles in front or on coming. No parked vehicles on the side, and no other fake obstacle detected, but localization becomes inconsistent and AV starts floating in the HD map. This results in AV wanting to turn in to the curb. Safety driver takes over to avoid unsafe situation.	1
AV has just made a right turn and there is an oncoming vehicle in the opposite lane, resulting in a narrow path between parked car (on the right) and on coming vehicle (on the left) for the AV to follow. Safety driver initiated the take over, when he noticed the steering move to the left. Cause: Wrong Prediction of on-coming vehicle trajectory for a small time instant causing the vehicle to move in the wrong direction for that time instant.	1

AV localization becomes inconsistent, as observed on the in-vehicle monitor. AV starts moving from center of the lane towards the curb. Safety driver takes over to avoid unsafe situation.	1
AV making wide left turn, with on coming vehicle in opposite lane of a narrow street. Driver makes a preventive intervention to avoid any unsafe situation. Cause: Lateral controls issue causing wider than usual turn.	2
AV making wide right turn, with on coming vehicle in opposite lane of a narrow street. Driver makes a preventive intervention to avoid any unsafe situation. Cause: Lateral controls issue causing wider than usual turn.	11
AV making wide right turn, with on coming vehicle in opposite lane of the road. Driver makes a preventive intervention to avoid any unsafe situation. Cause: Lateral controls issue causing wider than usual turn.	2
AV merging into a faster lane. Safety driver decided to take over to let faster oncoming vehicles pass the AV, before AV merging into their lane.	2
AV needs to make a left turn in narrow street with parked vehicles on right side after the turn. The planner is not able to create a consistent path around parked vehicles in to the turn. It keeps switching between finding a path and requesting AV to come to complete stop, at edge of decision boundary, resulting in AV to start slowing down. Safety Driver takes over to maintain a smooth traffic flow.	1
AV not able to plan a path through a narrow street with parked cars on either side, causing it to come to a stop. Driver takes over. Cause: Localization error in position causing issues in motion planning module.	1
Av planner fails to slow down for a right turn and goes straight instead after missing the turn. Safety Driver takes over to put the vehicle back to the testing route.	2

AV started to plan around parked car with little room. Safety driver decided to take over to avoid any close encounter.	1
AV steering oscillates, when the autonomous mode is initiated off the center of lane. Safety driver takes over to avoid any unsafe situation.	1
AV stops and waits at a tight corner, as the planner fails to generate a path to maneuver the tight corner with a parked car in its way. Safety driver takes over to continue testing.	1
AV takes a wide left turn on the curve of a narrow street, resulting in AV driving close to parked vehicle on the right. Driver makes a preventive intervention to avoid any close encounters. Cause: Error in Lidar-vehicle calibration results in a higher cross track error in lateral controller causing the wide turn.	1
AV takes a wide left turn on the curve of a narrow street. Driver makes a preventive intervention to avoid any close encounters. Cause: Error in Lidar-vehicle calibration results in a higher cross track error in lateral controller causing the wide turn.	1
AV takes a wide turn at a stop sign intersection, resulting in the AV stepping on the opposite lane boundary. Driver makes a preventive intervention. Error in Lidar-vehicle calibration results in a higher cross track error in lateral controller causing the wide turn.	1
AV taking a left turn, close to a parked car on a narrow street, resulting in an initial nudge away from the parked vehicle. Driver makes a preventative intervention to avoid unsafe situation with parked car.	1
AV turning right. Construction warning signs on the side of the turn not detected by AV. Driver takes over to avoid AV getting close to the construction zone.	1
AV turning right. Construction warning signs on the side of the turn not detected by AV. Driver takes over to avoid AV getting close to the construction zone.	24
AV vehicle slowed down for an object detected in its path near a yield sign. Safety driver took over for faster moving trailing vehicles.	1

