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Master’s Dissertation 2021

Proposal of Safety Zone for Automated Driving Vehicle to Reduce Traffic Accidents

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SUMMARY OF MASTER'S DISSERTATION

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Title

Proposal of Safety Zone for Automated Driving Vehicle to Reduce Traffic Accidents

Abstract

In recent years, a huge amount of people died or were injured in traffic accidents, which is considered as a serious social problem in many countries. Half of these traffic accidents are caused by human errors. To avoid traffic accidents caused by human errors, Automated Driving System is considered as an efficient method. For both human-driving vehicles and Automated Driving Vehicle, one of the most important points of safe driving is keeping enough distance from the surrounding vehicles. Based on this background, this research is intended to propose the definition of the safety zone for ADV to reduce traffic accidents.

In this paper, the definition related to ADS is introduced including the calculation method of safety distance, the standards of automation level, and definition and advantage of V2X Communication. The definition of the dangerous degree is proposed as an influencing factor of the safety zone which has not been considered in the previous studies. Based on the evaluation of dangerous degree, the calculation method of the safety zone is described. The architecture of the ADS considering safety zone based on the evaluation of dangerous degree is described utilizing System Modeling Language.

Based on the aforementioned architecture, the ADS that considering the safety zone is simulated utilizing the Driving Scenario Designer of MATLAB based on the designing of scenarios and driving control strategy. The simulation results show that the ego vehicle equipped with ADS considering safety zone can ensure the safety of not only the ego vehicle but also surrounding vehicles.

Key Word

Automated Driving System, Model-Based Systems Engineering, Safety Zone, System Architecture, Dangerous Degree

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1. Introduction

1.1 Research Background

There are 3,215 people are killed, 32,025 people are serous injured in traffic accidents last year in Japan, which caused huge damages for the economy and health. Japanese government has been paying attention to the safety of traffic for several years by improving people's awareness of safe driving. But the effectiveness is not obvious enough in recent years, therefore, other effective methods need to be developed to ensure the safety of transportation system.[1]

According to the analysis published by Cabinet Office of Japan, more than half of the fatal and serious injured traffic accidents are caused by human errors which contain traffic laws violation, driving operation mistakes, inattentive driving, etc. [2] Therefore, the solution of human errors during the process of driving is the key point to solve the traffic accidents problem, at the same time a huge challenge for government.

Automobile manufacturers started developing Automated Driving System (ADS) in the 1980s and have got significant progress in recent years. Considering the main function of ADS is to perceive the information of ADV's status and the surrounding environmental condition by sensors, then process the perceived information to analyze the target trajectory to decide the driving course and plan vehicle's motion for ADV. By this main function, ADS can help reduce the potential errors of operating the vehicle and making decisions that caused by human.[2]

Considering the above-mentioned three points, ADS is an efficient method to reduce traffic accidents caused by human errors and ensure the safety of the traffic participants.

While developing the ADS, social acceptance is a significant point that needs to be focus on. For the social acceptance of ADS, the result of an international survey shows that a large number of car drivers in Germany, China, the USA, and Japan questioned the safety and controllability of Automated Driving Vehicle (ADV).[4] [5] For automobile companies, an important task is to ensure the safety of ADV and surrounding road users in order to obtain the acceptance of potential consumers and the society.

In order to ensure the safety of not only the ADVs but also the human-driving vehicles, the most effective way is to keep enough distance between the ADV and surrounding objects. Many current Advanced Driver Assistance Systems (ADAS) are developed based on the idea of keeping enough distance with surrounding objects. For example, the Adaptive Cruise Control (ACC) is designed for road vehicles to maintain a safe distance from the ahead vehicle by adjusting the vehicle's speed, to assist the driving of vehicle and ensure the safety of vehicle.[6]

For safety concerns, Nissan motor corporation also provided a product called Safety Shield-360 to keep all-around collision-free based on the key point of safety distance keeping. This product is a comprehensive system of several ADASs including Automatic Emergency Braking with Pedestrian Detection, High Beam Assist, Lane Departure Warning, Blind Spot Warning, Rear Cross Traffic Alert and Rear Automatic Braking. With the combination of these 6 ADASs, Safety Shield-360 can monitor the front, behind and beside areas of the vehicle and step in to assist the driver to keep safe. [7]

Intel and Mobileye proposed a Responsibility Sensitive Safety (RSS) model to calculate the safety distance for ADV with front and rear vehicle. The proposed formula calculates the distances between the ADV and the front and rear vehicles so that the rear vehicle will not hit the front vehicle by estimating the velocity, reaction time, maximum of acceleration, and deceleration of the front and rear vehicles. [8]

The above-mentioned background can reflect the message that the research of the safety distance of ADS has an important promoting significance for the safety of transport system.

1.2 Previous Study

1.2.1 Researches of Safety Distance

There are a lot of researchers worked on the safety distance of ADV. Wu *et al.* analyze the consideration of driver's intention and driving circumstance based on fuzzy reasoning and establish a longitudinal minimum safety distance model, the results of simulations under three conditions show that the proposed model is accurate for safety distance calculation.[9]

Luo *et al.* propose a calculation model of safety distance by considering the braking process and relative velocity of vehicles, the simulation results show that the proposed model matches actual roads conditions better than the traditional model.[10]

Lin *et al.* study on the design of vehicle safety distance warning system which can measure the safety distance of the ego vehicle with the front driving vehicles and the obstacles. Then they propose a novel algorithm to evaluate the length of the safety distance is enough or not. The experiment result shows the proposed system can guarantee the safe of vehicles and can be further used into automated driving system.[11]

Intel and Mobileye found that human’s thoughts about safe driving are effective, basically can lead to safe driving under every driving scenario. Based on this, they built Responsibility Sensitive Safety, RSS. For RSS, there are five main safety rules. [8]

- Don’t hit the car in front of you
- Don’t cut in recklessly
- Right of way is given, not taken
- Be cautious in areas with limited visibility

- If you can avoid a crash without causing another one, you must

Based on these rules, they transformed human thoughts into a mathematical formula to calculate safety distance for ADV.

$$S_D = max\left\{\left[v_r t + \frac{1}{2}a_{rmax}t^2 + \frac{(v_r + ta_{rmax})^2}{2a_{rmin,brake}} - \frac{{v_f}^2}{2a_{fmax,brake}}\right], 0\right\} \tag{1-1}$$

v_r, v_f means the velocity of the rear and front vehicle

t means response time of rear vehicle

$a_{rmin,brake}$ means the minimum reasonable deceleration of the rear vehicle that is likely to be used by a human driver when he recognizes the front vehicle is braking

$a_{fmax,brake}$ means the maximum deceleration of the front vehicle

a_{rmax} means the maximum of rear vehicle's acceleration.

This formula shows a distance that can keep the rear vehicle safe (no collision with the front vehicle) at the worst situation. The worst situation means the front vehicle suddenly brakes with the maximum deceleration $a_{fmax,brake}$, at the same time, the rear vehicle accelerates at the maximum acceleration a_{rmax} during the response time t, then brakes immediately by at least the reasonable braking force that is likely to be used by a human driver in this situation which is the reasonable minimum deceleration of the rear vehicle $a_{rmin,brake}$. [12] Therefore, the safety distance between the front and rear vehicle should be the distance that the rear vehicle drives during the response time plus the braking distance of rear vehicle and minus the braking distance of the front vehicle like figure 1-1 shows.

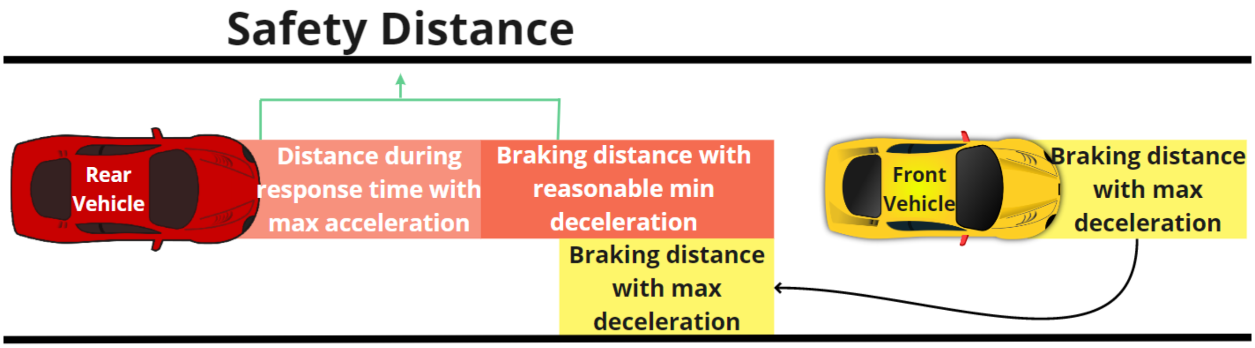


Figure 1-1 Introduction of Safety Distance

Chai et al. propose an efficiency-optimal RSS variant and evaluate both the original RSS and proposed RSS variant based on Human-in-the-loop Driving Simulation. The result shows that the original RSS model improves subjective safety judgment of human drivers. The efficiency-optimal RSS variant has a lower subjective safety score when compared to the original RSS. [13]

Orzechowski et al. evaluate RSS in city intersection simulations with Reachable Set Analysis and the results show that the RSS can guarantee absolute safety towards leading vehicles and ensuring appropriate gap and clearance times towards following vehicles of merging and crossing lanes respectively. [14]

For the above-mentioned studies of safety distance, they all only considered the longitudinal vehicles surrounding the ADV, which does not match with the real driving situations. Nevertheless, while calculating the safety distance, they only consider the vehicle's state and the driver's state. But there are more influencing factors for safety distance in the real situation. In this research, these two points are considered and introduced later in chapter 2.

1.2.2 Standards Related to ADS

In 2013, National Highway Traffic Safety Administration (NHTSA) provided a taxonomy of Operational Design Domain (ODD) for ADS. [15] It divided the automation level into 4 levels. In 2014, the American Automotive Engineers Association (SAE) standard the automation level into 5 levels based on the taxonomy of NHTSA. [16] Table 1-1 shows the similarities and differences of these two standers. Both of them are defined based on the automation level of perceiving information tasks and vehicle operation tasks. The main difference between these two standards is that in SAE's definition, level 4 is divided into level 4 and level 5 by the limitation of the driving situation. Considering the SAE's definition is more detailed, the U.S. government uses the standard of automation level developed by SAE as a federal guideline, which is also widely used by society.

Table 1-1 Analysis of Level of Automation by NHTSA and SAE Standard

Automation Level		Name	Definition	Monitor	Operator
NHTSA	SAE				
L0	L0	Human driving	The vehicle is only driven by human	Human driver	Human driver
L1	L1	Assisted driving	The vehicle provides the assistance of steer-wheel or speed while the human driver controls the rest	Human driver	Human driver
L2	L2	Partial assisted driving	The vehicle provides a certain assistance of steer-wheel and speed while the human driver controls the rest	Human driver / Vehicle	Human driver / Vehicle
L3	L3	Conditional auto-driving	The vehicle controls the majority of the driving operation while human driver still needs to pay attention to it	Human driver / Vehicle	Human driver / Vehicle
L4	L4	Highly automated driving	The vehicle controls all the driving operation while human need no attention but only for specific situation	Vehicle	Vehicle
	L5	Full automated driving	The vehicle controls all the driving operation while human need no attention	Vehicle	Vehicle

As table 1-1 shows, the automation level is divided into level 0-5 by SAE, which respectively corresponds to human driving, assisted driving, partially assisted driving, conditional auto-driving, highly automated driving, and fully automated driving.

Level 1 can assist the driver to complete some driving tasks safely, which contains, FCW (forward collision warning), [17] BSD (blind spot detection function), [18] etc. At this level, the human driver takes the responsibility of monitoring and operating the vehicle.

Level 2 can take the longitudinal driving controls and directional driving controls of the vehicle which contains ACC (Adaptive Curing Control), AEB (Autonomous Emergency Braking), [19] Automated Parking, [20] etc.

Level 3 can perform the DDT (Dynamic Driving Task) by the ADS, but the driver still has to pay attention to the environmental condition and be prepared to react to the DDT fallback request.

Level 4 can take the responsibility of perceiving information and controlling the vehicle. The driver is free from the most driving activities but only for specific situations.

Level 5 can totally realize fully automated driving. The ADS can perform the DDT completely without the situation limitation.

Currently, there are a lot of mature Advanced Driver Assistance Systems (ADAS) that are provided by the automobile manufacturers, [21] [22]but it still needs a long time to struggle from level 2 to level 3. Although Honda Moto launched the world's first level 3 ADV in April this year, but it hasn't been taken to the market yet. Some other automobile companies are aiming to launch L3 ADV in the next few years. [23] Therefore, my research towards level 3 to help the automobile manufacturers realize level 3, further way to help solve the social problem of traffic accidents.

1.2.3 V2X Communication

V2X communication is a new information communication technology that connects the vehicle with everything (V2X) in which V represents the vehicle and X represents everything that has interaction with the vehicle contains pedestrians, surrounding vehicle and the physical infrastructures by the network like figure 1-2 shows. [24][25][26] V2X is the real-time communication between the connected vehicles, and other surrounding objects and people which can enable the connection of Vehicle to Vehicle (V2V), Vehicle to Pedestrians (V2P) and Vehicle to Infrastructure (V2I). [27]

There are several use cases are listed as follow to explain how V2X works: [28]

V2I: The traffic light sends the information of impending change of light to the vehicle for adjusting the velocity.

V2P: The information of pedestrian's position and mission is been transformed to the vehicle for safety concern especially when the pedestrian is in the blind area of the vehicle.

V2V: The potential collision can be announced to alert other vehicles. For example, when the ego vehicle wants to brake, the ego vehicle will send this information to the rear vehicle to avoid the rear-end collision.

By V2X, the information that cannot be detected by the sensor can be detected by the connected vehicles which includes the drivers' state of the surrounding vehicles, the target trajectory of the surrounding vehicle, etc. With the information of both sensors and V2X communication, the accuracy of the prediction and decision-making of the ego vehicle will be highly improved. Therefore, in this research, V2X communication is considered to be included in the assumption.

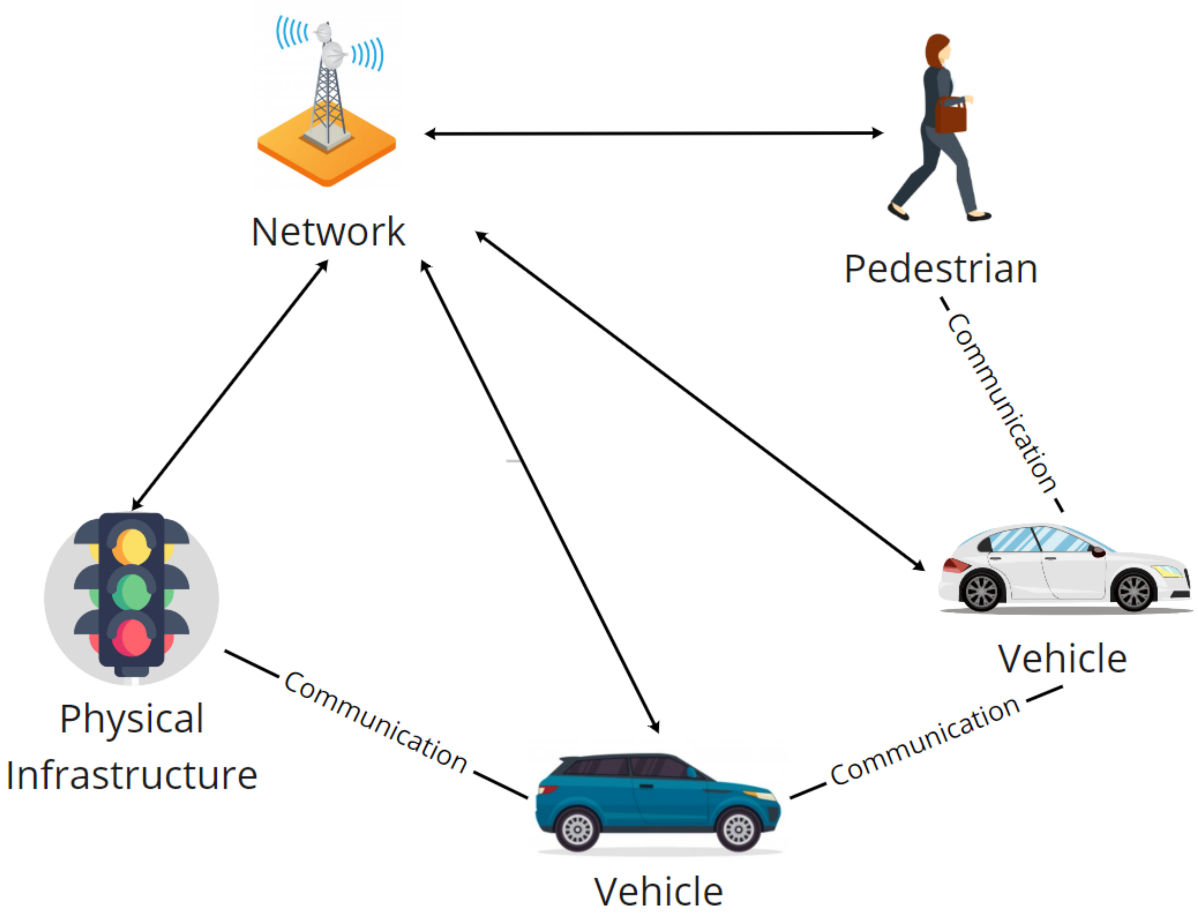


Figure 1-2 Introduction of the V2X Communication

1.3 Research Purpose and Basic Knowledge Related to Research

This research wants to improve the safety of ADS that potential ADV purchasers have a high concern about, and solve the social problem of traffic accidents by providing safety for the transportation system. Therefore, the definition of the safety zone is proposed to ensure the safety of ADV and surrounding vehicles. With the intention of establishing the calculation model of the safety zone for ADV, the influencing factors are analyzed, especially the definition of dangerous degree is proposed which hasn't been considered in previous researches. Several simulation scenarios are designed utilizing MATLAB to evaluate the performance of safety zone. In the simulation, the driving course and vehicle's behavior are planed based on the safety zone analysis. And the architecture of ADS with the function of calculating safety zone is described utilizing System Modeling Language (SysML).

This research is based on two main basic knowledge, one is the RSS model which is introduced in the previous study since comparing with other safety distance calculation models, the RSS model has better performance for safe driving. Another necessary knowledge is Model-Based System Engineering (MBSE).

MBSE is an approach of modeling the system for the whole life cycle phase from the conceptual design phase throughout development and later phase by supporting the activities of analyzing the system requirements, system designing, validation and verification. [29] Comparing with the traditional document-based system engineering, MBSE has the advantages for completeness, consistency, and can clearly shows the relationship between subsystems, and the interaction of the system and outside of system. Since MBSE has its advantage on traceability when designing systems, it's easy to understand a detailed part of the whole system, communicate between developers and improve the system quality. Considering that ADS is a complex system, MBSE is an effective method to describe it. [30]

System Modeling Language is a graphical modeling language for MBSE, which supports to describe the specification, analysis, design, verification and validation of the system and systems-of-systems (SoS). There are four main packages of diagrams in SysML, which are requirement diagram, structure diagram, behavior diagram and parameter diagram. [31] [32]The requirement diagram describes the physical and functional requirements of the system and the relationships between requirements and other requirements, design elements, and test cases. The structure diagram presents the structural elements and their composition, also the interconnection and interfaces between the parts of the block. The activity diagram introduces the behavior flow indicating the order of the actions which contains the inputs, outputs, control and how the actions transform between the inputs and outputs. The parameter diagram shows the relationship among system properties. SysML shows high traceability between requirements and design model which is a helpful method to describe the ADS and modify ADS.

