MASTER

Integration of AEB system into ACC system and impact assessment via traffic simulation

Ren, J.

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Master Thesis

Integration of AEB system into ACC system and impact assessment via traffic simulation

Author Name:	Jiabo Ren
Student Number:	1421204
Master Program:	Automotive Technology

supervisors

dr. ir. Ion Barosan
dr. ir. Lin Xiao
dr. ir. Antoine Schmeitz

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EINDHOVEN UNIVERSITY OF TECHNOLOGY

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Name

Jiabo Ren …………………………………………………..…………..

ID-number

1421204 …………………………………………………..…………..

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任嘉波 …………………………………………………..…………..

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Abstract

Future road transportation can be more safe. Enormous amount of effort from academia, industry and legislation bodies has been invested to achieve this ambition. Autonomous Emergency Braking (AEB) systems, equipped on the human-driven vehicles, can reduce road causalities and crash severity. However, if the safety-driven autonomous emergency systems and comfort-driven advanced driver assistance systems, such as Adaptive Cruise Control (ACC) systems run independently on the same vehicle, the overall benefit will be reduced. As the level of automation of automated vehicles increases to reach SAE Level 4 or higher, the effective integration of the two systems can further improve the performance of the vehicle and also financially beneficial.

This graduation project tries to find out what is a possible way to coordinate the functions of autonomous emergency systems and those of adaptive cruise control systems, and what impact this integration has on traffic flow and safety. This graduation project bases its methodology on model-based systems engineering principles to organize the research work. An integrated ACC+AEB system is proposed and the microscopic traffic simulation is applied to examine the impact on the traffic flow by simulating the driving scenario in a hypothetical highway road section near an on-ramp.

This graduation project makes contribution to the understanding of how (C)ACC vehicles behave in the safety critical situations and the limitations of the traditional AEB system when integrated with (C)ACC system. A state-chart based (C)AEB system is designed to be integrated into the existing (C)ACC system architecture and is proved to have better collision avoidance performance than the integration of (C)ACC system with a traditional AEB system. Furthermore, this graduation project provides insights on the impacts of the (C)AEB system has on the traffic flow. The benefits of integrating (C)AEB system into (C)ACC system on the traffic safety are revealed.

Key words: AEB, ACC, Traffic simulation, Autonomous driving

Acknowledgment

This master thesis is written as partial complement of the master Automotive Technology at Eindhoven University of Technology. The aim of this thesis is to create an integrated design for ACC system and AEB system and investigate the impact on the traffic flow of such an integration. This graduation project can not be finalized without the immense help and kind support from many people. I would like to take the opportunity to give my thanks to all those contributing to this graduation project.

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Eindhoven, September 2021
Jiabo Ren

Contents

Abbreviations

ACC	Adaptive Cruise Control
ADAS	Advanced Driver-Assistance Systems
AEB	Autonomous Emergency Braking
AV	Automated Vehicles
CACC	Cooperative Adaptive Cruise Control
HDV	Human-Driven Vehicles
INCOSE	International Council on Systems Engineering
MBSE	Model-Based Systems Engineering
MPR	Market Penetration Rate
SUMS	Sustainable Urban Mobility and Safety department
TIH	Time Integrated Hard Brake Time
TIT	Time Integrated Time-to-Collision
TTC	Time To Collision

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Chapter 1

Introduction

This chapter, first gives background information of the problem which the graduation project focuses on in the section **Problem context**, and presents more concrete context about the graduation project in the section **Project context**. The research scope is narrowed down and research questions are listed and explained in the section **Research questions**. Finally, the structure of the thesis is gone through in the section **Thesis structure**.

1.1 Problem Context

The global epidemic of road crash fatalities and disabilities is imposing a great threat to the public health. 22700 fatalities are reported in the EU countries in 2019 and the fatality rate was 51 fatalities per million inhabitants in the same year [2]. The target of reducing road fatalities by 50% during the 2010-2020 period would not be met according EU report [3]. In US, according to the National Highway Traffic Safety Administration, a statistical projection of traffic fatalities for 2019 shows that an estimated 36,120 people died in motor vehicle traffic crashes and the fatality rate was 1.10 fatalities per 100 million Vehicle Miles Traveled for that year [1].

Worldwide, the World Health Organization highlighted in the global road safety status report which was launched in December 2018, that the number of annual road traffic deaths reached 1.35 million [4]. Among those disastrous road accidents, human errors are accountable for the vast majority of them - about 94% [5]. However, human factors - though considered as critical reasons for the majority of crashes - such as recognition error, decision error and performance error can be avoided or relieved greatly by the emerging vehicular technologies, such as Advanced Driver-Assistance Systems (ADAS) and Automated Vehicles (AV).