Box truck parked on right side of AV. Slight bend on the road of traversal created a limited view of oncoming lane to the AV. AV decides to nudge left, but gets too close to the on coming vehicle from the opposite side. Safety driver initiates a take over to make get through the narrow zone between Box truck and the on coming vehicle.	1
Construction cones on the side not detected. AV got close to the cones. Safety Driver takes over before AV gets any closer to the construction zone.	3
Driver makes a preventive intervention, when he sees an on-coming vehicle on a narrow street with parked cars on either sides leaving narrow gap for both vehicles to pass each other.	8
Driver makes a preventive intervention, when he sees an on-coming vehicle on a narrow street with parked cars on either sides leaving narrow gap for both vehicles to pass each other.	1
Faster following vehicle. 25 mph max speed on 40 mph street	1
Lateral oscillation detected for a couple of seconds. The safety driver decided to take over. Cause: Lateral controller sensitivity to quick path change commands or localization errors causing oscillation.	5
Narrow path in front of the AV with parked cars on both sides. Another vehicle coming in the on coming lane. AV yields to the on coming vehicle and starts coming to a stop. Safety driver initiates take over to make sure the encounter is safe.	1
Narrow street with parked vehicles on either side. Gap on either side is less than AV Planner's safety thresholds, resulting in planner stopping the vehicle. Driver takes over.	1
Narrow street with parked vehicles on either side. Gap on either side is less than AV Planner's safety thresholds, resulting in planner stopping the vehicle. Driver takes over.	3
Narrow street with parked vehicles on one side and on-coming vehicle on the other side. Gap on either side is less than AV Planner's safety	1

thresholds, resulting in planner stopping the vehicle. Driver takes over to maneuver the AV through the narrow gap.	
Narrow street with two large parked vehicles (mail van and pickup truck) on either side. Gap on either side is less than AV Planner's safety thresholds, resulting in planner stopping the vehicle. Driver takes over.	1
Parked vehicle at the corner blocking path of AV while taking a right turn. AV perception appears to prevent vehicle from moving forward. Safety driver took over to continue the flow of traffic.	1
Perception detects a vehicle where construction vehicle is parked. Possible that the detected obstacle boundary is not accurate to the actual construction vehicle, resulting in planned path that is closer to the construction vehicle. Safety driver initiates a take over to make sure AV safely navigates the parked construction zone	1
Safety driver a takes over to let a faster trailing vehicle to pass.	1
Safety driver decided to pull over to the side to let a faster trailing vehicle pass.	1
Safety driver decided to take over to let a faster trailer vehicle pass the AV	2
Safety driver decided to take over to let a faster trailer vehicle pass the AV for their convenience. No AV system fault detected.	2
Safety driver decided to take over to let a faster trailing vehicle pass the AV.	1
Safety driver decides to take over to let a faster trailing vehicle pass.	8
Safety driver initiates a take over as a faster moving trailing vehicle gets too close to the AV.	1
Safety Driver makes a preventive intervention to avoid AV getting close to a pedestrian on road.	1
Safety Driver makes a preventive intervention to avoid AV getting too close to a parked vehicle on a narrow street.	1

Safety driver makes a preventive intervention, as he car in front is making a 2-point U-turn.	1
Safety driver makes a preventive intervention, with an on-coming vehicle on a narrow road	2
Safety driver makes a preventive intervention, with an on-coming vehicle on a narrow road. No AV system fault detected.	1
Safety Driver takes over when AV doesn't move forward at a stop sign. Cause: New route is commanded to the AV is negotiating a stop sign, which caused a problem in the motion planner.	1
Safety driver takes over, while AV trying to make a left turn after a stop sign, as he notices the computing load is high resulting in bad localization and controls performance.	1
Safety driver took over to pass a slow moving construction vehicle on side of the road.	1
Small steering oscillation detected for a couple of seconds. The safety driver decides to take over. Cause: Lateral controller sensitivity to quick path change commands or localization errors causing oscillation.	11
The AV is at a stop sign and is observed to be slower than usual to start when it has right of way. Safety driver takes over to avoid cross traffic waiting long for AV to negotiate intersection. The compute seems to be glitchy at the turn making planning, controls and localization performance bad.	1
Vehicle drifting on to on coming lane, due to effective loss of one or many of either localization, compute or network transport of the localization data. Results in driver take over.	1
Vehicle starts to drift from its expected path on the lane, possibly due to effective loss of either localization or compute or network transport of the localization data. Driver takes over quickly to avoid any unsafe situation.	4

Table A18 List of Disengagement Cases of SF Motors, Inc.