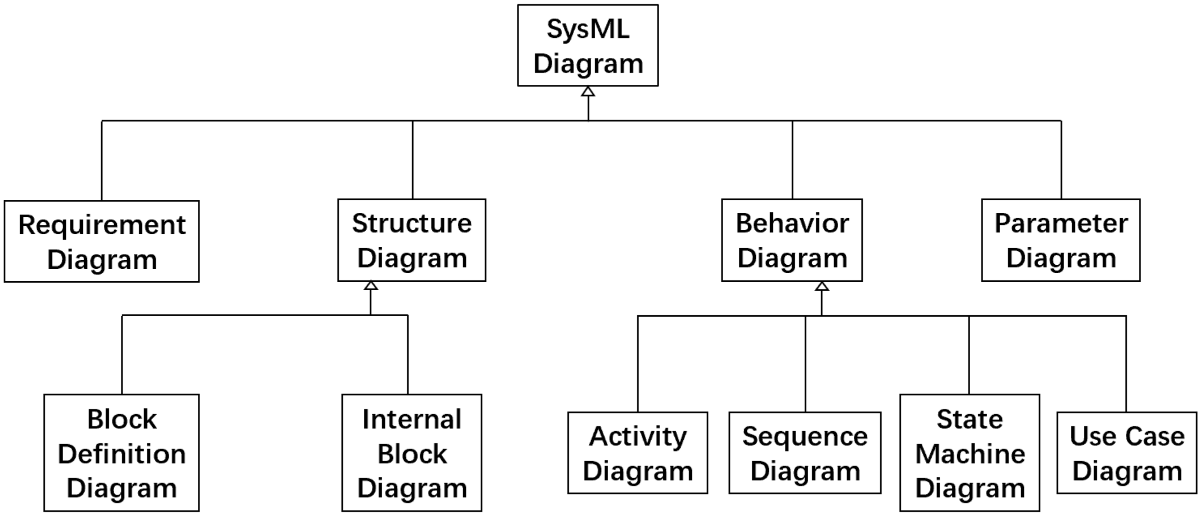


Figure 1-3 SysML Diagram Taxonomy

1.4 Dissertation Structure

This dissertation includes 6 main chapters which are followed by the acknowledgment.

The first chapter elaborates the necessity of developing ADS and the importance of safety, then the previous studies about safety distance are summarized. Also, the research purpose and research approaches are introduced which contains the definition of MBSE, SysML, and RSS model.

The second chapter introduces the definition of the safety zone and the influencing factors of the safety zone are analyzed. The definition of a dangerous degree that has not been considered in previous studies is proposed and the evaluation method is introduced.

The third chapter introduces the architecture of ADS considering safety zone based on the evaluation of dangerous degree utilizing SysML, which is the central idea of the following simulation. The architecture of ADS is described from the concept level to the detailed activity level, which shows how the simulation is processed clearly.

The simulation model for ADS considering a dangerous degree in chapter 4 is created based on the architecture described in chapter 3. The importance and strategy of scenario creating for introduces first. Then the vehicle dynamic and driving control method is introduced based on the scenarios. In the later part, the parameters that are used in the simulation model are specified and summarized.

The simulation results and the discussion about the results compose chapter 5. Future research is also mentioned based on the current research. The sixth chapter is an overall summary of this research. Finally, there is an acknowledged chapter for this paper.

2. Proposal of Safety Zone for ADS

This chapter describes the definition of the proposed safety zone and analyzes the influencing factors of the safety zone. The two classic scenes are described to make the safety zone easier to understand. While defining the safety zone, an important definition of dangerous degree is proposed which hasn't been considered in the previous studies.

2.1 Definition of Safety Zone

The safety zone is an area of the vehicle that other objects should not be inside in order to keep not only the ADV but also the surrounding vehicles safe. As figure 2-1 shows, the safety zone is an oval-shaped area composed of the safety distances (S_D) of all directions. S_{D_i} is the safety distance of the ADV with the surrounding vehicle i, $(i = 1,2,3,4)$.

There are four vehicles surround the ADV, for each of them, the ADV has the safety distance S_{D_i} at the direction of that surrounding vehicle i. The length of the blue line is the safety distance S_{D_1} between ADV and vehicle 1. The length of the green line is the safety distance S_{D_2} between ADV and vehicle 2. The length of the orange line is the safety distance S_{D_3} between ADV and vehicle 3, and the same, the length of the yellow line is the safety distance S_{D_4} between ADV and vehicle 4. Then the four safety distances are fitted into an oval-shaped area, which is the proposed safety zone of the ADV like the green circle shows. When there are no vehicles at the certain directions, the minimum safety distances will be taken to compose the safety zone.

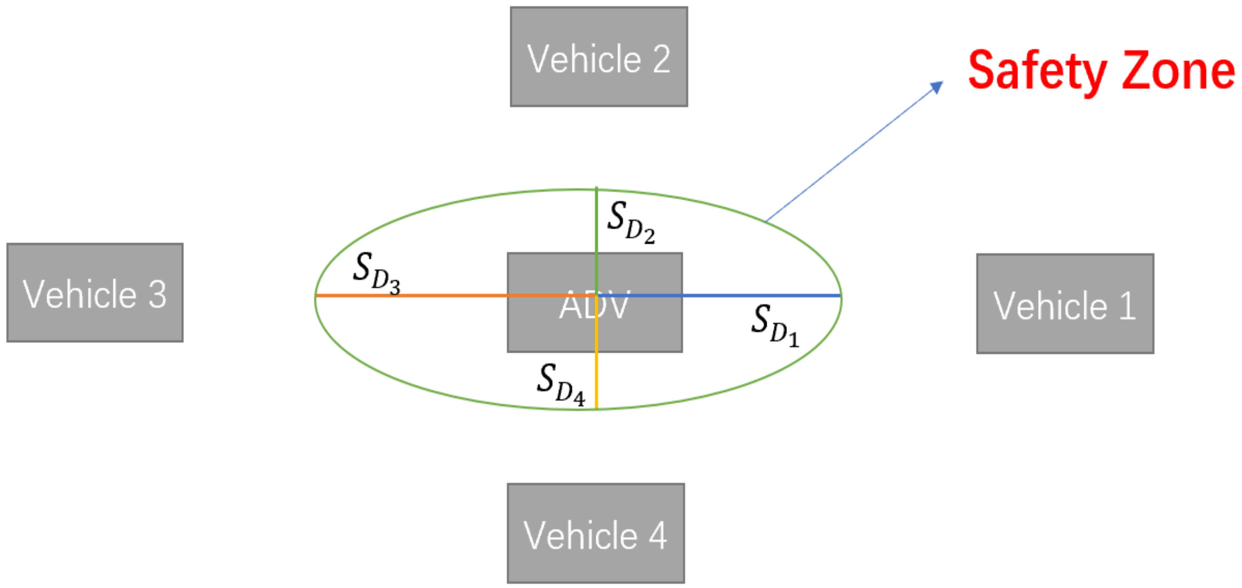


Figure 2-1 Schematic Diagram of Safety Zone

The classic scenes of the safety zone are shown below in Figures 2.2-2.3. The yellow vehicle is the ego vehicle equipped with ADS, and red vehicles are surrounding vehicles which may be the human-driving vehicles or ADV. The blue circle is the safety zone of the ego vehicle.

Figure 2-2 shows the safe scene, all the surrounding vehicles are outside the safety zone of the ego vehicle, so both the ADV and surrounding vehicles are safe. In this situation, the ego vehicle can drive at the expected speed that the user sets, or accelerate to reach the speed limit of the road which can raise the traffic efficiency, as long as all the surrounding vehicles are outside the safety zone of the ego vehicle.

Figure 2-3 shows the dangerous scene, there is a surrounding vehicle inside the safety zone of the ego vehicle, so that vehicle is dangerous which means it has the possibility to have a collision with the ego vehicle. At that time, if the ego vehicle takes no reactions to the dangerous scenario, the accident may happen in the following seconds, which means in this scenario, the

ADV has to be aware and make some response to avoid the potential collision, at the same time, send the information of dangerous attention to surrounding vehicles by V2X communication until all the vehicles become safe again as figure 2-2 shows.

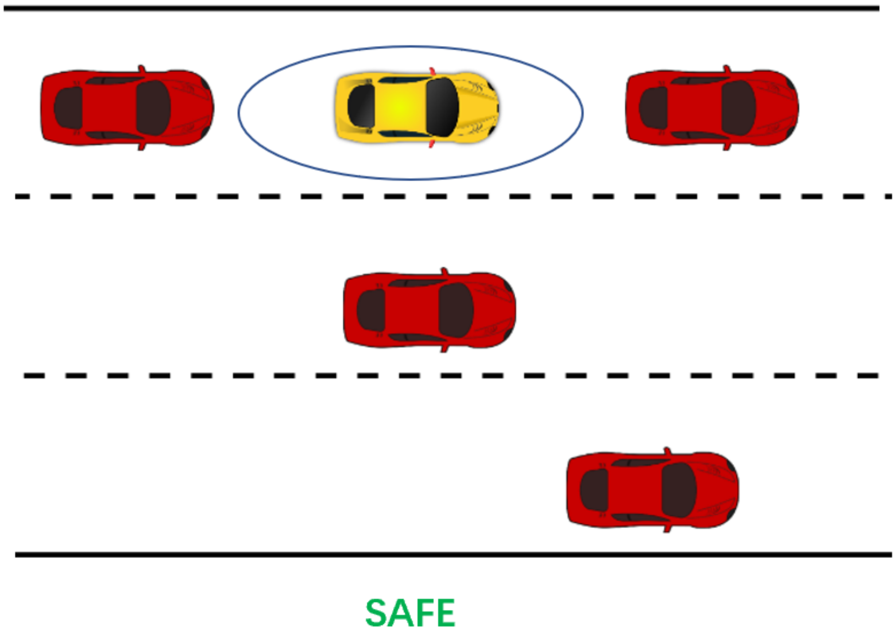


Figure 2-2 The Schematic Diagram of Safe Scene Based on Safety Zone

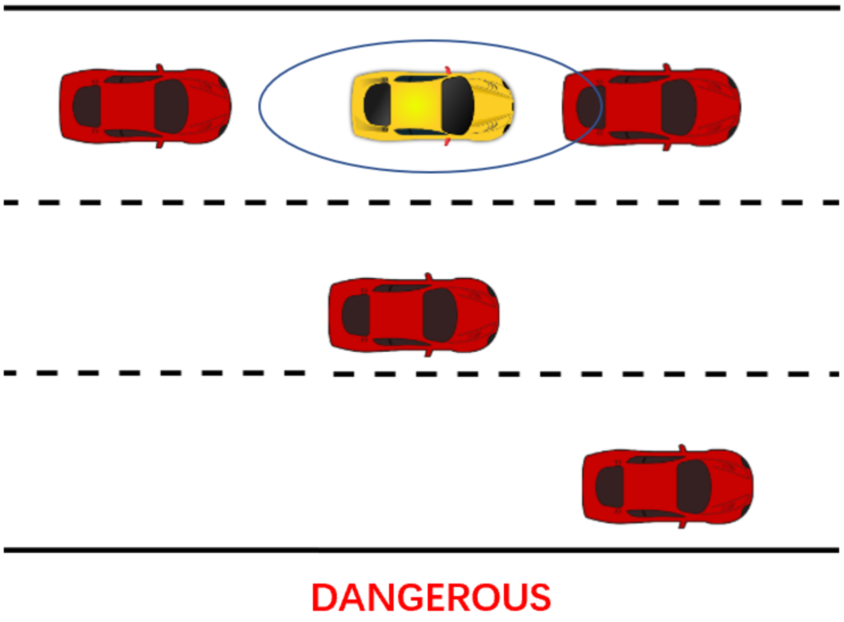


Figure 2-3 The Schematic Diagram of Dangerous Scene Based on Safety Zone

2.2 Influencing Factors of Safety Zone

As the above introduction, the safety zone is composed by the safety distances, therefore, the size of the safety zone is decided on the safety distances of the ADV. Based on the interview with experienced drivers, the analyzed influencing factors are summarized below.

- Environment condition (e.g., weather, light, the state of road face, the slope angle of the road)

Weather conditions and light conditions affect the drivers' visibility and sensors' performance, therefore, can affect the size of the safety zone. Also, the state of the road face and the slope angle of road affect the friction force of the road and the gravitational force of the vehicle, which also affect the size of the safety zone.

- Vehicle's state (e.g., velocity, acceleration)

Velocity and acceleration affect the safety distance directly as the RSS model formula 1−1 shows.

- Vehicle's performance (e.g., types of vehicles that will affect the maximum of acceleration and deceleration)

The maximum acceleration and deceleration also affect the safety distance directly as the RSS model formula 1−1 shows.

- Driver's state (e.g., fatigue, drunk, healthy condition)

The driver's state affects the reaction time of the driver in the human-driving vehicles which may make the vehicle that he/she drives more dangerous since the surrounding vehicles of ADV may contain human-driving vehicles.

- Driving skill of a driver (e.g., high, average, low)

Same as the driver's state, the driving skill of a driver in the surrounding vehicle can affect the size of the safety zone.

Driver's driving behavior may be decomposed to longitudinal driving controls (e.g., speed, acceleration) and directional driving controls (e.g., steering). The difference in driver's driving skills can be reflected in the difference in driver's driving behavior. [33] In my research, the driving skill will be categorized into high, average, and low.

High driving skill level: The driver's driving behavior of both longitudinal and directional driving is stable, and does not have sudden acceleration and deceleration.

Average driving skill level: The driver's driving behavior of longitudinal is stable, but the driving locus weakly fluctuates while curving. And the vehicle motion behavior has a low frequency of sudden acceleration and deceleration.

Low driving skill level: The driving locus strongly fluctuates for both longitudinal and directional driving. And the frequency of sudden acceleration and deceleration is high and causes the sudden acceleration and deceleration of vehicle motion.

2.3 Definition of Dangerous Degree

Considering the accidents on the highway are more serious than normal roads because of the high speed, [34] the basic assumption of this research is the three-lanes, one-way road highway, so, the vehicles are allowed to change the lane. The speed limitation of this road is from 15 m/s to 35 m/s (which means the vehicles on the highway do not stop expect an emergency situation). As the five main influencing factors mentioned above, two of them can be directly concerned in the original formula of the RSS model as formula 1-1 shows.

$$S_D = max\left\{\left[v_r t + \frac{1}{2} a_{rmax} t^2 + \frac{(v_r + t a_{rmax})^2}{2a_{rmin,brake}} - \frac{{v_f}^2}{2a_{fmax,brake}}\right], 0\right\} \tag{1-1}$$

The influencing factors of the safety distance in the original formula are velocity of the rear and front vehicle, response time of the drivers, minimum deceleration of the rear vehicle, maximum deceleration of the front vehicle and the maximum acceleration of the rear vehicle. According to this research, there are three more influencing factors that RSS model does not consider, which makes the original safety zone calculating formular not good enough.

Therefore, in this research, the other three influencing factors need to be concerned in the definition of a dangerous degree. The dangerous degree shows the dangerous level of the ego vehicle's surrounding vehicles, the greater the dangerous degree is, the more dangerous the surrounding vehicle is. As the influencing factors analysis that mentioned in chapter 2.2, the dangerous degree of a surrounding vehicle is decided by the environmental condition, the driver's state, and the driving skill level of the driver in the human-driving vehicle that arounds the ego vehicle. Therefore, the dangerous degree needs to be formulated into the safety distance calculation equation by the dangerous degree index Q.

Also, since the possibility of happening the worst situation is quite low in the real situation. The worst situation represents the front vehicle suddenly brakes with the maximum deceleration, at the same time, the rear vehicle accelerates at the maximum acceleration during the response time, then brakes immediately by at least the reasonable braking force that is likely to be used by a human driver in this situation. Therefore, the maximum acceleration of the rear vehicle can be replaced by the current acceleration of the rear vehicle.

Considering the above-mentioned points, the calculation formula of safety distance has been modified as formula 2-1.

$$S_D = max\left\{\left[v_r t + \frac{1}{2} a_r t^2 + \frac{(v_r + t a_r)^2}{2 a_{rmin,break}} - \frac{{v_f}^2}{2 a_{fmax,break}}\right] Q, 0\right\} \tag{2-1}$$

v_r, v_f means the velocity of the rear and front vehicle

t means response time of rear vehicle

$a_{min,brake}$ means the minimum reasonable deceleration of the rear vehicle that is likely to be used by a human driver when he recognizes the front vehicle is braking

$a_{max,brake}$ means the maximum deceleration of the front vehicle

Q means dangerous degree index which shows the dangerous degree of surrounding vehicles.

a_r means the instant acceleration of rear vehicle when the front vehicle decelerates.

The dangerous degree Q is decided by Q_{EC} which presents the environmental condition, and Q_{driver} which presents the state and driving skill level of the driver in a human-driving vehicle as formula 2-2 shows. Therefore, the calculation formula is shown below. Considering the traffic efficiency, the safety distance should not be meaningless large, the dangerous degree of environmental condition and driver are no more than 2 as formula 2-3 shows.

$$Q = Q_{EC} * Q_{driver} \tag{2-1}$$

$$\begin{cases} 1 \le Q_{EC} \le 2 \\ 1 \le Q_{driver} \le 2 \end{cases} \tag{2-2}$$

3. Architecture of ADS Considering Safety Zone

Based on the study of ADS in paper [35][36][37][38], this chapter describes the context definition of ADS, the interface between the ADS and external environment, the activities of ADS while performing DDT on the highway with the function of calculating safety zone.

3.1 ADS Operational Use Case

According to the definition of Level 3 of ADS, the driver has to take the control of the vehicle when the ADS cannot handle the situation and request the Dynamic Driving Task (DDT) fallback. Therefore, the ADS has to monitor the state and interface with the driver. Also, the ADS has to perceive the external information as below:

- Physical Infrastructure e.g., the speed limit of the road
- Environmental Condition e.g., weather, lightness
- Traffic Participants e.g., the velocity, position, trajectory of the surrounding vehicle
- Ego Vehicle's State e.g., the velocity, position, condition of the ego vehicle

After perceiving the necessary information, the ADS should be able to integrate and analyze the information. Then based on the analysis, the appropriate plan of driving course and vehicle's behavior will be designed by ADS to ensure the safety of ego vehicle and surrounding vehicles considering the efficiency of traffic and comfortableness of the vehicle's riders.

Besides, the ADS also has to send the DDT command and realize the DDT according to the planned driving course and vehicle's behavior by the ADV.

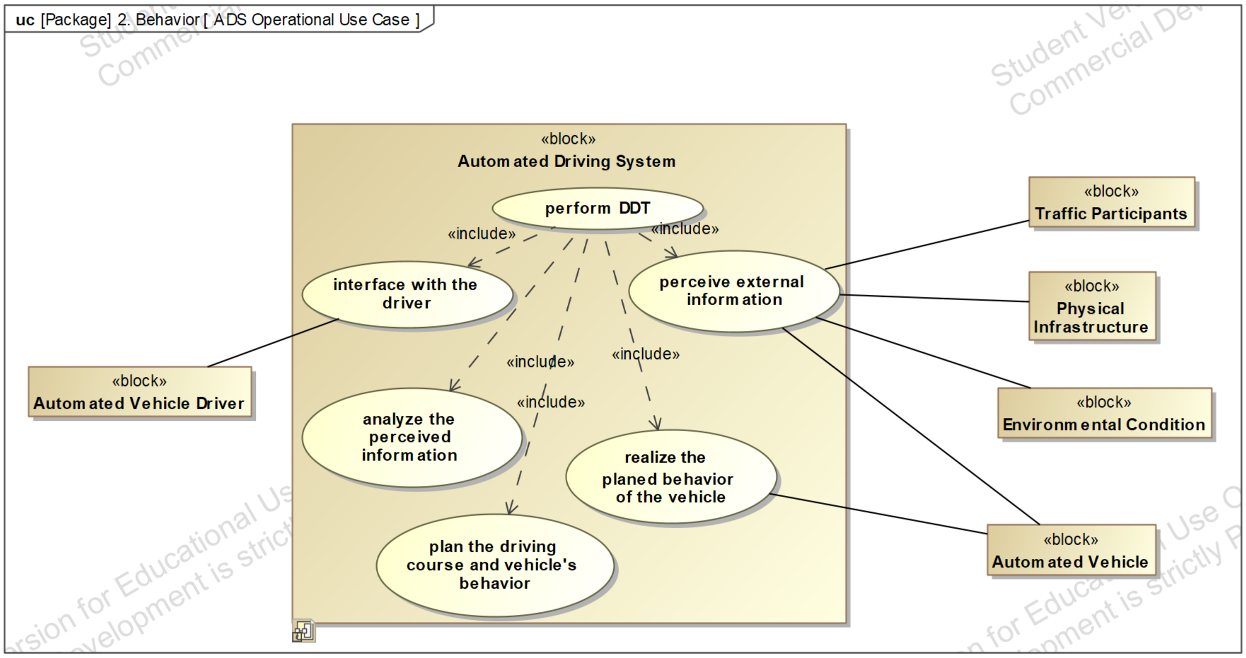


Figure 3-1 ADS Operational Use Case Diagram

3.2 Subsystems of ADS

Referring to the ADS use case, there are three subsystems of ADS to complete the entire process.