Not surprisingly, the development and rollout of AV is done in an incremental manner which makes the mixed traffic of AV and human-driven vehicles (HDV) not an unusual scene in the public roads. This can have a negative impact on the traffic flow. New threats for road safety would emerge due to the human-machine interaction - the interaction between AV and the drivers of subject vehicle and of other vehicles in the road. This is because, firstly, the fact that AV requires a take-over from the driver in the critical situations maybe induce more radical driving behaviours in comparison with the behaviors of HDV. Secondly, the heterogeneity of the mixed traffic flow may result in more conflicts in the roads and thus decrease the road safety. Some real-world AV-involved crashes are recorded, most of which are rear-end crashes [6]. How AV and other new vehicular technologies will affect the traffic flow in terms of road safety and traffic efficiency, is calling for more systematic investigation.

1.2 Project Context

This graduation project is initiated by the microsimulation team in the Sustainable Urban Mobility and Safety department (SUMS), TNO. SUMS has the ambition to support national and international governments and industry with the design, implementation, monitoring and evaluation and then timely adjustment and scale-up of smart innovative measures in the living environment. The aim of SUMS is to find the optimal balance between the needs of users in terms of mobility and safety and, on the other hand, the quality of the living environment [7]. The activities of microsimulation team in SUMS are mainly about the research on the complex vehicle interactions and intelligent transportation systems via microscopic traffic simulation and modelling the new forms of mobility such as autonomous driving and Mobility-as-a-Service.

The motivation of this graduation project are twofold. First of all, from the earlier work done by the microsimulation team, the AV' behavior with the inclusion of Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) has been implemented in the microscopic traffic simulation model. The modelling of an Autonomous Emergency Braking (AEB) system is needed for a more realistic automated driving behavior simulation.

Furthermore, there are gaps in the research literature needed to be filled. Most of research about collision avoidance systems from industry and academia are in the vehicle level and evaluates the safety benefits in terms of fatality and injury reduction. There is not much work which have been done in the traffic level. For more detailed explanation regarding the state of art and the research gaps, please refer to **Chapter 2. Literature Review**.

1.3 Problem Definition and Research Questions

ACC systems can reduce stress for the driver by automatically controlling vehicle speed and maintaining a predefined preferred distance to the preceding vehicle. ACC systems focus on the driving comfort instead of safety. Autonomous Emergency Braking (AEB) systems are designed to help driver react to the emergency situations better, for example, by braking earlier and stronger. The current development of ACC systems and AEB systems are separated and not well connected. Research about AEB systems are mostly for HDV. In a HDV, AEB systems can issue the warning of a potential collision in advance and assist the driver with hard braking later if necessary. The state-of-the-art AEB systems require the drivers to be fully attentive on the driving tasks. This contradicts the fact that human drivers are tend to be distracted more easily when ACC systems are controlling of the AVs. It remains unclear as to how AEB systems can be adapted for ACC systems so that a unified integration of both systems can improve driving comfort as well as driving safety, not to say the impact of such an integration on the traffic flow.

Hence, the research questions of this graduation project are:

1. **What are the limitations of the ACC vehicles in the critical driving situations?**
2. **How to design an AEB system for ACC vehicles which can avoid rear-end collisions without driver's take-over?**
3. **What impacts the integrated ACC+AEB system has on the traffic flow?**

1.4 Outline and Contribution

The thesis has eight chapters.

Chapter 2. Literature Review gives the state of art for two research topics: AEB system development and safety assessment of the mixed traffic.

Chapter 3. Methodology introduces the methodology applied to this graduation project. Specifically speaking, Model-based systems engineering approach would be introduced, i.e. what is model-based systems engineering and how its systematic approach buttresses this graduation project. Afterwards, the traffic simulation techniques will be introduced and the reason why microscopic simulation was chosen in this project over other traffic simulation techniques is explained.

Chapter 4. Requirements and System Context of AEB system contains the requirements of the integrated ACC+AEB system which are going to be built, the system context including the external systems interacting with the ACC+AEB system and the interface. From Chapter 4 on, the substantial content of this graduation project is to be unveiled.

Chapter 5. ACC System Structure and Performance Analysis shows the structure and the behavior of the ACC systems in case of emergency. The limitations of ACC+traditional AEB system are examined.

The findings from Chapter 5 lead to the integrated design of ACC+AEB system in **Chapter 6. Integrated ACC+AEB System: Functions, Architecture and Performance**. Chapter 6 focuses on the design of a new AEB system without binding with the assumptions and principles hold for HDVs. The functional view and the architecture of the integrated ACC+AEB system is presented in Chapter 6. Finally, Chapter 6 reveals what are the effects on the vehicle's behavior of the integrated ACC+AEB system.