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
SF Motors, Inc.	61
Highway	36
Test Driver	36
Hardware Issue: Smart camera stop working	1
Hardware Issue: Wrong GPS state	2
Localization Issue: Vehicle drove too close to the right lane	1
Localization Issue: Wrong GPS state	1
Motion & Planning Issue: Wrong trajectory at highway exit	21
Perception Issue: Smart camera lane detection offset too close to the left	2
Safety precaution: Heavy traffic	1
Safety precaution: Heavy traffic on highway entrance	3
Safety precaution: Heavy traffic to complete lane change	1
Safety precaution: vehicle merging	2
Safety precaution: Vehicle too close to the right lane	1
Street	25
Test Driver	25
Hardware Issue: Smart camera stop working	2
Localization Issue: Failed to stop within a certain distance of stop line at traffic light	5
Localization Issue: Wrong GPS state	8
Motion & Planning Issue: Planning node crashed on urban street	1
Motion & Planning Issue: Smart camera output problem from visualizer	1
Motion & Planning Issue: wrong trajectory at the curve from visualizer with a new module	2
Perception Issue: Smart camera lane detection offset too close to the left	1

Perception Issue: Vehicle too slow to start after the stop at traffic light	1
Safety precaution: DBW beeping noise	1
Safety precaution: Smart camera output problem from visualizer	3

Table A19 List of Disengagement Cases of Telenav, Inc.

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Telenav, Inc.	2
Parking facility	2
Test Driver	2
The car was performing a parking maneuver, when the driver had to take control, because the back wall was within 1.5 meter from the car rear bumper. This event was caused by the error in object detection by rear ultrasonic sensor.	1
The car was performing a parking maneuver, when the driver had to take control, because the sidewall was within 0.4 meters from the car. This event was caused by the error in object detection by ultrasonic sensor.	1

Table A20 List of Disengagement Cases of Toyota Research Institute

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Toyota Research Institute	1215
Street	1215
Test Driver	1215
Safety Driver disengaged due to cut-in issue.	26
Safety Driver disengaged due to harsh braking.	14
Safety Driver disengaged due to inappropriate braking proposal.	348
Safety Driver disengaged due to inappropriate braking, caused by perception issue.	222
Safety Driver disengaged due to inappropriate steering.	92
Safety Driver disengaged due to issue with lane change maneuver.	49
Safety Driver disengaged near crosswalk due to overly conservative vehicle behavior.	131
Safety Driver disengaged to ensure proper behavior at traffic light.	184
Safety Driver disengaged to manually drive through crosswalk.	43
Safety Driver disengaged to re-center vehicle in lane.	8
Safety Driver disengaged upon judging that vehicle was too close to other road user or obstacle.	31
Safety Driver disengaged upon judging that vehicle was too close to road boundary.	62
Safety Driver proactively disengaged upon recognizing that a planned maneuver or action did not conform to internal guidelines.	5

Table A21 List of Disengagement Cases of Udelv, Inc

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Udelv, Inc	49
Street	49
Test Driver	49
Control issue: the vehicle control and actuation system could not, or did not, accurately follow the trajectory planned by the autonomy system	2
Perception issue: sensor data (radar, Lidar, and camera), or autonomy system's interpretation of sensor data, had a shortcoming or inaccuracy that affected driving behavior	32
Planning issue: the trajectory planned by the autonomy system was flawed, in that it disrupted traffic flow, resulted in unsafe maneuvering, or did not advance vehicle toward destination	15

Table A22 List of Disengagement Cases of Valeo North America Inc.