- Perception System which perceives the necessary external information from sensors which includes camera, lidar, radar, Global Position System (GPS), etc.
- Human Machine Interface (HMI) System monitors the state of driver and realizes the interface between the driver and ADS.
- Decision and Control System which analyzes the context and plans the driving course and vehicle's behavior of ADV then realizes the DDT according to the target trajectory.

3.3 ADS Context

While processing the driving task, full focus and attention on the surrounding environment is required for both human drivers and ADS since the surrounding environment are changing while driving. For the human drivers, the observation can affect the decision about vehicle control which highly depends on the experience and state of the driver. Since from level 3 of ADS, the ADS will take the responsibility of the information perceiving, if the ADS is able to provide safety for traffic system, the better ability of information perceiving than human observation is required for ADS. Thus, context analysis is the challenge for ADS. As figure 3-3 shows, ADS is described as interacting mainly with the external environment, driver, and vehicle.

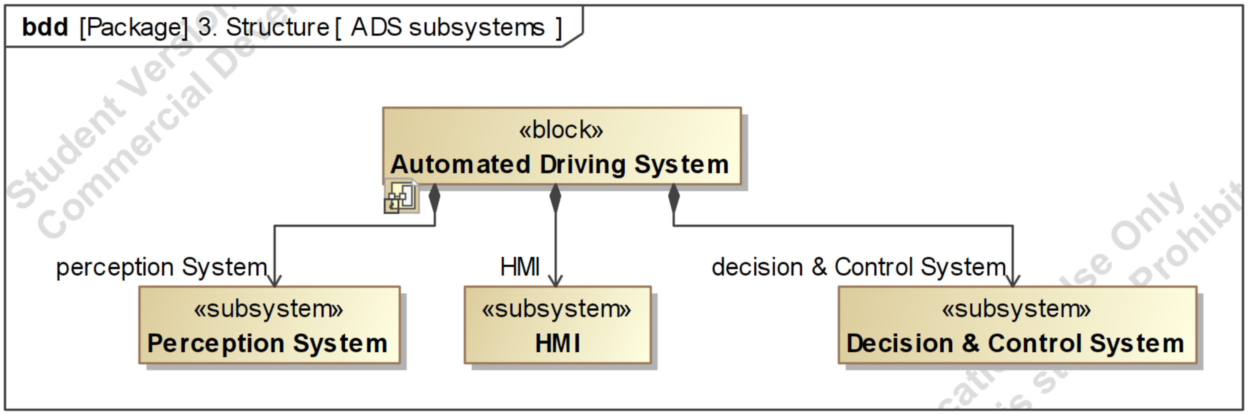


Figure 3-2 Subsystems of ADS

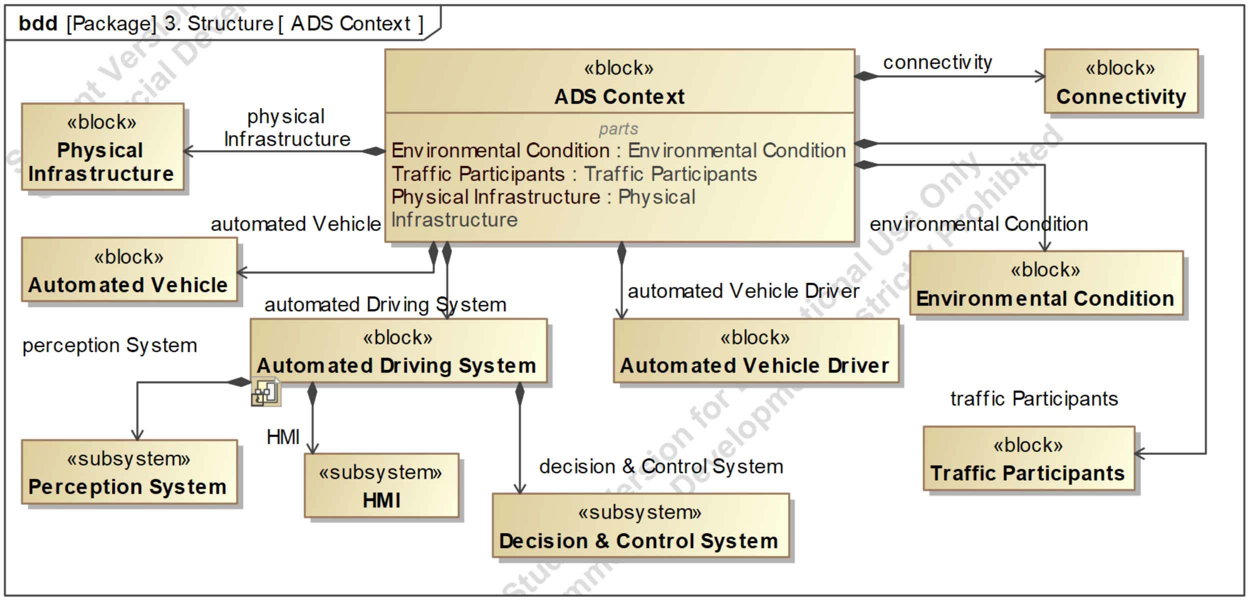


Figure 3-3 ADS Context Diagram

3.4 Activity of ADS performs DDT on highway Considering Safety Zone

The figure 3-4 is the activity diagram of ADS performs DDT on highway Considering Safety Zone which shows the interaction of activities allocated to the blocks. The object flows between the ADS and external of the system while ADS performs DDT on the highway is also described. Since the scenario is the highway, the traffic participants are only vehicles, the information of traffic participants is inputted to ADS. The environmental condition keeps changing during the driving process, the performance of ADS is based on the feedback of the environment thus, the input of ADS contains the environmental condition. The road marks limit and leads the driving of ADV which can affect the ADS as an input. The described ADS is level 3 which means the driver is still involved in the driving process, therefore the behavior and state of the driver need to be monitored and transformed to ADS. At the same time, the state of the ego vehicle is also be monitored by the ADS to analyze the context. After the processing of ADS, the output includes three parts, which are the integrated DDT information for drivers to operate the vehicle when necessary; the DDT command that leads the vehicle’s movement; the DDT information and suggestion to surrounding vehicles.

Figure 3-5 shows the allocation of the activities with the subsystems of ADS and the interaction of these activities. Also, how the ADS performs dynamic driving tasks considering the safety zone on the highway is clearly described. At first, the perception system perceives the information of objects, the state of ego vehicle, environmental condition, and signages. However, the scenario is the highway, thus the perceived objects are vehicles. The perceived information includes:

- Velocity, position, trajectory, performance, number of riders, state of the driver of surrounding vehicles, and ego vehicle.

- Aerodynamic drag coefficient, the mass density of air, friction force coefficient of the road surface, the slope angle of the road
- Speed limitation of the road

Then based on the perceived information, the ADS can analyze the context and understand the current scenario. Based on the scenario, the dangerous degree of surrounding vehicles can be evaluated. After the evaluation of the dangerous degree, the safety zone of the ego vehicle is calculated. Combining the result of safety zone calculation and the analyzed context, the decision & control system decides the driving course and plans the vehicle's behavior for the ego vehicle. Then the decision & control system keeps analyzing how to realize the DDT and output the driving control to the external system. When necessary, the HMI sends DDT fallback request information to the driver and gives the right of control of the vehicle to the driver.

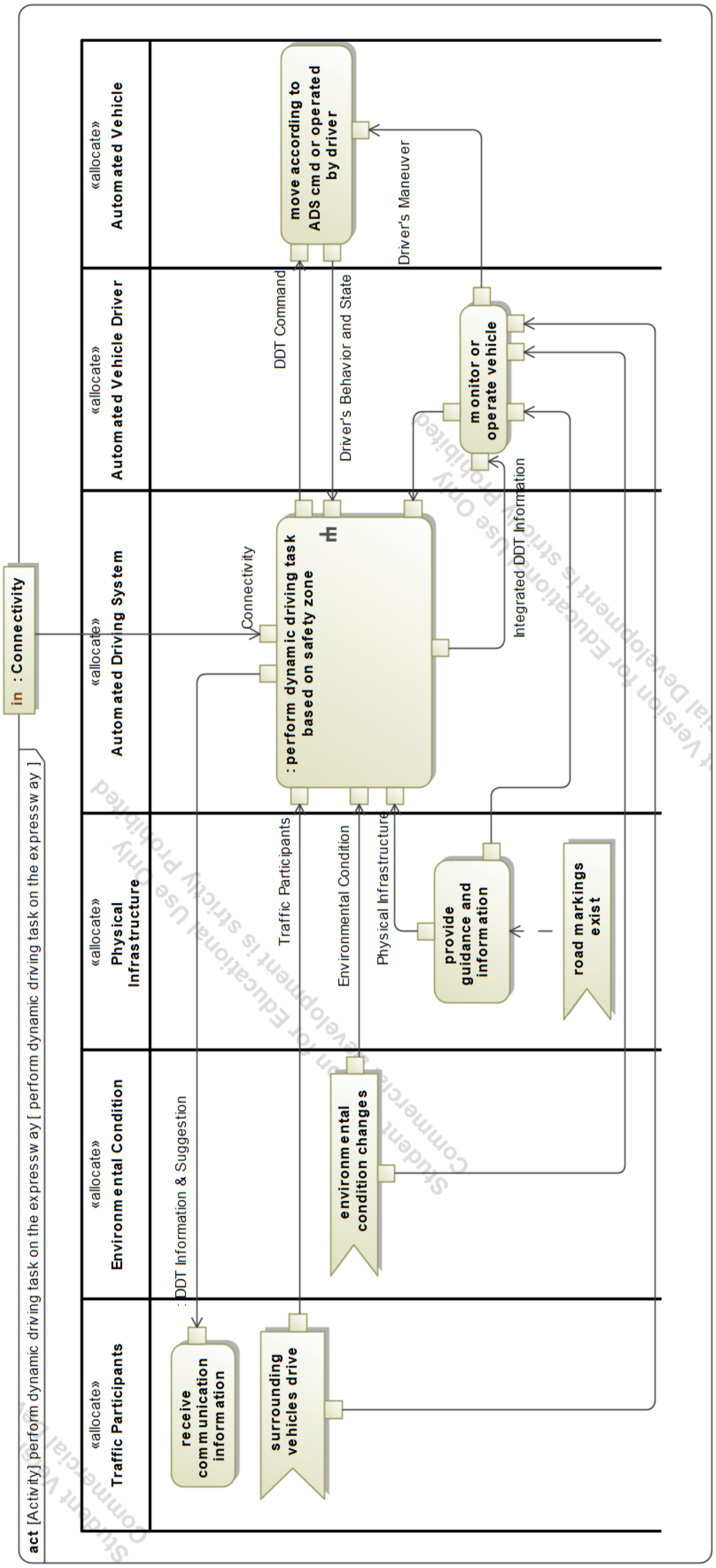


Figure 3-4 Activity Diagram of ADS Performing Dynamic Driving Task on the Highway

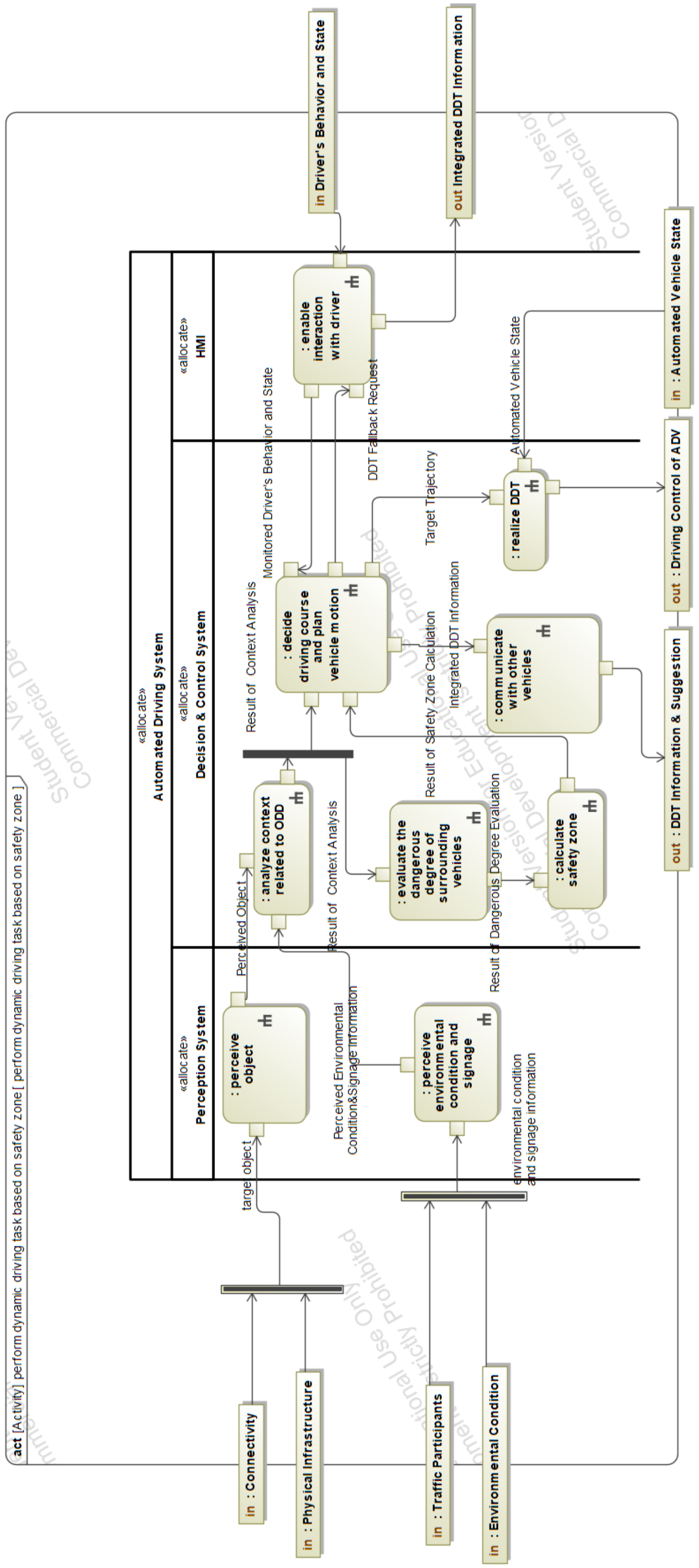


Figure 3-5 Activity Diagram of ADS Performing Dynamic Driving Task Based on Safety Zone

3.5 Internal interconnections of Blocks of ADS

Figure 3-7 describes the item flows within the subsystems that internal the ADS which shows the interconnections of the blocks. While ADS processing the DDT, the perception system perceives the external information and transforms it into the perceived object and environmental condition, and also the signage information on the road. Then decision & control system receives the information from both the perception system and V2X communication, then outputs the planned DDT command and sends the DDT information and suggestions utilizing V2X communication. When the situation the ADS cannot deal with happens, the HMI system requests the driver to fall back the DDT based on the monitored driver's behavior.

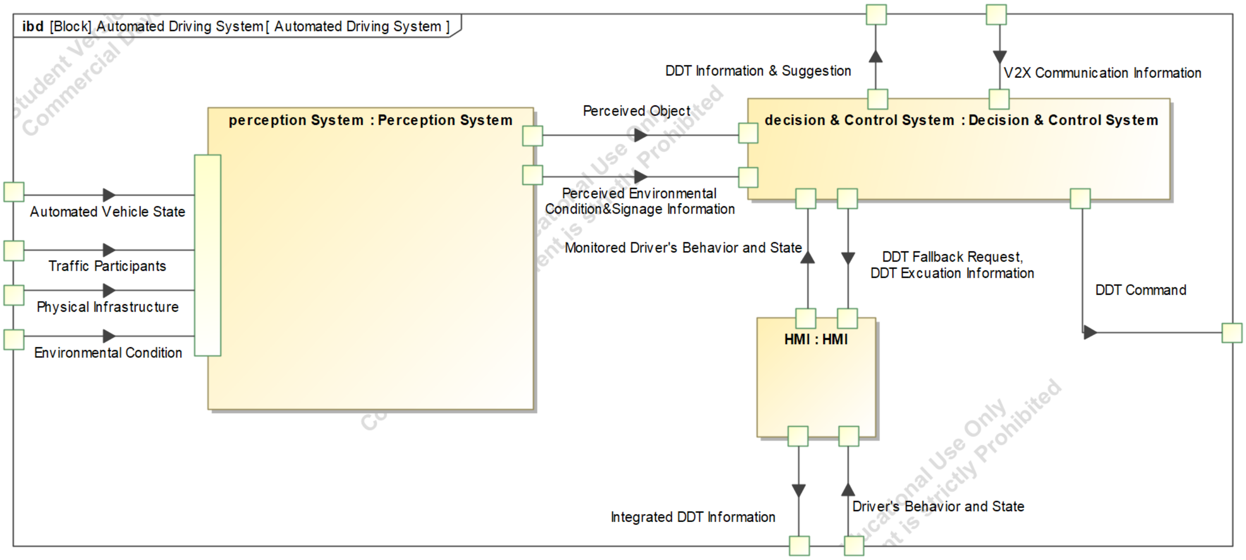


Figure 3-6 Internal Block Diagram of ADS

3.6 Detailed Activities of ADS Performs DDT on highway Considering Safety Zone

While perceiving the object, first, the data of the object(s) is from both sensors and V2X communication. Then the sensed data is filtered since there may be noises. The filtered data is used to recognize the detailed information of the object. The location and trajectory of the recognized objects can be estimated and predicted.

At the same time, the data of environmental condition and physical infrastructure is also sensed and filtered for recognizing the environmental condition and physical infrastructure. Then the ADS analyzes the meaning of the signage and output the information.

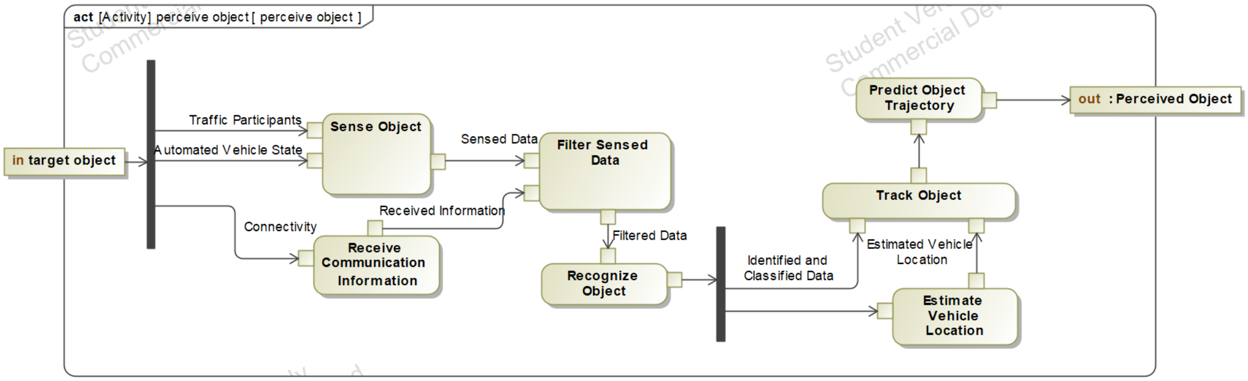


Figure 3-7 Activity Diagram of ADS Perceiving Object

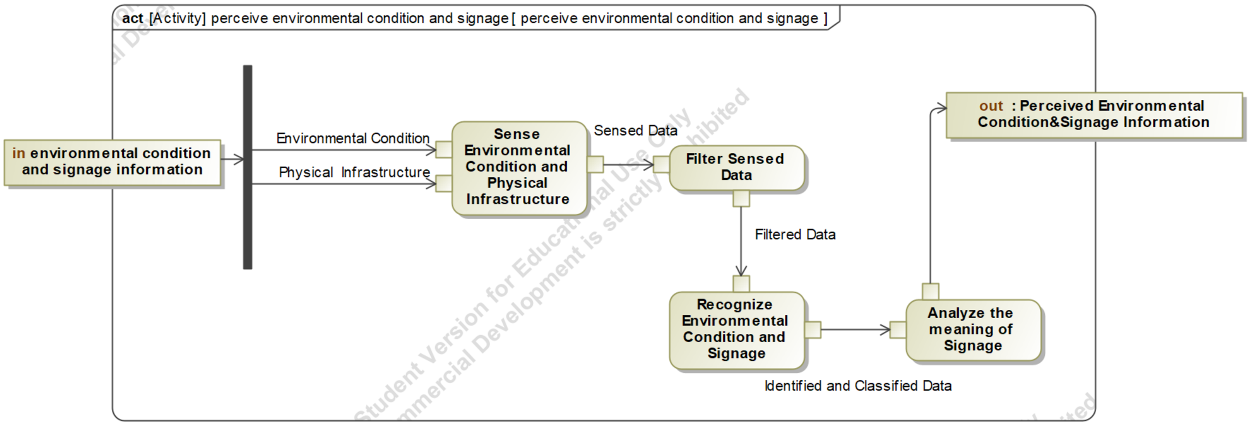


Figure 3-8 Activity Diagram of ADS Perceiving Environmental Condition and Signage

The perceived object, environmental condition, and signage information are integrated to define the scene and scenery, and also the situation that composes the context of ADS.