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Valeo North America Inc.	99
Street	99
AV System	20
Car software crashed, and system needed to be rebooted, under investigation	1
Controls disengaged after requested a deceleration beyond limit	19
Test Driver	79
Car approaching stop intersection too fast, deceleration profile for longitudinal control required tuning	1
Car approaching stop intersection too fast, deceleration profile for longitudinal control required tuning	3
Car backing out into vehicle and pedestrians J-walking on opposite side of street	1
Car creeping forward during red light at intersection, confidence in red light detection was fluctuating	1
Car creeping into crosswalk when stopping for intersection, incorrect map annotation for crosswalk intersection	1
Car detected green traffic light color when red, misclassification in perception	1
Car detected red traffic light color instead of green, misclassification in perception	3
Car did not detect vehicle in front, perception saw vehicle in motion when static	1
Car did not drive once traffic light turned green, acceleration request too low for longitudinal control	1
Car did not see vehicle to right during 4-way stop, perception issue	1

Car did not slow down soon enough for detected vehicle, perception saw vehicle in motion when static	4
Car driving too slow due to stopped truck straddling lane	1
Car getting close to curb of sidewalk while driving due to oscillation in lateral control	2
Car steering into bike lane, disagreement between actual and estimated positions	2
Car stopped in middle of intersection and did not proceed after pedestrian was finished crossing crosswalk	1
Car stopped on right turn on red (did not complete turn), slow down command during turn execution	1
Car stopped too far from line at intersection, map annotation incorrect	2
Car stopped, then proceeded to make right turn on red however did not have sufficient view of oncoming traffic	1
Car stopping too close to crosswalk at intersection, map annotation incorrect	1
Car taking too long to make a lane change, perception judged space insufficient	1
Car too slow to cross stop-intersection when it was its turn due to controls logic	1
Car too slow to cross stop-intersection when it was its turn to go (at 4 way stop) due controls logic	1
Car too slow to make left turn at intersection, due to internal system speed constraint	4
Car too slow to make left turn at intersection, intersection deemed not clear although car had right of way	2
Car was going to cross 4-way stop intersection when it was not its turn, perception insufficient	1
Delivery truck parked in lane, would break rules to cross into oncoming lane to get around it	13

Detected green traffic light color when red, misclassification in perception	1
Detected red traffic light color when green, misclassification in perception	2
Industrial garbage bin obstructing lane	1
Parked vehicle sticking out in road	2
Person on scooter weaving in lane	1
Reckless driver behind car trying to undertake during right turn.	1
Reckless driver making 3-point turn backing into our lane	1
Reckless driver tailgating	1
Reckless driver tailgating us at a stop	1
Reckless driver trying to undertake on right turn at red light	2
Right turn at traffic light too slow, due to internal system speed constraint	1
Speed not reduced during right turn, curvature in map annotation not correctly defined	1
Stopped at pedestrian crossing when there was no pedestrian, yield sign misinterpreted as pedestrian	3
Stopped on right turn at red light too early before proceeding, planning needs to be modified to account for right turn visibility at intersection	1
Under steer on right turn, control tuning needs improvement	4
Vehicle backing up from parking spot into lane	1
Vehicle in adjacent lane was too close to car	1
Vehicle on left of 3-way stop intersection not detected, sensors inputs into fusion layer did not agree with high confidence that a perpendicular facing vehicle was at the intersection	1
Yellow light detected in middle of right-turn at traffic light	1