Then the result of context analysis is inputted to analyze the driving behavior of surrounding vehicles to evaluate the driver’s dangerous degree of the vehicle that he/she drives.

Also, the dangerous degree of the environmental condition is analyzed mine while. These two dangerous degrees are integrated into the dangerous degree of every surrounding vehicle.

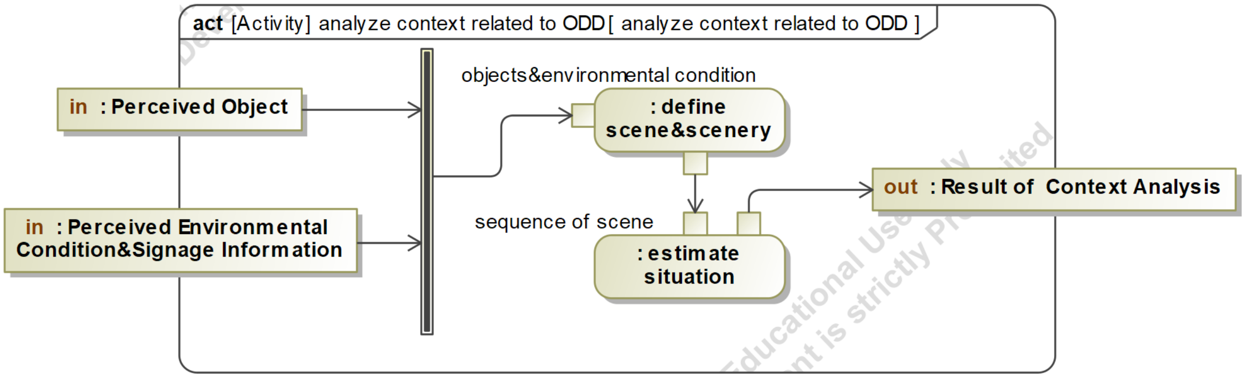


Figure 3-9 Activity Diagram of ADS Analyzing Context Related to ODD

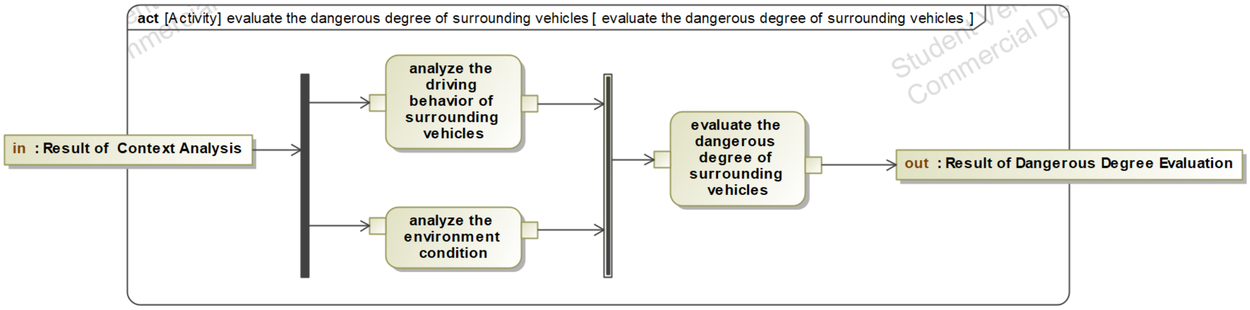


Figure 3-10 Activity Diagram of ADS Evaluating Dangerous Degree of Surrounding Vehicles

With the result of dangerous degree of every surrounding vehicle, the four safety distances for ego vehicle and surrounding vehicles are calculated. Then the four safety distances are fitted into an oval shape as the safety zone of the ego vehicle.

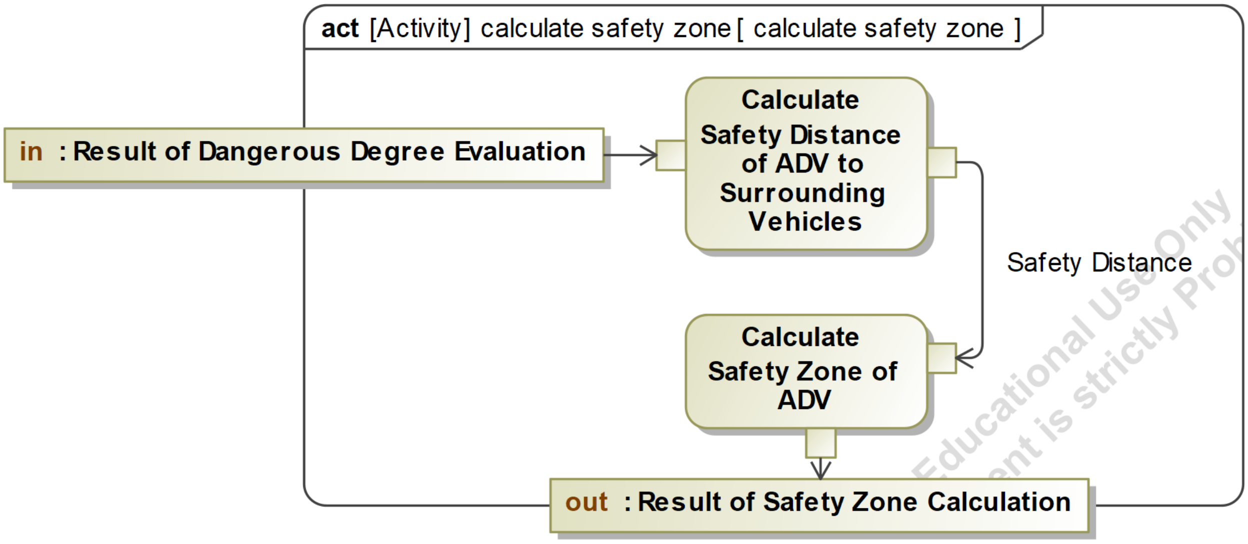


Figure 3-11 Activity Diagram of ADS Calculating Safety Zone

Figure 3-12 describes how the ADS avoids the collision based on the safety zone. By comparing the relative distances and the safety distance for ego vehicle and the surrounding vehicles, whether the surrounding vehicle is inside the safety zone of the ego vehicle can be checked.

As figure 3-13 shows, the relative distance is the real distance between the ego vehicle and the surrounding vehicle. The safety distance is the distance from the gravity center of the ego vehicle to the edge of the safety zone in the direction of that surrounding vehicle. When the surrounding vehicle’s relative distance is less than the safety distance, that vehicle is inside the safety zone of the ego vehicle which means dangerous, otherwise, that surrounding vehicle is outside the safety zone if the ego vehicle which means safe.

The number of the surrounding vehicles inside the safety zone of the ego vehicle affects the method of avoiding the collision. When the number is not more than 1, the ego vehicle can avoid the collision by only adjusting the velocity and doesn’t need to change the lane. When there is more than one vehicle inside the safety zone of the ego vehicle as figure 3-14 shows, the ego vehicle has to change the lane to avoid accidents as figure 3-15 shows. While the ego vehicle changing the lane, it needs to decelerate a little in order to drive smoothly.

The command of changing velocity or lane will be integrated to decide the driving course and plan the vehicle's behavior as the output.

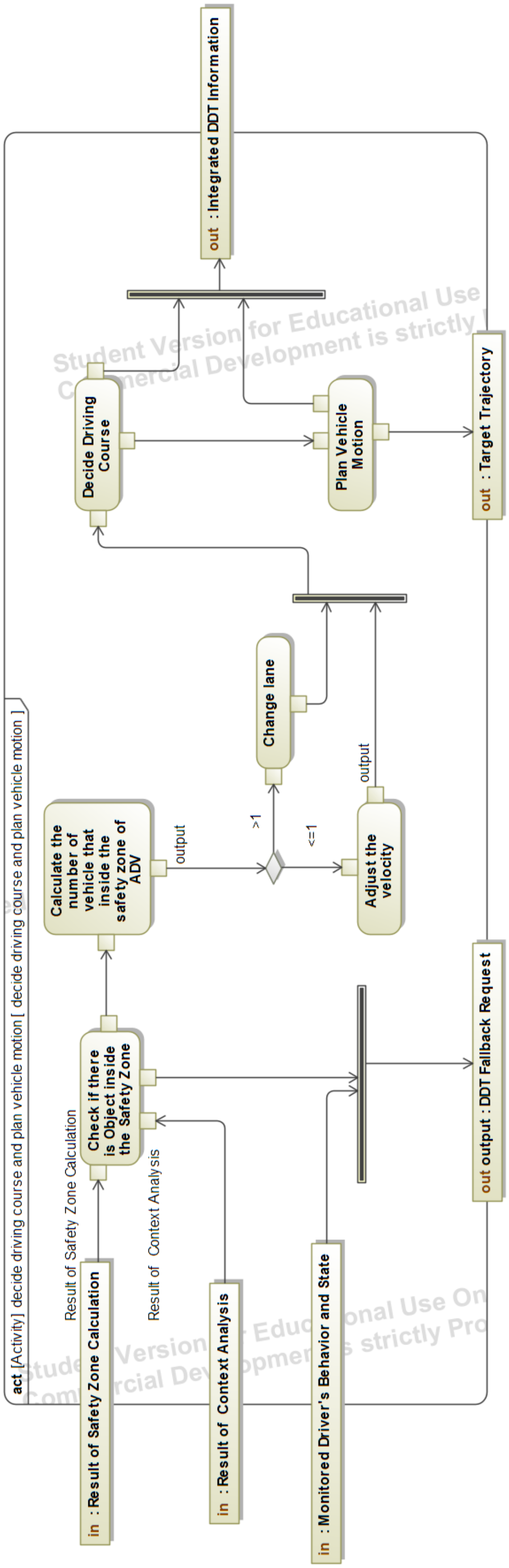


Figure 3-12 Activity Diagram of ADS Deciding Driving Course and Planning Vehicle Motion

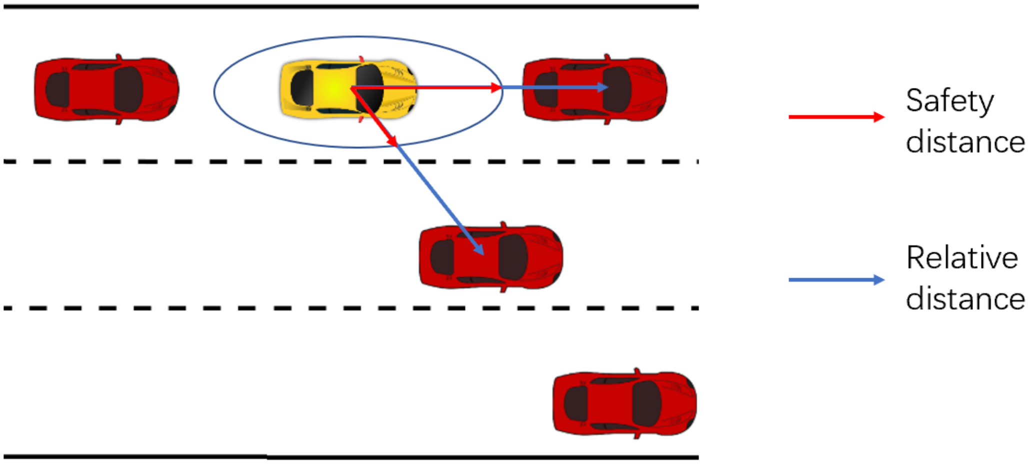


Figure 3-13 Schematic Diagram of Relative Distance and Relative Distance

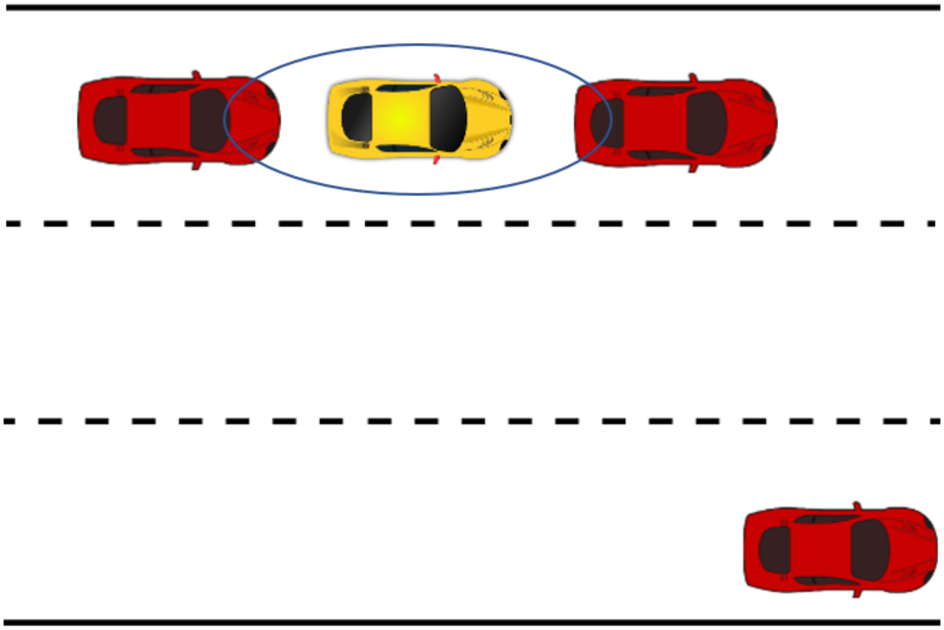


Figure 3-14 Schematic Diagram of 2 vehicles inside the Safety Zone

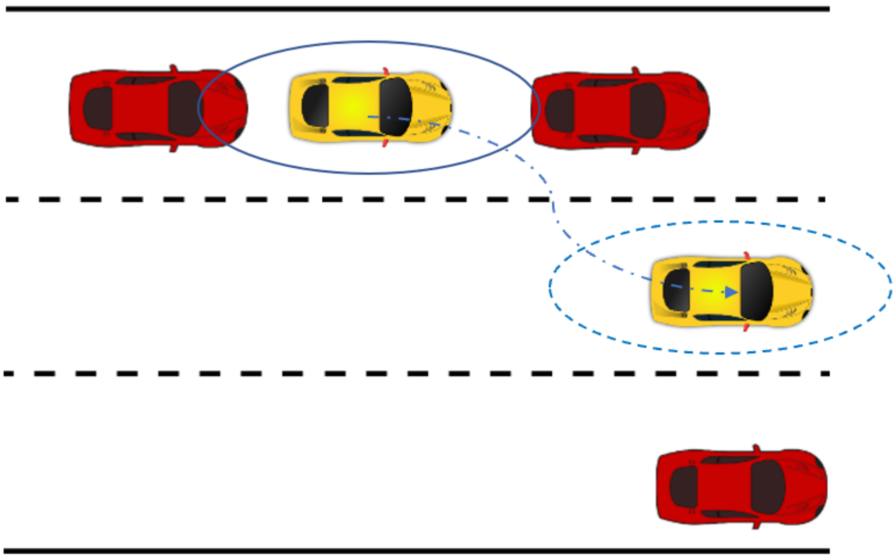


Figure 3-15 Schematic Diagram of Ego Vehicle Changing Lane to Avoid Collision

After deciding the driving course and vehicle's behavior of the ego vehicle, ADS sends the integrated DDT information and basic suggestions to the surrounding vehicle to notice the possibility of collision as figure 3-15 shows. In the real situation, the surrounding vehicle may notice the danger by the V2X communication and follow the suggestion to avoid the collision, but this research's assumption is that the surrounding vehicles ignore the notification and the situation is still dangerous because if the ADS considering the safety zone can ensure the safety of ego vehicle and surrounding vehicles in the dangerous scenarios, it means that the ADS can ensure the safety of them under all scenarios by considering the safety zone.

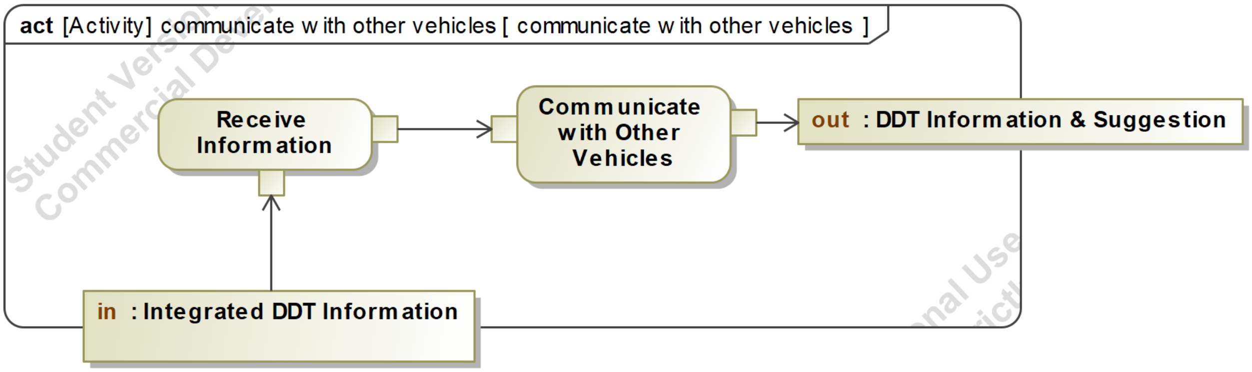


Figure 3-16 Activity Diagram of ADS Communicating with Other Vehicles

Since vehicles are drove by the force provided by the motor and the steering angle of the wheel, only the DDT command cannot drive the vehicle directly. Thus, the DDT command needs to be transformed into driving control information to realize the DDT. While transforming, the vehicle dynamics are required to be analyzed which will be introduced later in chapter 4.

There are also some situations that ADS cannot deal with, at that time, ADS will send DDT fallback requests to the driver based on the monitoring of the driver's state and behavior. In order to make the driver operate the vehicle quickly, the information of ADS' current action, situation, and potential risk will be integrated and provided to the driver.