Table A23 List of Disengagement Cases of Waymo LLC

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Waymo LLC	21
Highway	4
AV System	3
Disengage for adverse weather conditions experienced during testing	3
Test Driver	1
Disengage for unwanted maneuver of the vehicle that was undesirable under the circumstances	1
Street	17
AV System	2
Disengage for unwanted maneuver of the vehicle that was undesirable under the circumstances	2
Test Driver	15
Disengage for a perception discrepancy for which a component of the vehicle's perception system failed to detect an object correctly	8
Disengage for a recklessly behaving road user	1
Disengage for incorrect behavior prediction of other traffic participants	1
Disengage for unwanted maneuver of the vehicle that was undesirable under the circumstances	5

Table A24 List of Disengagement Cases of WeRide Corp

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
WeRide Corp	2
Highway	2
Test Driver	2
Discrepancy in perception around heavy traffic.	1
Discrepancy in planning around heavy traffic.	1

Table A25 List of Disengagement Cases of Zoox, Inc

Manufacturer, **Disengagement Location,** **Disengagement Initiated by,** Disengagement Description	Cases
Zoox, Inc	63
Street	63
Test Driver	63
Perception discrepancy; incorrect system detection of passenger opening door	1
Planning discrepancy, incorrect trajectory estimating during parking maneuver	1
Planning discrepancy; during double parked vehicle avoidance maneuver, system planned incorrect trajectory	2
Planning discrepancy; during double parked vehicle avoidance maneuver, system planned incorrect trajectory	3
Planning discrepancy; during double parked vehicle avoidance maneuver, system planned incorrect trajectory into adjacent lane of traffic	1
Planning discrepancy; during left turn maneuver, system planned faulty trajectory based on position of proceeding vehicle	1
Planning discrepancy; incorrect system estimation of free space	1
Planning discrepancy; system planned incorrect trajectory around delivery vehicle	1
Planning discrepancy; system planned incorrect trajectory around parked vehicle	6
Planning discrepancy; system planned incorrect trajectory based on position of adjacent vehicle	1

Planning discrepancy; system planned incorrect trajectory based on position of proceeding vehicle	1
Planning discrepancy; system planned incorrect trajectory due to oncoming vehicle cutting into lane of traffic	2
Planning discrepancy; system planned incorrect trajectory due to proceeding vehicle exiting parked state	3
Planning discrepancy; system planned incorrect trajectory due to vehicle exiting parked state	3
Planning discrepancy; system planned incorrect trajectory of proceeding vehicle	1
Planning discrepancy; system planned incorrect trajectory through left turn in intersection	3
Planning discrepancy; system planned incorrect yield at intersection due to an oncoming vehicle during left turn maneuver.	1
Prediction discrepancy; incorrect trajectory estimation for a vehicle cutting into lane of traffic	15
Prediction discrepancy; incorrect trajectory estimation for a vehicle cutting into lane of traffic during double parked vehicle avoidance maneuver	1
Prediction discrepancy; incorrect trajectory estimation for a vehicle entering 4-way intersection early	1
Prediction discrepancy; incorrect trajectory estimation for a vehicle entering intersection	1
Prediction discrepancy; incorrect trajectory estimation for a vehicle in intersection yielding for pedestrians	1
Prediction discrepancy; incorrect trajectory estimation for vehicle making illegal U-turn in an intersection	1
Prediction discrepancy; incorrect trajectory estimation of a vehicle driving through red-light	1
Prediction discrepancy; incorrect trajectory estimation of a vehicle reversing into curbside parking	1

Prediction discrepancy; incorrect trajectory estimation of adjacent vehicle making left turn in an intersection	3
Prediction discrepancy; incorrect trajectory estimation of approaching motorcycle	1
Prediction discrepancy; incorrect trajectory estimation of approaching vehicle	1
Prediction discrepancy; incorrect trajectory estimation of proceeding vehicle making illegal left turn in an intersection	2
Prediction discrepancy; incorrect trajectory estimation of proceeding vehicle making left turn in an intersection	1
Prediction discrepancy; incorrect yield estimation for a vehicle cutting into the lane of traffic in intersection	1

Appendix B: Disengagement Cases Related to Communication

Table B1 List of Disengagement Cases Related to Driver Intervene & Safety Precaution

No.	Disengagement Description	Cases
1	AV at a junction where AV has the right of way to move forward. Oncoming car cutting across does not come to a complete stop. Prediction module appears to cause AV to stop. Safety driver does a preventive intervention to continue flow of traffic.	1
2	Car backing out into vehicle and pedestrians J-walking on opposite side of street	1
3	Delivery truck parked in lane, would break rules to cross into oncoming lane to get around it	13
4	Disengage for a recklessly behaving road user	1
5	Driver makes a preventive intervention, when he sees an on-coming vehicle on a narrow street with parked cars on either sides leaving narrow gap for both vehicles to pass each other.	9
6	Driver precautionary intervened for a reckless cutting in vehicle	1
7	Driver precautionary disengagement due to aggressive cut-in by other vehicle	3
8	Driver precautionary disengagement due to aggressive driver passing during lane change	1
9	Driver precautionary disengagement due to aggressive driver passing in lane merge zone	2
10	Driver precautionary disengagement due to aggressive maneuver by vehicle in the adjacent lane	1
11	Narrow path in front of the AV with parked cars on both sides. Another vehicle coming in the on coming lane. AV yields to the on coming vehicle and starts coming to a stop. Safety	1

	driver initiates take over to make sure the encounter is safe.	
12	Parker cars on both sides of a narrow street, with another vehicle approaching from oncoming lane. AV yields to the oncoming vehicle and starts coming to a stop. Driver takes over to ensure encounter is safe.	1
13	Planning, driver precautionary intervened for a reckless left vehicle makes a right turn from a go straight lane	1
14	Planning, driver precautionary intervened for a reckless neighbor vehicle cuts in our lane	1
15	Planning, driver precautionary intervened for reckless behind vehicle rushing to enter zigzag (Single lane to two lanes split)	2
16	Reckless Agent/Road User; Prediction discrepancy; On city road in heavy traffic with cloudy sky during dusk	1
17	Reckless driver behind car trying to undertake during right turn.	1
18	Reckless driver making 3-point turn backing into our lane	1
19	Reckless driver tailgating	1
20	Reckless driver tailgating us at a stop	1
21	Reckless driver trying to undertake on right turn at red light	2
22	Safety driver a takes over to let a faster trailing vehicle to pass.	1
23	Safety driver decided to pull over to the side to let a faster trailing vehicle pass.	1
24	Safety driver decided to take over to let a faster trailer vehicle pass the AV	2
25	Safety driver decided to take over to let a faster trailer vehicle pass the AV for their convenience. No AV system fault detected.	2
26	Safety driver decided to take over to let a faster trailing vehicle pass the AV.	1
27	Safety driver decides to take over to let a faster trailing vehicle pass.	8
28	Safety Driver disengaged due to cut-in issue.	26
29	Safety Driver disengaged to ensure proper behavior at traffic light.	184
30	Safety Driver disengaged to manually drive through crosswalk.	43
31	Safety driver initiates a take over as a faster moving trailing vehicle gets too close to the AV.	1

32	Safety Driver makes a preventive intervention to avoid AV getting close to a pedestrian on road.	1
33	Safety Driver makes a preventive intervention to avoid AV getting too close to a parked vehicle on a narrow street.	1
34	Safety driver makes a preventive intervention, as he car in front is making a 2-point U-turn.	1
35	Safety driver makes a preventive intervention, with an on-coming vehicle on a narrow road	2
36	Safety driver makes a preventive intervention, with an on-coming vehicle on a narrow road. No AV system fault detected.	1
37	Safety driver took over to pass a slow moving construction vehicle on side of the road.	1
38	Safety precaution: vehicle merging	2
39	The Test Driver chose to stop preemptively to let a cyclist clear from the AV's path	1
40	The Test Driver chose to stop preemptively to let a pedestrian clear from the AV's path	8
41	The Test Driver chose to stop preemptively to let another vehicle clear from the AV's path	31
42	Unexpected or reckless behavior of other road user	1
43	Vehicle backing up from parking spot into lane	1