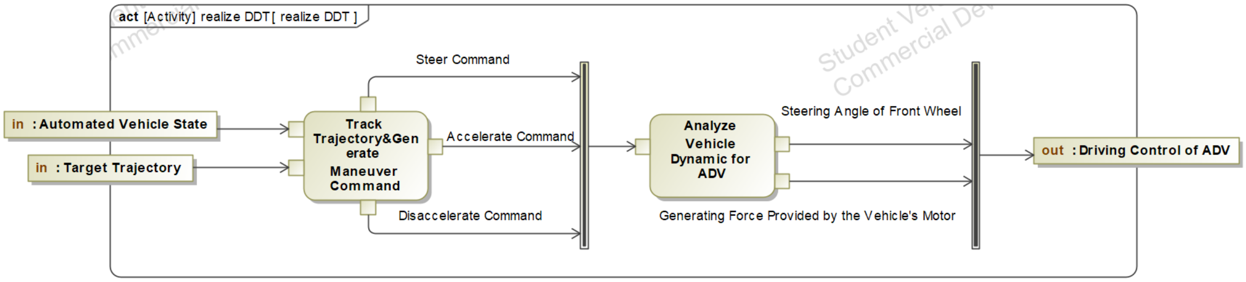


Figure 3-17 Activity Diagram of ADS Realizing DDT

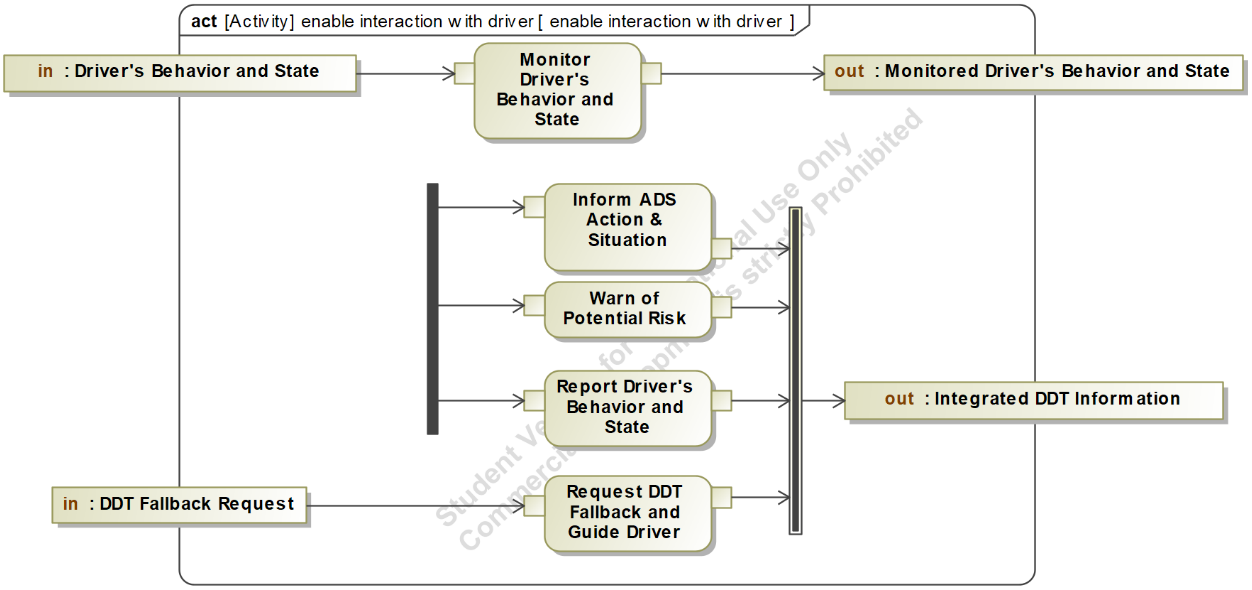


Figure 3-18 Activity Diagram of ADS Enabling Interaction with Driver

4. Simulation Model for ADS Considering Dangerous Degree of Surrounding Vehicles

This chapter is based on the activity diagrams shown in chapter 3, to simulate the performance of ADV performing DDT on highways considering safety zone based on the dangerous degrees of surrounding vehicles. The simulation is based on the Driving Scenario Designer of MATLAB.

4.1 Simulation Scenarios Designing

The simulations are based on different scenarios, the strategy of designing the scenarios in this research and the reason for creating several scenarios are introduced.

4.1.1 Simulation Assumptions

As mentioned in chapter 2.3, this research's assumption is on the highway with a speed limit of 15-35 m/s. A more detailed assumption of simulation is as below.

- The ego vehicle is an ADV equipped with ADS L3 and a front-wheel driving vehicle.
- The surrounding vehicles contain both human-driving vehicles and ADV which are equipped with L1-3 ADS.
- The ego vehicle perceives information from both sensors and V2X communication which contains velocity, position, trajectory, performance, number of riders, state of the driver of surrounding vehicles, and itself. The ego vehicle also perceives the environmental condition information includes aerodynamic drag coefficient, the mass density of air, friction force coefficient of the road surface, and slope angle of the road.

- For all the designer scenarios, they are dangerous scenarios which mean there has at least one collision happens for ADV and surrounding vehicle since if the ADS with the function of calculating safety zone can keep ADV and surrounding vehicles safe under the dangerous scenario, it means the proposed ADS can keep ADV and surrounding vehicles safe under normal scenarios.

4.1.2 Simulation Scenarios Creation

The scenario is an indispensable factor that affects the decision of driving course and vehicle's behavior. [39] The scenery is the static elements geospatially. The environmental snapshots which including the scenery and all the dynamic objects become a scene. The definition of scenario is the timely development between the scenes in a sequence of scenes. Based on the clear definition of scenario, figure 4-1 and 4-2 is a simple example that shows how the scenarios affect the ADS of making the decision.

The yellow and red dotted lines represent the forward trajectory of the ego vehicle and surrounding vehicles. The vehicle in the middle line wants to change the lane but it may cause a collision with the ego vehicle, therefore the ego vehicle has to make the reaction to avoid the potential collision.

The different scenarios lead to different reactions of the ego vehicle. When the scenario is as figure 4-1 shows, the ego vehicle can accelerate or decelerate to avoid the right vehicle, but for safety concerns, normally the ego vehicle decelerates to give the road to the right vehicle to avoid the collision. However, when the scenario is like figure 4-2 shows, there is also a rear vehicle that follows the ego vehicle, it may make the collision with the rear vehicle if the ego vehicle chooses to have deceleration. Therefore, in the scenario, the better choice for an ego vehicle is to accelerate to pass the right vehicle before it changing the lane. Because of the above-mentioned reason, the designing of different scenarios is the key point of this simulation model.

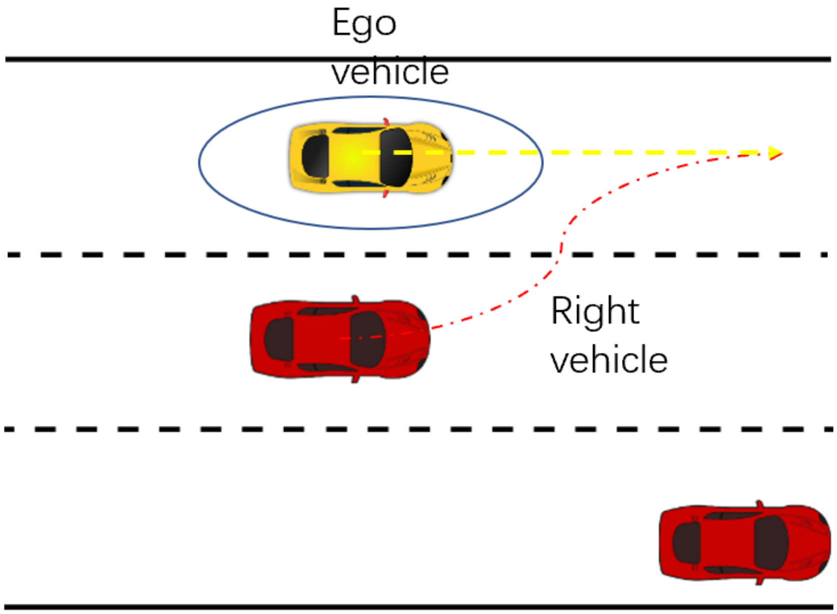


Figure 4-1 Schematic Diagram of the Dangerous Scenario-A

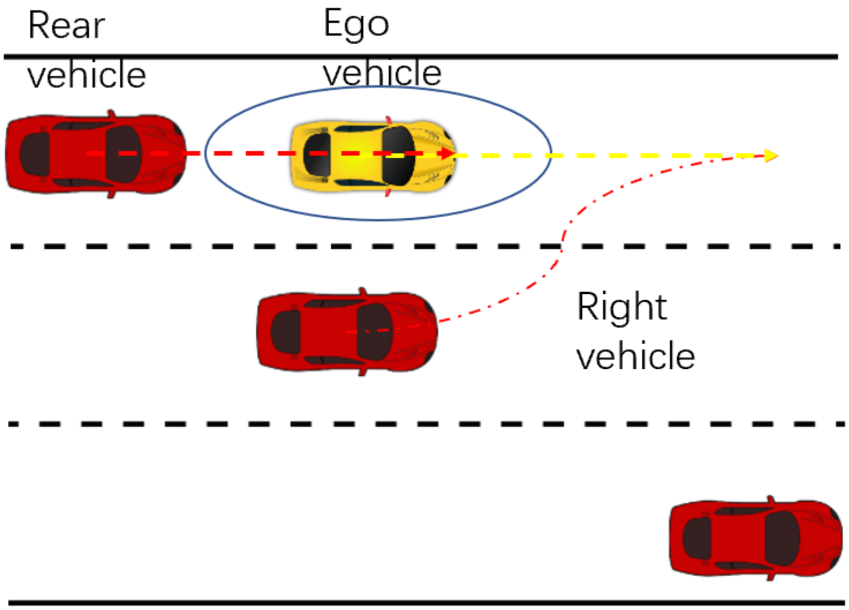


Figure 4-2 Schematic Diagram of the Dangerous Scenario-B

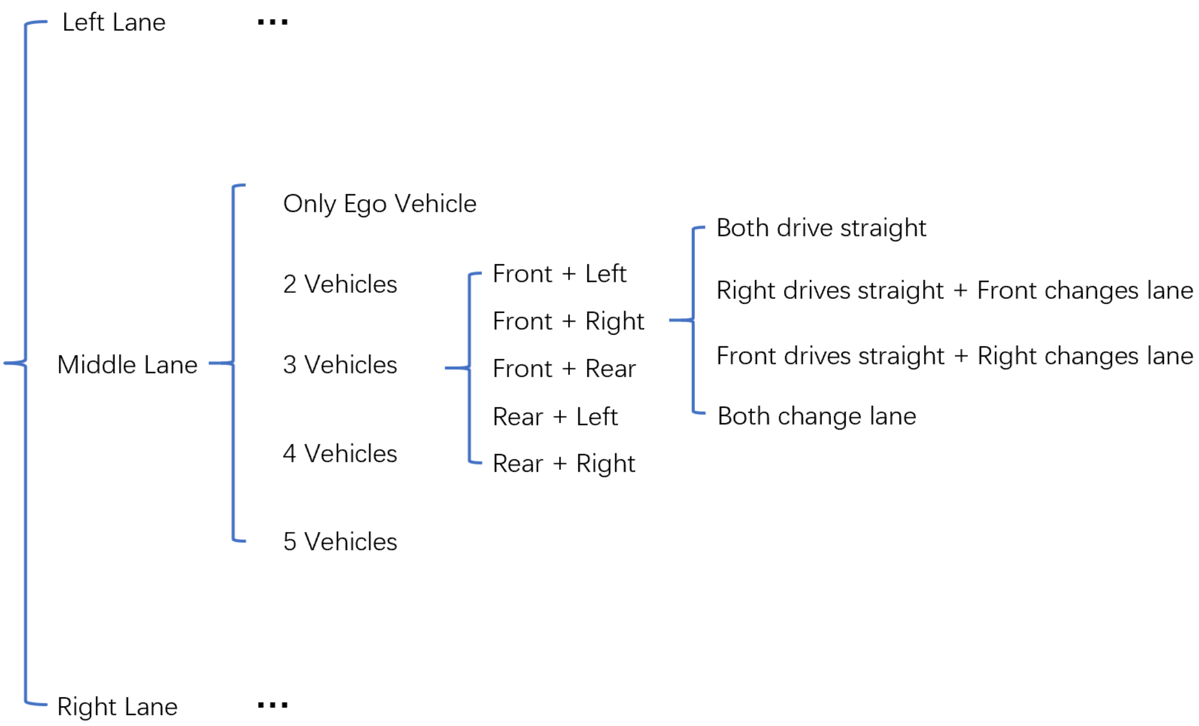


Figure 4-3 Strategy of Designing the Scenarios

Based on the assumption, the scenarios are designed from the following perspective.

- The lane that the ego vehicle is driving on → Left / Middle / Right
- The number of vehicles (ego vehicle + surrounding vehicles) → 1-5
- The position of the surrounding vehicles → Right / Left / Front / Rear
- The driving mission of the surrounding vehicles → Drive Straight / Change Lane

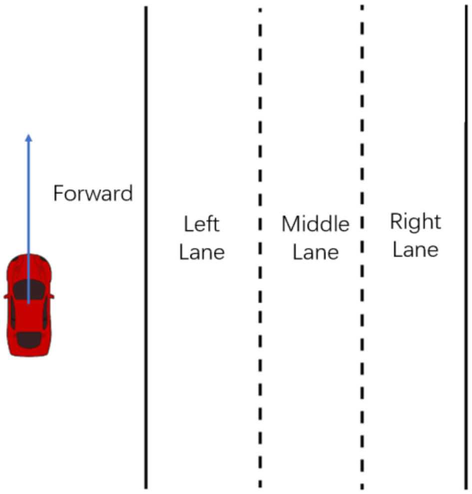


Figure 4-4 Schematic Diagram of the Road and Lanes

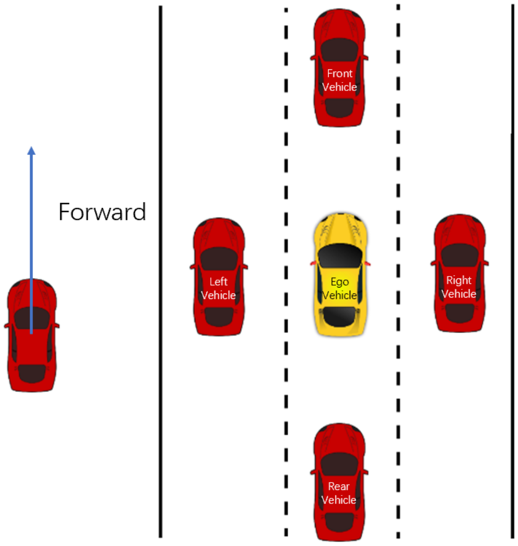


Figure 4-5 Schematic Diagram of Naming the Surrounding Vehicles

4.1.3 Simulation Environment

Since the simulation model is based on the driving scenarios designing, the Driving Scenario Designer APP in MATLAB is adopted as the simulation platform. Utilizing a driving scenario designer, the width, bank angle, number of lanes, width of lanes, type of lanes, and the center point of the road can be designed. For the vehicles, the velocity, trajectory, and position are designed in this simulation. After creating the scenario like figures 4-6 show, the MATLAB function can be generated for the driving scenario designer. After the programming of MATLAB, the result can be shown as the animation utilizing a driving scenario designer.

The code of simulation is programmed based on MATLAB R2020b. the hardware environment is listed as follows:

- OS: Windows 10
- Processor: 1.80 GHz
- Memory: 16.0 GB
- Graphics: Radeon Graphics
- Network: None
- Storage: 512 GB

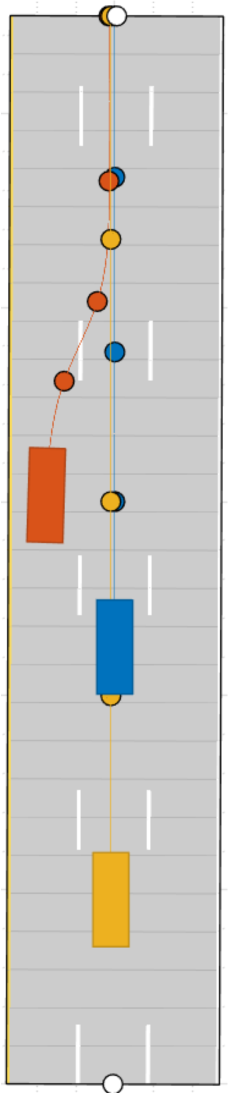


Figure 4-6 Schematic Diagram of Driving Scenario Designer

4.2 Vehicle Dynamics of Ego Vehicle

For the ego vehicle, in order to realize the target vehicle behavior and driving course, the command should be the value of generating force and the turning angle of the wheel to perform longitudinal and lateral driving control. Therefore, the analysis of vehicle dynamics is necessary. Since in this research, the ADV only performs the longitudinal and lateral driving task, the vehicle dynamics is considering 2 Degree of Freedom (DOF).

As figure 4-7 shows, the 2 DOF presents the longitudinal movement which is driving along the x-axis and the yaw movement around the z-axis.

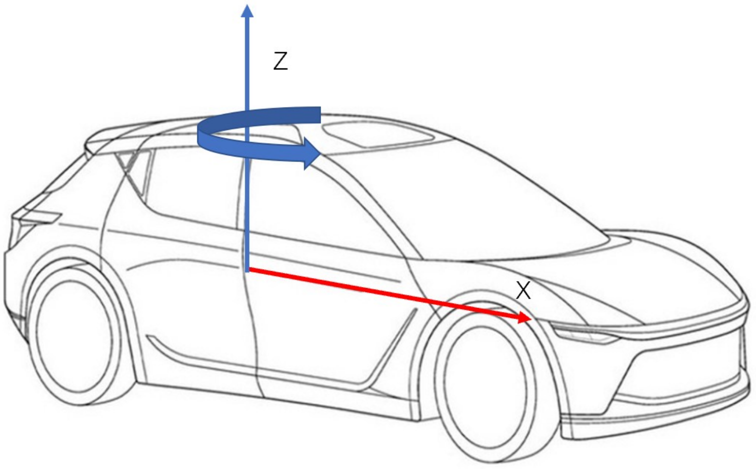


Figure 4-7 Schematic Diagram of 2DOF

For longitudinal vehicle dynamics, the positive direction in the direction of the velocity of the vehicle.

The longitudinal vehicle dynamics are divided into four scenarios the deceleration, acceleration, upslope, and downslope. For the upslope, the slope angle is positive, and for the downslope, the slope angle is negative. For the accelerating situation, the value of the acceleration is positive, otherwise, it's negative. [40][41] There are five forces that can be analyzed as below:

F_m is the generating force provided by the vehicle's motor

F_{air} is the aerodynamic drag force

F_f is the friction force of the road

F_s is the gravitational force

F_a is the provided force to the vehicle

The relationship of the force on the vehicle is as follows:

$$F_a = F_m - F_{air} - F_f - F_s \tag{4-1}$$

The force of the gravity on the vehicle is as follows:

$$G = mg \tag{4-2}$$

m is the mass of the vehicle, g is the gravitational acceleration

$$F_{air} = \frac{1}{2} C_D A \rho v^2 \tag{4-3}$$

C_D is the aerodynamic drag coefficient

A is the effective frontal vehicle cross-sectional area

ρ is the mass density of air

v is the velocity of the vehicle

$$F_f = Gf \cos\alpha \tag{4-4}$$

f is the friction force coefficient of the road surface

α is the incline angle

$$F_s = G \sin\alpha \tag{4-5}$$

$$F_a = ma \tag{4-6}$$

a is the acceleration of the vehicle, when the vehicle is accelerating, a>0; when the vehicle is decelerating, a<0

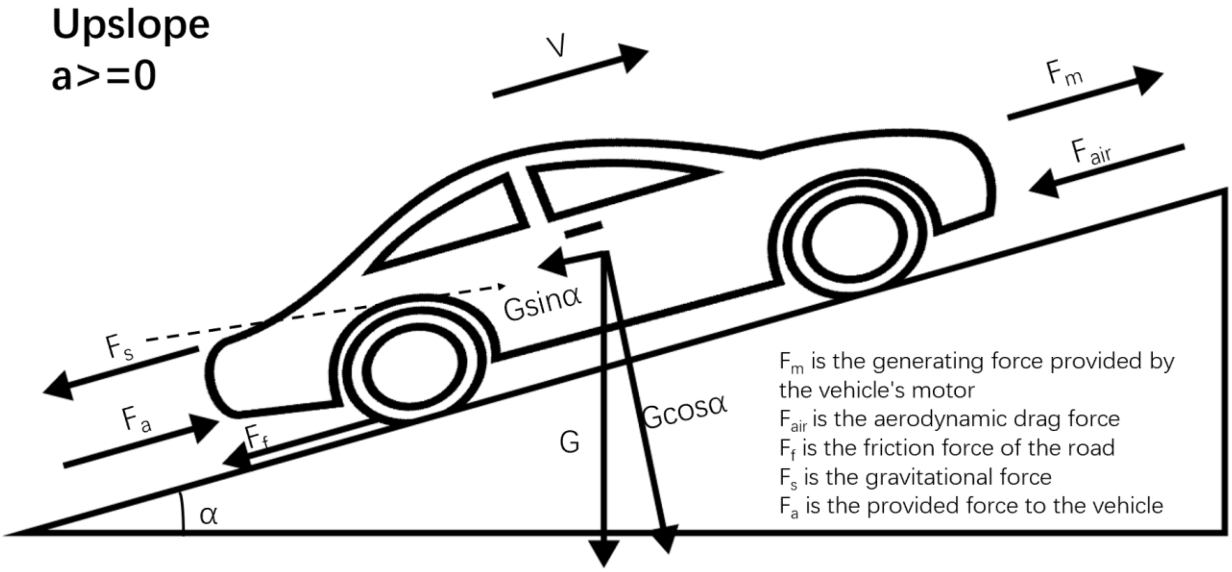


Figure 4-8 Longitudinal Vehicle Dynamics of Upslope and Acceleration

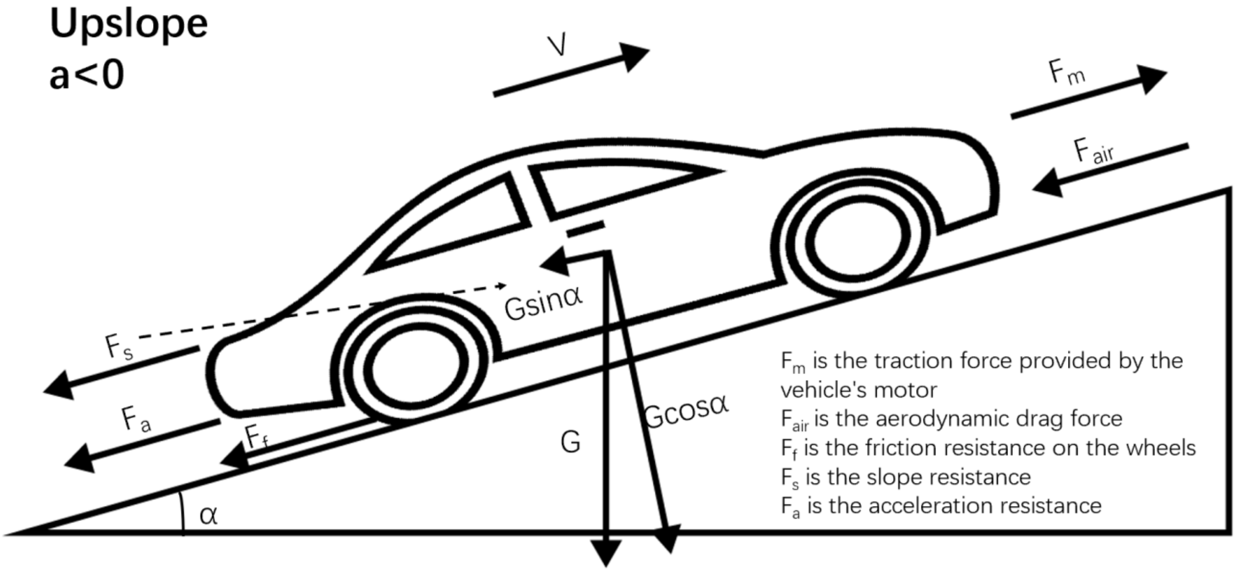


Figure 4-9 Longitudinal Vehicle Dynamics of Upslope and Deceleration

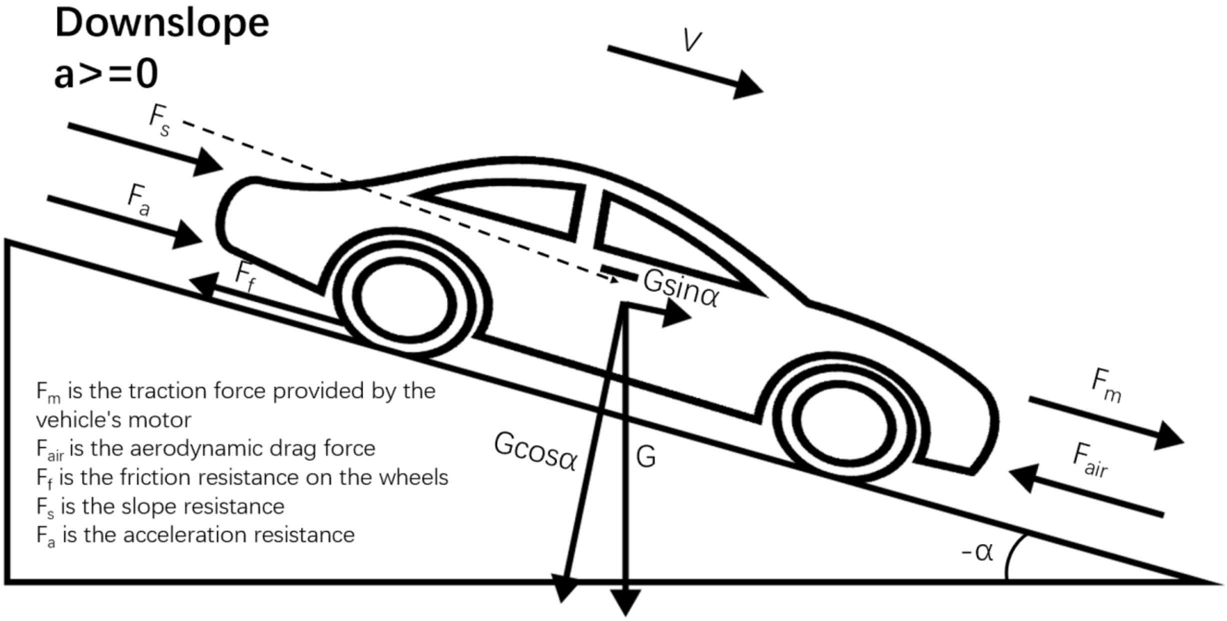


Figure 4-10 Longitudinal Vehicle Dynamics of Downslope and Acceleration

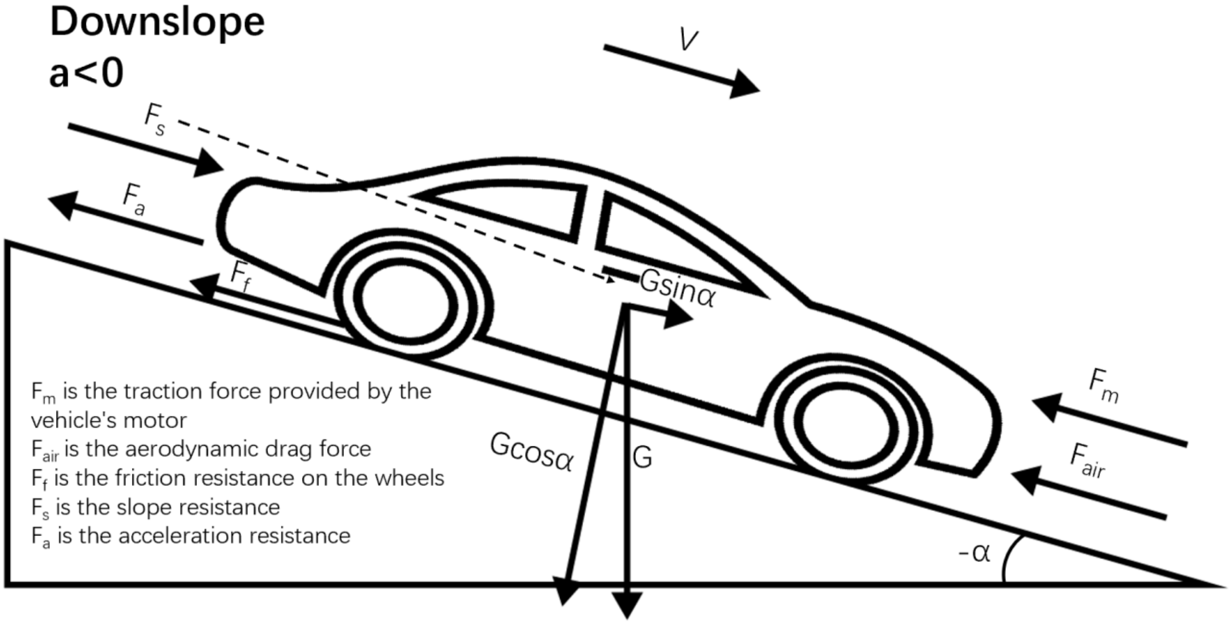


Figure 4-11 Longitudinal Vehicle Dynamics of Downslope and Deceleration

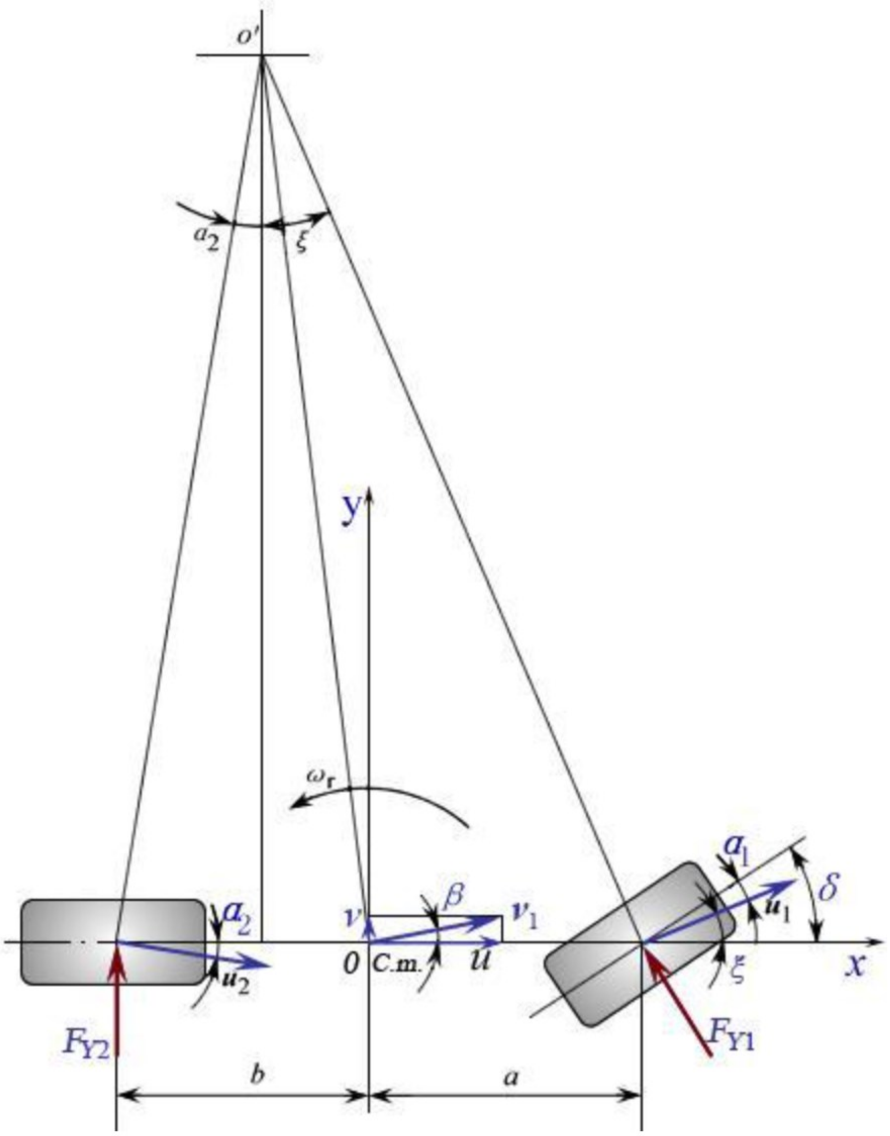


Figure 4-12 Lateral Vehicle Dynamics Analysis

The lateral vehicle dynamics is focused on the directional movement, which is summarized into the following formulas [42][43] :

$$(k_1 + k_2)\beta + \frac{1}{u}(ak_1 - bk_2)\omega_r - k_1\delta = m(v + \dot{u}\omega_r) \tag{4-7}$$

$$(ak_1 - bk_2)\beta + \frac{1}{u}(a^2k_1 + b^2k_2)\omega_r - ak_1\delta = I_Z\dot{\omega}_r \tag{4-8}$$

k_1 is the cornering stiffness of front wheel

k_2 is the cornering stiffness of rear wheel

β is the angle of the GC (gravity center) of the vehicle

a is the distance from GC to front axel

b is the distance from GC to rear axel

δ is the steering angle of the front wheel

u is the velocity on the x-axis

I_Z is the momentum of Inertia of the vehicle

ω_r is the angular velocity of the vehicle

Based on the calculation result, the stability of the vehicle while performing the directional driving tasks can be evaluated by the stability factor K:

$$K = \frac{m}{L^2}\left(\frac{a}{k_2} - \frac{b}{k_1}\right) \tag{4-9}$$

K is the stability factor

L is the wheelbase of the vehicle.

When K>0, the vehicle is oversteering, when the velocity is driving with high velocity while turning, it is dangerous.

When K<0, the vehicle is understeering.

4.3 Ego Vehicle's Driving Control

The ego vehicle's driving course is depending on the number and position of the surrounding vehicles inside the safety zone of the ego vehicle. Based on the analysis in chapter 3, the definition of error is proposed to plan the vehicle's driving course as figure 4-13 shows.

$$error_i \ = R_{D_i} - S_{D_i} \tag{4-10}$$

R_{D_i} means the real relative distance between ego vehicle and the surrounding vehicle i as the blue line shows in figure 4-13.

S_{D_i} means the safety distance of the surrounding vehicle i as the red line shows in figure 4-13.

The error is shown as the green line in figure 4-13When the error is positive, that surrounding vehicle i is safe, otherwise, it’s dangerous.

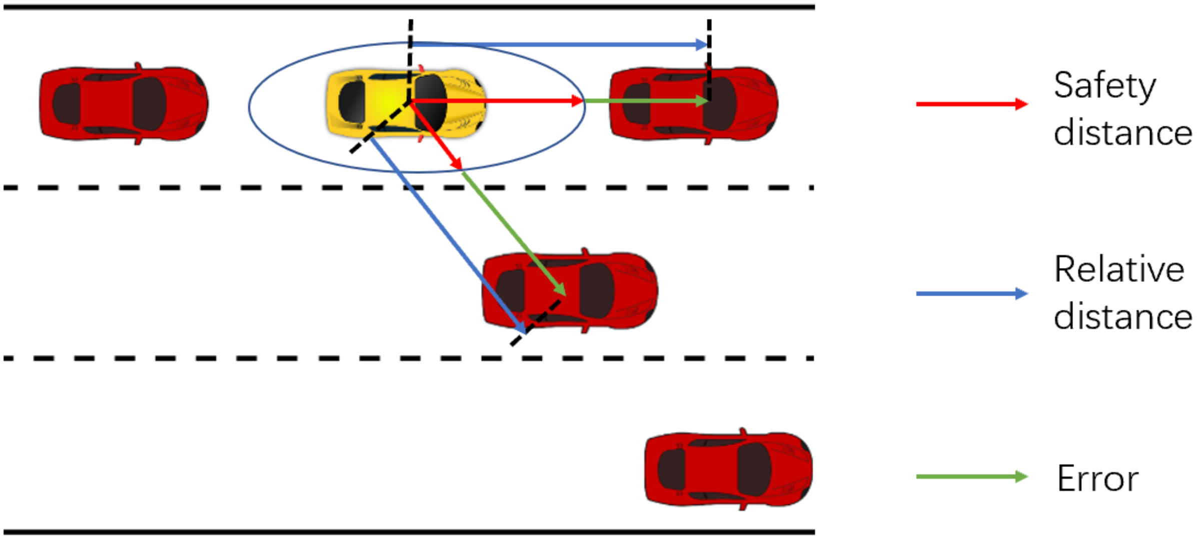


Figure 4-13 The Schematic Diagram of Defining Error

The generating force is depending on the error and position of surrounding vehicles. Then the generating force is inputted to the longitudinal vehicle dynamics to calculate the acceleration of the ego vehicle as formula (15)-(18) shows:

$$F_s = F_{s0} + k * error_i \tag{4-11}$$

k is the driving control strategy.

F_{s0} is the generating force when the acceleration of the vehicle is 0.

F_s is the aimed generating force of the vehicle.

After deciding the aimed generating force of the vehicle, the acceleration of the vehicle is calculated referring to the longitudinal vehicle dynamics.

$$F_a = F_m - F_{air} - F_f - F_s \tag{4-12}$$

F_m is the generating force provided by the vehicle's motor

F_{air} is the aerodynamic drag force

F_f is the friction force of the road

F_s is the gravitational force

F_a is the provided force to the vehicle

$$a = \frac{F_a}{m} \tag{4-13}$$

m is the mass of the vehicle

a is the acceleration of the vehicle

$$v = v_0 + a \tag{4-14}$$

v_0 is the velocity before the accelerating

v is the velocity with the acceleration

In some situations, the ego vehicle needs to change the lane to avoid dangerous vehicles. When there is a vehicle on the aimed lane, as figure 4-14 shows, the ego vehicle needs to change to the middle lane where the black vehicle is driving on. At that time, since only the vehicles that drive in the front, rear, left and right direction of the ego vehicle can be calculated directly by formula 2-2, the safety distances between the ego vehicle and other surrounding vehicles such as the black vehicle are calculated by the safety zone of the ego vehicle and the angle α as figure 4-15 shows.

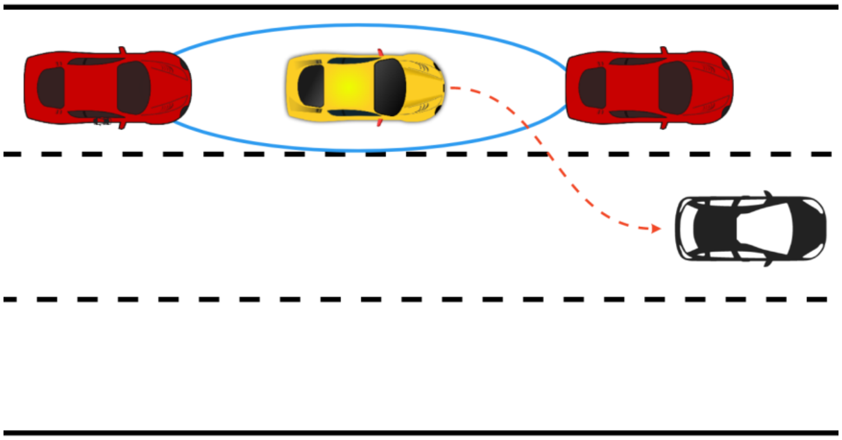


Figure 4-14 The Schematic Diagram of Lane Changing

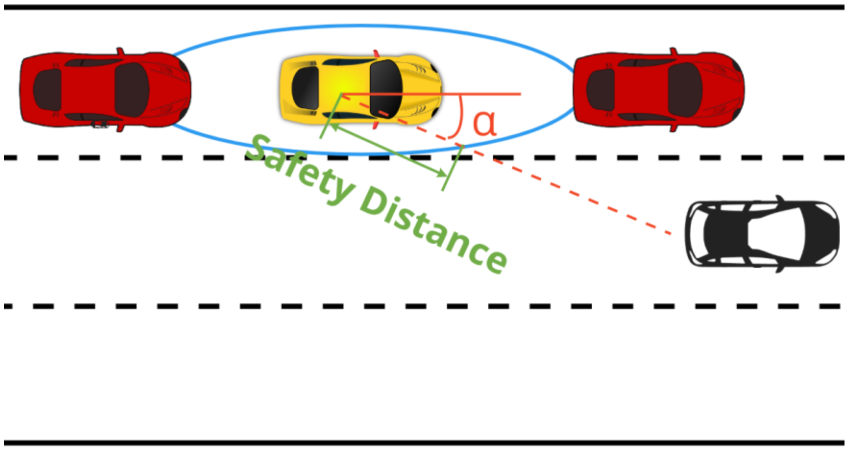


Figure 4-15 Calculation Method of Safety Distance with Other Surrounding Vehicles

Then the turning angle of the ego vehicle $\beta(i)$ can be calculated by the relative distance of x and y-direction between the ego vehicle and the black vehicle $\Delta x\_i \ and \ \Delta y\_i$ as formula 4-15 shows. When the relative distance of y-direction between the ego vehicle and the black vehicle Δy_i becomes 0, the process of changing lanes is finished. During the whole process of changing lanes, the relative distance between the ego vehicle and the black vehicle must always be greater than the safety distance between the ego vehicle and the black vehicle as formula 4-18 shows.

$$\beta(i) = \tan^{-1}\frac{\Delta y\_i}{\Delta x\_i} \tag{4-15}$$

$$\Delta x\_i = positionx(black\_i) - positionx(ego\_i) \tag{4-16}$$

$$\Delta x\_i = positionx(black\_i) - positionx(ego\_i) \tag{4-17}$$

i means the timepoint.

$positiony(black\_i)$ is the y coordination of the black vehicle at time i.

$positionx(ego\_i)$ is the x coordination of the ego vehicle at time i.

$positiony(ego\_i)$ is the y coordination of the ego vehicle at time i.