Table B2 List of Disengagement Cases Related to Sensing & Data Input

No.	Disengagement Description	Cases
44	An issue with pedestrian detection caused the system to disengage. The system asked the operator to take control of the vehicle.	1
45	AV did not detect construction ditch on side of the road. Safety driver took over as a precaution.	2
46	AV falsely detects a pedestrian yield sign as a pedestrian, causing the AV to come to a stop. Safety driver initiates take over to maintain smooth traffic flow.	15
47	AV falsely detects a pedestrian yield sign as a pedestrian, causing the AV to come to a stop. Safety driver initiates take over to maintain smooth traffic flow. No AV system fault detected.	1
48	AV turning right. Construction warning signs on the side of the turn not detected by AV. Driver takes over to avoid AV getting close to the construction zone.	25
49	Box truck parked on right side of AV. Slight bend on the road of traversal created a limited view of oncoming lane to the AV. AV decides to nudge left, but gets too close to the on coming vehicle from the opposite side. Safety driver initiates a take over to make get through the narrow zone between Box truck and the on coming vehicle.	1
50	Car creeping forward during red light at intersection, confidence in red light detection was fluctuating	1
51	Car creeping into crosswalk when stopping for intersection, incorrect map annotation for crosswalk intersection	1
52	Car detected green traffic light color when red, misclassification in perception	1
53	Car detected red traffic light color instead of green, misclassification in perception	3
54	Car did not detect vehicle in front, perception saw vehicle in motion when static	1
55	Car did not see vehicle to right during 4-way stop, perception issue	1

56	Car too slow to make left turn at intersection, intersection deemed not clear although car had right of way	2
57	Car was going to cross 4-way stop intersection when it was not its turn, perception insufficient	1
58	Detected green traffic light color when red, misclassification in perception	1
59	Detected red traffic light color when green, misclassification in perception	2
60	Disengage due to perception mismatch	15
61	Disengage for a late detection of a pedestrian riding a scooter.	1
62	Disengage for unwanted vehicle maneuver due to perception of a parked vehicles	1
63	Driver disengagement due to perception discrepancy in the detection of merging vehicle	3
64	Driver disengagement due to perception discrepancy in the detection of vehicle in adjacent lane	1
65	Incorrect perception lead to undesirable motion plan	1
66	Incorrect perception of traffic signal lead to undesirable motion plan	4
67	Mapping, unable to detect oncoming vehicle due to missing road graph	1
68	Object Perception: late perception of in-road crosswalk sign	1
69	Perception detects a vehicle where construction vehicle is parked. Possible that the detected obstacle boundary is not accurate to the actual construction vehicle, resulting in planned path that is closer to the construction vehicle. Safety driver initiates a take over to make sure AV safely navigates the parked construction zone	1
70	Perception Discrepancy: Lost track of open door of parked vehicle	1
71	Perception discrepancy; incorrect system detection of passenger opening door	1
72	Perception, driver took over to avoid hitting a gate which is accidently closed by a community safety guard	1
73	Person on scooter weaving in lane	1
74	Precautionary takeover to address perception, AV lane encroachment	1
75	Precautionary takeover to address perception, other road user behaving	7

	poorly	
76	Reduced visibility of a vehicle due to occlusions resulted in an undesirable motion plan	1
77	Stopped at pedestrian crossing when there was no pedestrian, yield sign misinterpreted as pedestrian	3
78	The software detected a pedestrian in the AV's path and triggered an Estop	2
79	The software detected another vehicle in the AV's path and triggered an Estop	2
80	Vehicle in adjacent lane was too close to car	1
81	Vehicle on left of 3-way stop intersection not detected, sensors inputs into fusion layer did not agree with high confidence that a perpendicular facing vehicle was at the intersection	1
82	Yellow light detected in middle of right-turn at traffic light	1