$positionx(black\_i)$ is the x coordination of the black vehicle at time i.

$\beta(i)$ is the turning angle of the ego vehicle at time i.

Δy_i is the relative distance of y-direction between the ego vehicle and the black vehicle at time i.

Δx_i is the relative distance of x-direction between the ego vehicle and the black vehicle at time i.

$$\sqrt{(\Delta y\_i + \Delta x\_i)^2} \geq S_{D_b} \tag{4-18}$$

$\mathrm{S}_{\mathrm{D}_\mathrm{b}}$ is the safety distance between the ego vehicle and the black vehicle.

After calculating the turning angle of the ego vehicle, the steering angle of the front wheel δ of the ego vehicle is calculated by inputting the turning angle β.

When the ego vehicle has to change the lane, but there is no surrounding vehicle on the aimed road, there will be a virtual vehicle be added on the road of the aimed lane as figure 4-16 shows. If the first turning angle of the vehicle β is set as -20 degree, The first position of the virtual vehicle is showed as below:

$$positiony(virtual\_1) = positiony(road\ central) \tag{4-19}$$

$positiony(virtual\_1)$ is the y coordination of the virtual vehicle at time 0 which is the time that ego vehicle needs to change the lane.

$positiony(road\ central)$ is the y coordination of the aimed road's center.

$$\Delta y\_1 = positiony(virtual\_1) - positiony(ego\_1) \tag{4-20}$$

Δy_1 is the relative distance of y-direction between the ego vehicle and the virtual vehicle.

$positiony(ego\_1)$ is the y coordination of the ego vehicle at time 0.

$$\Delta x\_1 = \frac{\Delta y\_1}{\tan{(\beta\_1)}} \tag{4-21}$$

Δx_1 is the relative distance of x-direction between the ego vehicle and the virtual vehicle.

$$positionx(virtual\_1) = \Delta x\_1 + positionx(ego\_1) \tag{4-22}$$

$positionx(virtual\_1)$ is the x coordination of the virtual vehicle at time 0.

Then the virtual vehicle drives straight at the constant speed the same as the speed of ego vehicle at the time that the virtual vehicle was added. Since the relative position keeps changing along the driving of virtual vehicle, the turning angle is changed and can be calculated by the relative distance between the ego vehicle and the virtual vehicle. Therefore, the turning angle of the ego vehicle can be calculated as below:

$$v(virtual\_i) = vego(1) \tag{4-23}$$

$$positiony(virtual\_i) = positiony(road\ central) \tag{4-24}$$

$$positionx(ego\_i) = positionx(ego\_i - 1) + vego(i) * \cos(\beta_{i-1}) * t \tag{4-25}$$

$$positiony(ego\_i) = position\ y(ego\_i - 1) + vego(i) * \sin(\beta_{i-1}) * t \tag{4-26}$$

$$positionx(virtual\_i) = position(irtual\_i - 1) + v(virtual_i) * t \tag{4-27}$$

$$\Delta y\_i = positiony(virtual\_i) - positiony(ego\_i) \tag{4-28}$$

$$\Delta x\_i = positionx(virtual\_i) - positionx(ego\_i) \tag{4-29}$$

$$\beta(i) = \tan^{-1}\frac{\Delta y\_i}{\Delta x\_i} \tag{4-30}$$

$vego(1)$ is the velocity of ego vehicle at the time 0 when the virtual vehicle was added.

i means the timepoint.

t is the time between two timepoints.

$v(virtual\_i)$ is the velocity of the virtual vehicle at time i.

$positiony(virtual\_i)$ is the y coordination of the virtual vehicle at time i.

$positionx(ego\_i)$ is the x coordination of the ego vehicle at time i.

$positiony(ego\_i)$ is the y coordination of the ego vehicle at time i.

$positionx(virtual\_i)$ is the x coordination of the virtual vehicle at time i.

$\beta(i)$is the turning angle of the ego vehicle at time i.

Δy_i is the relative distance of y-direction between the ego vehicle and the virtual vehicle at time i.

Δx_i is the relative distance of x-direction between the ego vehicle and the virtual vehicle at time i.

After calculating the turning angle of the ego vehicle, the steering angle of the front wheel δ of the ego vehicle is calculated by inputting the turning angle β.

With this calculation, the vehicle will perform the trajectory as figure 4-18 shows.

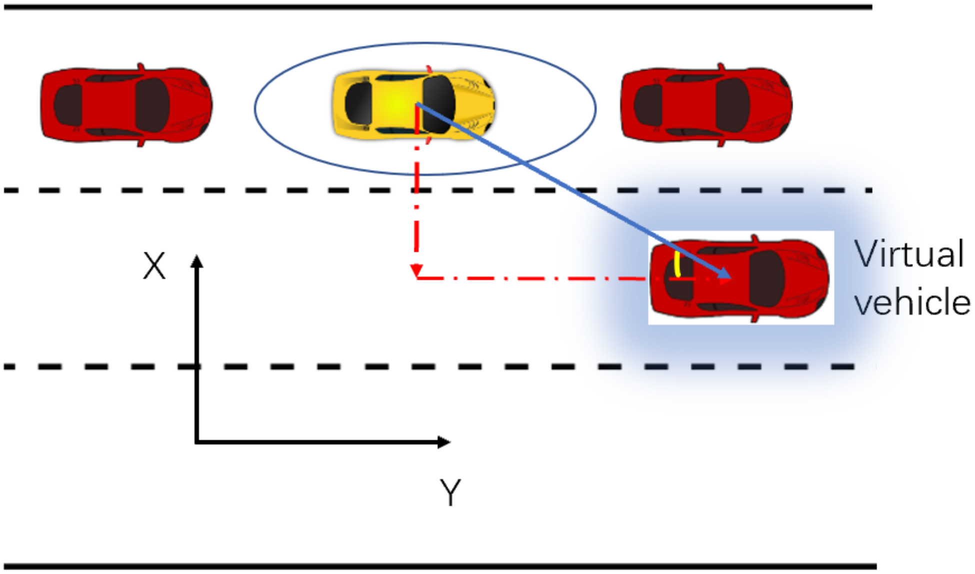


Figure 4-16 Schematic Diagram of the Virtual Vehicle for Ego Vehicle Changing Lane at time 0

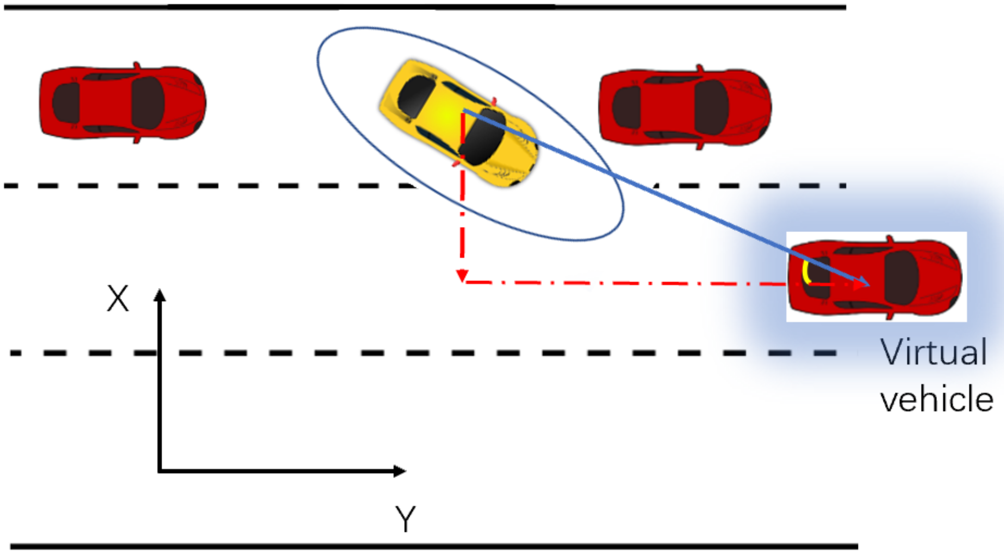


Figure 4-17 Schematic Diagram of the Virtual Vehicle for Ego Vehicle Changing Lane at time *i*.

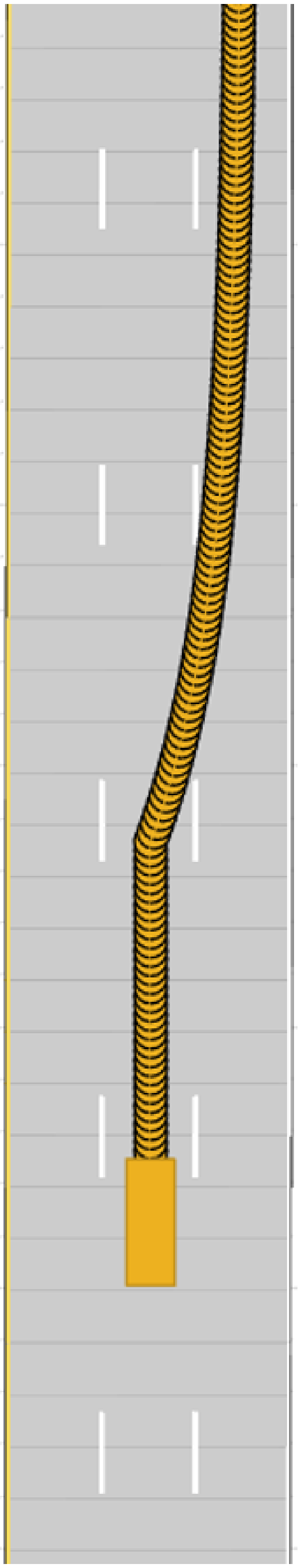


Figure 4-18 Result of Ego Vehicle Changing Lane

4.4 Simulation Parameters

This part summarized the parameters that were used in the formula in the previous chapters. The simulation scenarios setting parameters are shown as the table below:

Table 4-1 Parameters and value of the Simulation

Parameter	Value	Unit
Simulation time	10	s
Sample time	0.01	s
Length of the road	300	m
Number of lanes of the road	3	
Width of the lane	3.6	m
Length of the vehicle	4.848	m
Width of the vehicle	1.842	m
Height of the vehicle	1.517	m
Front overhang	0.911	
Rear overhang	1.119	

The parameters that defined and used in the programming code are specified as below:

Table 4-2 List of Parameters and Specification of the Simulation

List of Parameters	Specification
g	Gravitational acceleration
m_vehicle	Weight of the vehicle
m_human	Weight of the riders in the vehicle
n_front/ n_rear/ n_left/ n_right	Number of the riders in the vehicle
wayfront/ wayrear/ wayleft/ wayright	Waypoints of the vehicle that read from the driving scenario designer
speedfront/ speedrear/ speedleft/ speedright	Velocity of the vehicle that read from the driving scenario designer
waypointrearx/ waypointfrontx/ waypointleftx/ waypointrightx waypointreary/ waypointfronty/ waypointlefty/ waypointrighty	x/ y coordinate of the vehicle
trear/ tfront/ tleft/ tright	Timepoints that related to the waypoints of the vehicle
yaw_rear_original/ yaw_front_original/ yaw_left_original/ yaw_right_original	Degree of yaw of the vehicle that read from the driving scenario designer
speedrearaver/ speedfrontaver/ speedleftaver/ speedrightaver	Average speed of the vehicle between two waypoints
theta_rear/ theta_front/ theta_left/ theta_right	Central angle of the vehicle between two waypoints

a_ego/ a_front/ a_rear/ a_left/ a_right A_front/ A_rear/ A_left/ A_right/ A_ego	Acceleration of the vehicle Effective frontal vehicle cross-sectional area
psi_front/ psi_rear/ psi_left/ psi_right/ psi_ego	Arc length of the vehicle
omega_front/ omega_rear/ omega_left/ omega_right/ omega_ego	Angular velocity of the vehicle
Iz_front/ Iz_rear/ Iz_left/ Iz_right/ Iz_ego	Momentum of Inertia of the vehicle
beta_front/ beta_rear/ beta_left/ beta_right/ beta_ego	Turning angle of the GC (gravity center) of the vehicle
delta_front/ delta_rear/ delta_left/ delta_right/ delta_ego	Steering angel of the front wheel
k_1_front/ k_1_rear/ k_1_left/ k_1_right/ k_1_ego/ k_2_front/ k_2_rear/ k_2_left/ k_2_right/ k_2_ego	Cornering stiffness of front/rear wheel of the vehicle
K_front/ K_rear, K_left, K_right, K_ego	Stability factor of the vehicle
t	Reaction time of the driver
F_s	Gravitational force
F_f	Friction force of the road
F_a	Provided force to the vehicle
F_m	generating force provided by the vehicle's motor
F_air	aerodynamic drag force
Q_turn	Dangerous degree of turning for the vehicle
f	friction force coefficient of the road surface
Q _EC	Dangerous degree of the environmental condition
Q_driver	Dangerous degree of the driver

dsafe_	Safety distance
relative_	Real relative distance
vego	Velocity of the ego vehicle
waypointego	Coordination of the waypoints of the ego vehicel

5. Simulation Results and Discussion

5.1 Simulation Results

The simulations under different scenarios are done and the classic scenario 1_3_2_1 is taken to be discussed below.

For scenario 1_3_2_1, the velocity of the front and the rear vehicle is showed in figure 5-1 and the information of the starting point forego vehicle is showed in figure 5-2. These three vehicles are driving on the 3-lanes, one-way highway. The front vehicle is on the left lane, starts by 27 m/s and decelerates to 25 m/s. The rear vehicle is on the left lane, starts by 35 m/s and decelerates to 33m/s. The ego vehicle starts on the left lane by 25 m/s. It can be noticed that the velocity of the rear vehicle is much higher than the ego vehicle, which means if the ego vehicle takes no reaction, it will have a collision between the ego vehicle and the rear vehicle, which represents the designed scenario1_3_2_1 is a dangerous scenario. Figure 5-3 and figure 5-4 shows the velocity and steering angle of the front wheel for the ego vehicle considering the safety zone based on the dangerous degree evaluation. Considering the generating force of the ego vehicle's motor is not as clear as the velocity, therefore the velocity is chosen to represent the longitudinal control of the ego vehicle. The simulation result is summarized to the following points:

- From 0 s ~1.5 s, only the rear vehicle is dangerous, ego vehicle accelerates to avoid the potential collision.
- From 1.5 s ~ 3.4 s, since the ego vehicle is accelerating and front vehicle is decelerating, front vehicle becomes dangerous. At that time, there are two vehicles inside the safety zone of ego vehicle. Ego vehicle changes the lane to avoid the potential collision.
- While ego vehicle changing the lane, it decelerates to avoid oversteering.

- From 3.4 s ~ 10 s, all the vehicles are safe, ego vehicle accelerates to improve traffic efficiency.

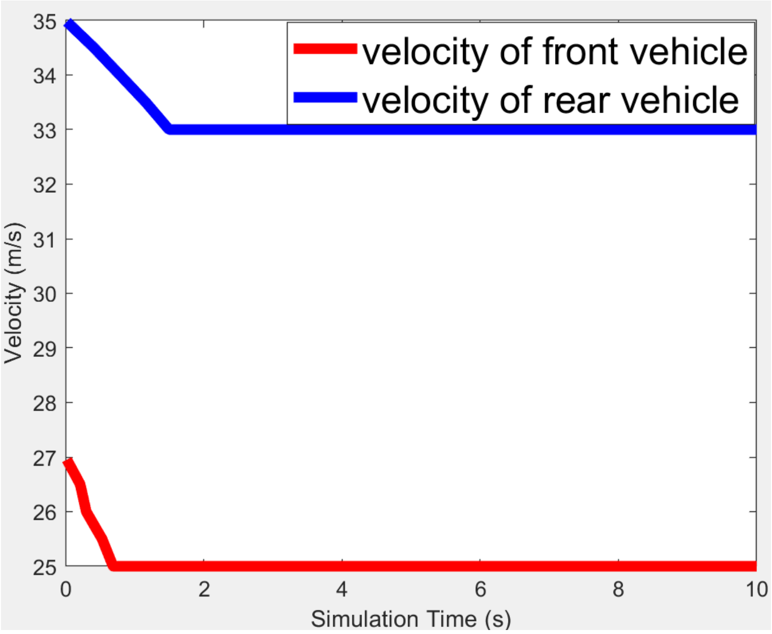
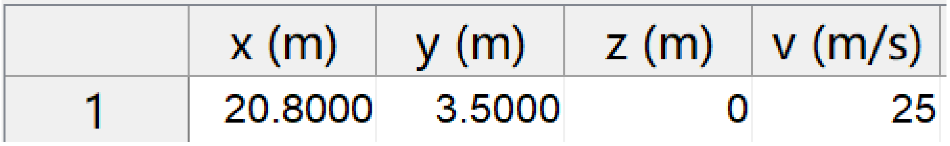


Figure 5-1 Velocity of Rear and Front Vehicle During Simulation



	x (m)	y (m)	z (m)	v (m/s)
1	20.8000	3.5000	0	25

Figure 5-2 Position and Velocity of Ego Vehicle at Time 0

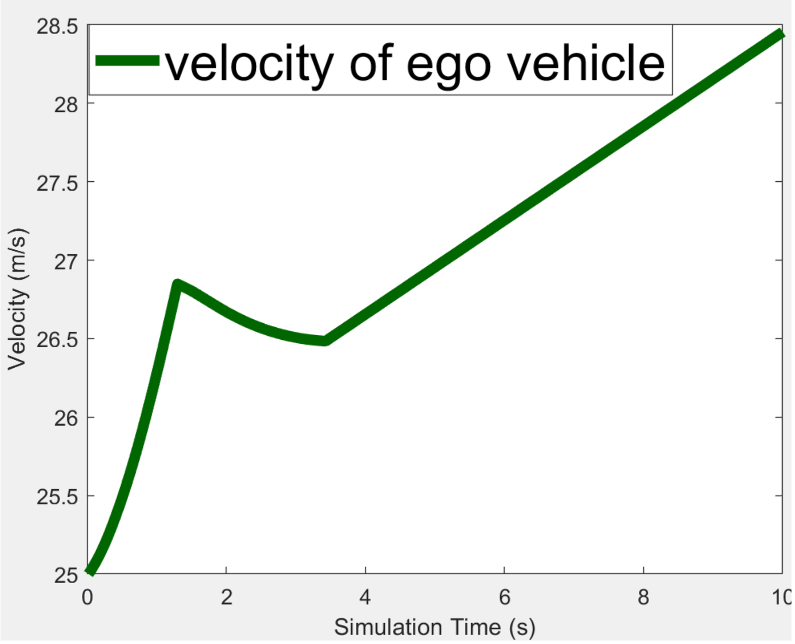


Figure 5-3 Velocity of Ego Vehicle

Figure 5-4 Steering Angel of the Front Wheel of Ego Vehicle

Based on the simulation results, the ego vehicle's control strategy is summarized in table 5-1.

As introduced in chapter 4.3, when a certain error is positive, that certain vehicle is inside the safety zone of the ego vehicle, which means the possibility to have a collision with the ego vehicle. Therefore, when the negative error occurs, the ego vehicle has to make an appropriate reaction to keep the ego vehicle and surrounding safe.

Considering the speed limitation of the highway is 15-35 m/s in this research's assumption, the ego vehicle needs to drive under that speed limitation, in the table, the V means the velocity of the ego vehicle, when the value is 1, it means the ego vehicle is driving followed the speed limit.

Table 5-1 Driving Control Strategy of Ego Vehicle

No.	Error (front)	Error (rear)	Error (left)	Error (right)	V	Driving Course	Generating Force
1	+	+	+	+	1	Accelerate	$F_s = F_{s0} + 25 * error(front)$
2	+	+	+	+	0	Maintain	$F_s = F_{s0}$
3	+	+	+	-	1	Decelerate	$F_s = F_{s0} + 25 * error(right)$
4	+	+	-	-	1	Decelerate	$F_s = F_{s0} + 25 * \min(error(right), error(left))$
5	+	+	-	+	1	Decelerate	$F_s = F_{s0} + 25 * error(left)$
6	+	-	+	+	1	Accelerate	$F_s = F_{s0} - 25 * error(rear)$
7	+	-	+	-	1	Accelerate	$F_s = F_{s0} - 25 * \min(error(right), error(rear))$
8	+	-	-	-	1	Accelerate	$F_s = F_{s0} - 25 * \min(error(right), error(rear), error(left))$
9	+	-	-	+	1	Accelerate	$F_s = F_{s0} - 25 * \min(error(left), error(rear))$

10	-	+	+	+	1	Decelerate	$F_s = F_{s0} + 25 * error(front)$
No.	Error (front)	Error (rear)	Error (left)	Error (right)	V	Driving Course	Generating Force
11	-	+	+	-	1	Decelerate	$F_s = F_{s0} + 25 * \min(error(left), error(rear))$
12	-	+	-	-	1	Decelerate	$F_s = F_{s0} + 25 * \min(error(left), error(right), error(front)$
13	-	+	-	+	1	Decelerate	$F_s = F_{s0} + 25 * \min(error(left), error(front))$
14	-	-	+	+	1	Change Lane	$F_s = F_{s0} + 25 * (-4)$
15	-	-	+	-	1	Change Lane	$F_s = F_{s0} + 25 * (-4)$
16	-	-	-	-	1		
17	-	-	-	+	1	Change Lane	$F_s = F_{s0} + 25 * (-4)$

5.2 Discussion

Considering the simulation results, the most iconic part is from 0s to 1.5s, therefore the results of this period are taken to discuss.

Checking with the relative distance and safety distance of the rear vehicle, since the velocity of the rear vehicle is much higher than the ego vehicle, therefore the relative distance is always larger than the safety distance.

Checking with the relative distance and safety distance of the front vehicle, since the front vehicle has decelerated, the safety distance is getting larger. But from 0s to 1.3s, the relative distance is always larger than the safety distance, during that period, the front vehicle is safe.

Based on the above analysis, considering the velocity of the ego vehicle is under the speed limit of the road, the ego vehicle chooses to accelerate to avoid the collision with the rear vehicle.

However, the acceleration of the ego vehicle makes the safety distance of the front vehicle getting larger, and at 1.3s, the front vehicle becomes the dangerous vehicle. From 1.5s, the front vehicle and rear vehicle are both inside the safety zone of the ego vehicle. Only the adjustment of velocity cannot ensure the safety of the ego vehicle and surrounding vehicle, therefore, from 1.3s, the ego vehicle starts to change the lane. In order to change the lane smoothly, the ego vehicle has the deceleration and the steering angle of the front wheel. After changing the lane, the ego vehicle and surrounding vehicles are safe, therefore the ego vehicle chooses to accelerate to reach the speed limit of the road. The control of ego vehicle is following table 5-1. The results of generating force are also showed in figure 5-9.

The results show that the ego vehicle and avoid the potential collision successfully, which can lead to the conclusion of the ADS that considering the safety zone can ensure the safety of not only the ego vehicle and also the surrounding vehicle.

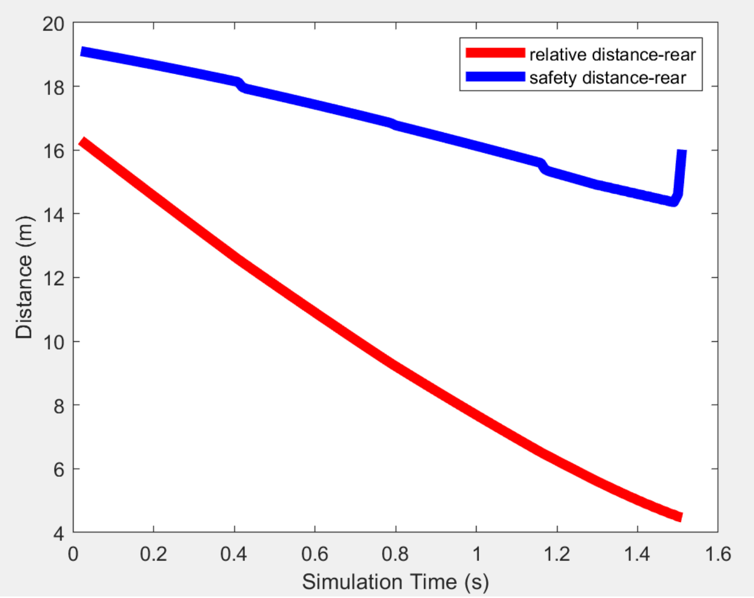


Figure 5-5 Relative Distance and Safety Distance of Rear Vehicle by 1.5s

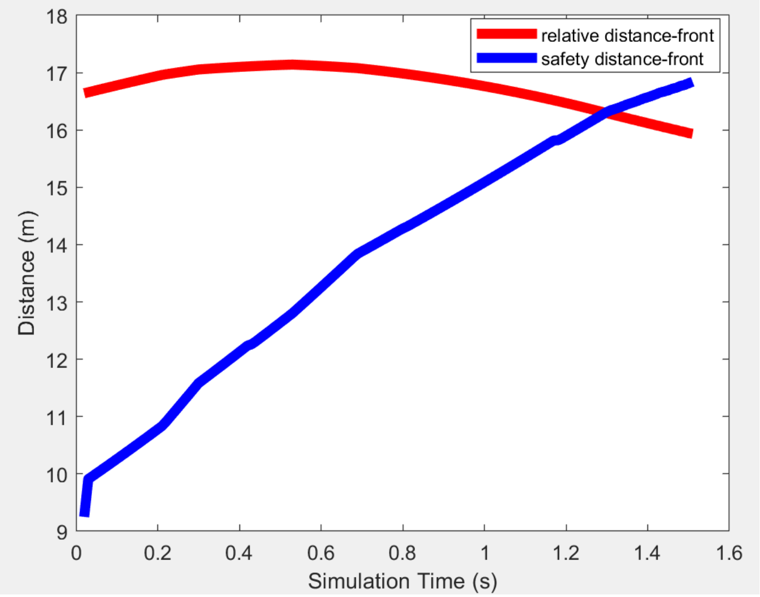


Figure 5-6 Relative Distance and Safety Distance of Front Vehicle by 1.5s

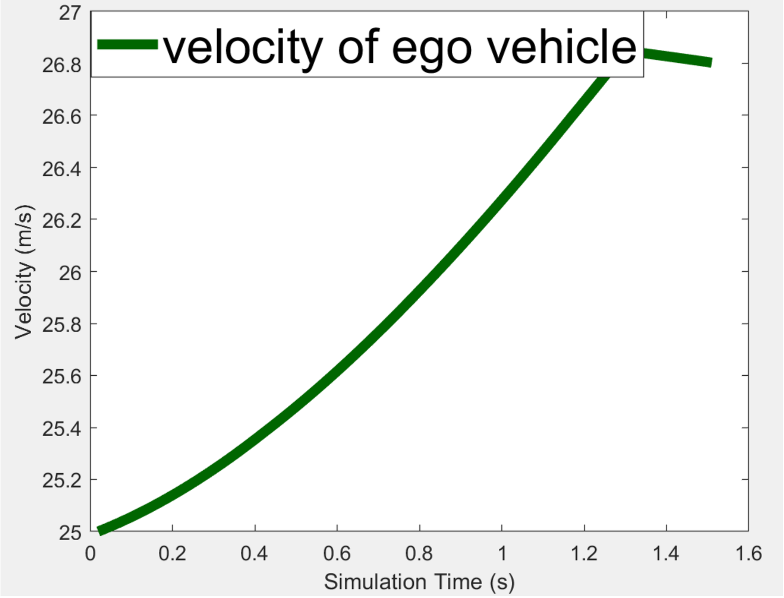


Figure 5-7 Velocity if Ego Vehicle by 1.5s

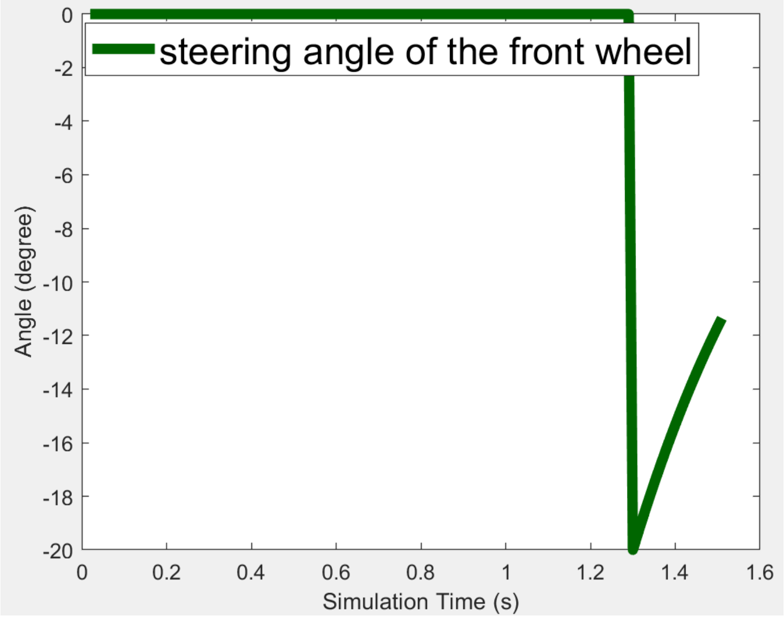


Figure 5-8 Steering Angle of the Front Wheel of Ego Vehicle by 1.5s

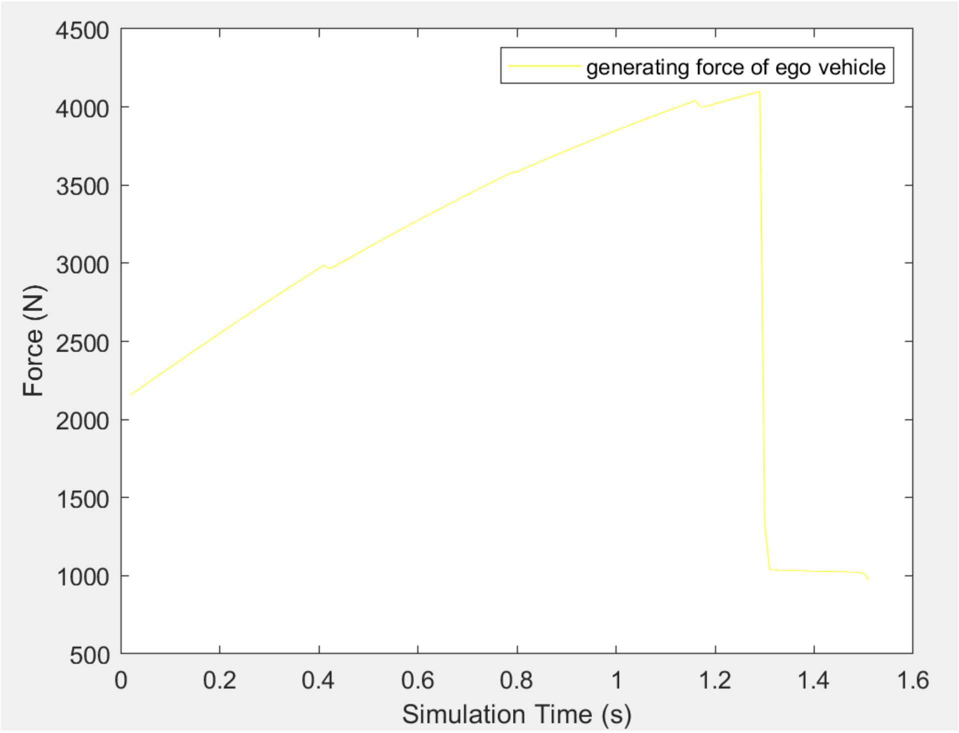


Figure 5-9 Generating Force of Ego Vehicle by 1.5s

During this research and simulations, there are several insights for future research:

- Considering the surrounding vehicle may contain ADV, and the different ADS provided by different companies may have a difference on the performance, therefore, the evaluation of the performance of the ADS based on the perceived information needs to be considered in future research.
- Based on the above idea, it's necessary to recognize the ADV and human-driving vehicles that around the ego vehicle, based on the recent published research [44], this recognition method could be utilized in future research.
- During this research, the slide wind did not be considered while doing vehicle dynamics analysis, which could be involved in future research.

- The assumption of this research is on the highway, but in current research, the process of exiting the highway has not been considered, which needs to be added in future research.
- Since safety zone may change depending on the situation around the ego vehicle with ADS, safety distance constructing the safety zone needs to be defined based on the situation.

6. Conclusion

In this paper, the definition and calculation method of the safety zone and dangerous degree are proposed. The architecture of the ADS considering the safety zone and dangerous degree is described utilizing SysML. The operational context of the system is described in detail. The internal object flow between the subsystems of the ADS, the activities within the system, and the interfaces inside the system have also been modeled based on the approach of MBSE. The architecture description defines how the ADS works with the function of safety zone calculation to avoid the potential collision and ensure the safety of ego vehicle and surrounding vehicles. Based on the above architecture, this proposed ADS is simulated based on scenarios designing utilizing Driving Scenario Designer and programmed with MATLAB. The results of the simulations show the proposed ADS is able to ensure the safety of ego vehicle and surrounding vehicles safety which means can be helpful to provide safety to the transportation system.

In the first chapter, the necessity of ADS is illustrated. The ADS is an effective method to reduce the accidents caused by human error, further solve the social problem. However, the problem of social acceptance for ADS is pointed out which proved the importance of safety. From the safety concern, the researchers did a lot of studies of safety distance, but the notice of all surrounding vehicles has not been taken. Then the research purpose is described.

Based on the analysis and literature review of chapter 1, the proposal of defining the safety zone is introduced in the second chapter. While analyzing the influencing factors of the safety zone, the definition of a dangerous degree is proposed. The dangerous degree is decided by the environmental condition, driver's state, and driving skill level of the driver. Based on the analysis above, the calculation of the safety zone is introduced.

The third chapter describes the architecture of the ADS considering the proposed safety zone and dangerous degree utilizing SysML. It introduces the conceptual use case of ADS, then the context of ADS is illustrated, also introduces the subsystems of ADS. Detailed the activities of the ADS performing the dynamic driving task on highway considering safety zone and the object flow of the internal ADS are also described.

Based on the analysis of the architecture, scenario-based simulations are created to evaluate the performance of the proposed ADS. The necessity of scenarios designing is clearly explained. As the preparation of the simulations, the vehicle dynamics are analyzed. Then the detail of the ego vehicle's driving control is introduced with the output of generating force of the ego vehicle's motor and the steering angle of the front wheel of the ego vehicle.

With the simulation results discussion, the vehicle driving control method is listed which is proofed by the simulations. Based on the current, the insights about future research are considered.

Through the simulations, the effectiveness of the proposed ADS is proofed, which means the safety of ego vehicle and surrounding vehicles can be ensured by the proposed ADS that considers the safety zone and dangerous degree.

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Appendix

1. The problem that happened during my research which leaded to failed results and the solutions are listed as below:

Problem: While creating the driving scenarios, the method is to set waypoints for the vehicles. So, I only set 5 waypoints for each vehicle. However, while calculating the relative distance, I used the waypoints directly. The result is unnormal because the response of the ego vehicle is not consisted with the proposal. The reason of the unnormal result is the waypoints i for the vehicles are not at the same timepoint since the distance and velocity between two waypoints are different from vehicle to vehicle.

Solution: Calculating the velocity of the vehicles each 0.01s. This calculation is based on the following formula:

$$a_i = \frac{{v_i}^2 - {v_{i-1}}^2}{2x_i}$$

a_i is the acceleration from waypoint $i-1$ to waypoint i.

x_i is the distance from waypoint $i-1$ to waypoint i.

v_i is the velocity of waypoint i.

$$v_{t_j} = v_{i-1} + a_i * t$$

$$t = T_j - T_{i-1}$$

T_{i-1} is the time of waypoint i.

v_{t_j} is the velocity at timepoint j.

t is the time from T_{i-1} to T_j.

$$\Delta x_j = \frac{{v_{t_j}}^2 - {v_{i-1}}^2}{2a_i}$$

x_j is the distance from waypoint $i-1$ to timepoint j.

$$position_j = position_{i-1} + \Delta x_j$$

$position_{i-1}$ is the position of waypoint $i-1$.

$position_j$ is the position at timepoint j.

MATLAB code:

```
for i=2:5
    waypointleftx(i)=wayleft(i,1);
    waypointlefty(i)=wayleft(i,2);
    tleft(i)=tleft(i-1)+2*((waypointleftx(i)-waypointleftx(i-
    1))^2+(waypointlefty(i)-waypointlefty(i-
    1))^2)^0.5/(speedleft(i)+speedleft(i-1));
    l_left(i)=((waypointleftx(i-1)-waypointleftx(i))^2+(waypointlefty(i-1)-
    waypointlefty(i))^2)^0.5;
    aleft(i)=((speedleft(i))^2-(speedleft(i-1))^2)/2*l_left(i);
end

for i=1:1000

 T(i)=0.01*i;
 if T(i) > tleft(1) && T(i) <= tleft(2)
    vleft(i)= speedleft(1)+aleft(i)* (T(i)-tleft(1))
    speedleftaver(i)= (vleft(i)- vleft(i-1))/2
     positionleftx(i)=waypointleftx(1)+speedleftaver(i)*(T(i)-tleft(1));
```

```
   positionlefty(i)=waypointlefty(1)+(waypointlefty(2)-
   waypointlefty(1))*(T(i)-tleft(1))/(tleft(2)-tleft(1));
elseif T(i) > tleft(2) && T(i) <= tleft(3)
   vleft(i)= speedleft(2)+aleft(i)* (T(i)-tleft(2))
   speedleftaver(i)= (vleft(i)- vleft(i-1))/2
   positionleftx(i)=waypointleftx(2)+speedleftaver(i)*(T(i)-tleft(2));
   positionlefty(i)=waypointlefty(2)+(waypointlefty(3)-
   waypointlefty(2))*(T(i)-tleft(2))/(tleft(3)-tleft(2));
elseif T(i) > tleft(3) && T(i) <= tleft(4)
   vleft(i)= speedleft(3)+aleft(i)* (T(i)-tleft(3))
   speedleftaver(i)= (vleft(i)- vleft(i-1))/2
   positionleftx(i)=waypointleftx(3)+speedleftaver(i)*(T(i)-tleft(3));
   positionlefty(i)=waypointlefty(3)+(waypointlefty(4)-
   waypointlefty(3))*(T(i)-tleft(3))/(tleft(4)-tleft(3));
elseif T(i) > tleft(4) && T(i) <= tleft(4)
   vleft(i)= speedleft(4)+aleft(i)* (T(i)-tleft(4))
   speedleftaver(i)= (vleft(i)- vleft(i-1))/2
   positionleftx(i)=waypointleftx(4)+speedleftaver(i)*(T(i)-tleft(4));
   positionlefty(i)=waypointlefty(4)+(waypointlefty(5)-
   waypointlefty(4))*(T(i)-tleft(4))/(tleft(5)-tleft(4));
elseif T(i) > tleft(4) && T(i) <= tleft(4)
   vleft(i)= speedleft(5)
   speedleftaver(i)= (vleft(i)- vleft(i-1))/2
```

```
            positionleftx(i)=waypointleftx(5)

            positionlefty(i)=waypointlefty(5)

          end

          end
```

2. MATLAB code for calculating turning angle of the ego vehicle by setting virtual vehicle.

```
for i=N+1:1000

        relative_virtual_y(N)=positionvirtualy(N)-waypointego(N,2);

        error_front(i-1)=relative_front(N)-dsafe_front(N);

        F_air_ego_now(i-1)=F_air_ego_now(N);

        vvirtual(i-1)=vego(N);

        positionvirtualy(i)=positionvirtualy(i-1);

        positionvirtualx(i)=positionvirtualx(i-1)+vvirtual(i-1)*0.01;

        F_m_x_ego(i)=F_m_x_ego(1)-20*abs(error_rear(i));

        a_ego(i)=(F_m_x_ego(i)-F_air_ego_now(1)-F_f_ego-

         F_s_ego)/(m_ego*c_ego);

        vego(i)=vego(i-1)+a_ego(i)*0.01;

        waypointego(i,1)=waypointego(i-1,1)+vego(i)*0.01;

        delta_ego_rad(i-1)=delta_ego(i-1)*pi/180;

        waypointego(i,2)=waypointego(i-1,2)+vego(i-1)*tan(delta_ego_rad(i-

        1))*0.01;

        relative_virtual_y(i)=positionvirtualy(i)-waypointego(i,2);

        relative_virtual_x(i)=positionvirtualx(i-1)-waypointego(i-1,1);
```

```
        delta_ego_rad(i)=atan(relative_virtual_y(i)/relative_virtual_x(i));

        delta_ego(i)=delta_ego_rad(i)*180/pi;

end
```