Chapter 7. Traffic Impact Assessment contains the evaluation of the impact of the integrated ACC+AEB system on the traffic flow via microscopic traffic simulation.

Chapter 8. Conclusions and Future Work presents the conclusions of the project and the future work suggested.

The contribution of this graduation project can be summarized as follows:

1. Investigate the ACC vehicles' behavior in the emergency situations. Outline the collision avoidance capabilities of ACC systems, both with and without the integration with a traditional AEB system.
2. Design an AEB system enabling an better collision avoidance capability and realize its integration with the given ACC system.
3. Assess the impact of the AEB system on the traffic flow in a highway road section with a merging bottleneck.

1.5 Summary

In this chapter, the **Problem Context** section contains a description of the big picture within which the potential impact on the real world of the project can be deduced. In **Project Context** the specific context of and the motivation for this graduation project is given so that a background with a clearer focus is depicted. Next, the focus of the project is further boiled down to a well-formulated problem definition and precise research questions in section **Problem Definition and Research Questions.** Finally a glance of the content of the whole thesis is given and the main contributions of this project is summarized in section **Outline and Contribution**.

Chapter 2

Literature Review

In this chapter, the state of art of two research domains are going to be probed, namely, the design of AEB system and its integration with ACC system, and the impact evaluation of the mixed traffic.

2.1 AEB System Development

The AEB systems are designed to avoid accidents utilizing driver visual/audible alerts as well as automatic partial and full-braking in a number of scenarios. Considering the scope of this graduation project, the AEB systems mentioned are those for passenger cars and applicable in car-to-car collision scenarios. AEB systems can be classified as a type of collision avoidance system. As shown in Fig 2.1, collision avoidance systems consist of three blocks, namely, the threat assessment block, the decision-making block and the intervention module [11]. The threat assessment block is responsible for processing the environment data to give an estimate of the risk for the situation. Based on the risk estimation given by the threat assessment block, the decision making block decides whether the intervention is needed and, if so, what intervention should be in place. The intervention module is a controller for the lowest level of actuators, e.g. throttle, brake and steering wheels. Based on the outputs of the decision making block, there are two distinctive strategies to

Figure 2.1: Block Diagram of Collision Avoidance Systems [11]

avoid a collision: by longitudinal control only, and by controlling the vehicle's behaviour simultaneously in longitudinal and lateral directions. Longitudinal collision avoidance means to brake proactively to avoid an imminent collision in critical situations but not to give any command to steering wheels. AEB systems are the representative of the longitudinal collision avoidance strategy.

In this section, the development and research work about AEB system will be explored. The overall structure of this section is shown in Fig 2.2. To begin with, a couple of examples of AEB system available in the commercial passenger cars will be presented so that the readers can have an overview of how AEB system functions in the real cars. The techniques used to realize AEB functionalities for vehicles from one OEM always somewhat differ from that of another. However, some common characteristics of AEB systems can be recognized. Then the UN Regulation No.152 with regard to AEB systems for passenger cars is introduced.

Next, we focus on the research work from academia. AEB development began in 1973 to mitigate the number of severe traffic accidents. Since then, there is continuous innovation [25]. The main goal of this graduation project is to integrate AEB system into ACC system; we first look into the innovations for stand-alone AEB systems and then conclude this section with the techniques used in the ACC+AEB integration work.

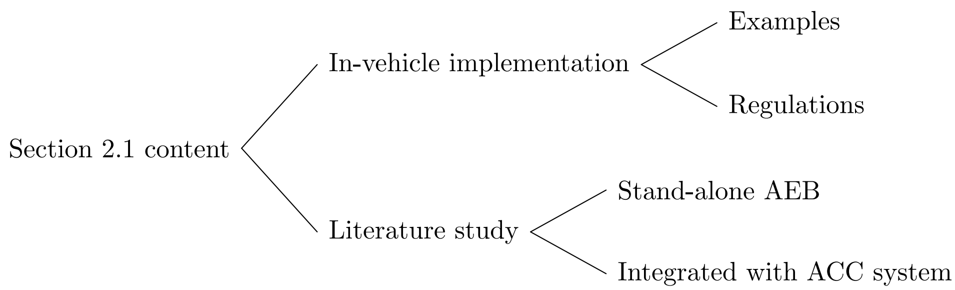


Figure 2.2: Section 2.1 structure

2.1.1 Available AEB systems on the Market and Relevant Regulations

Fig. 2.3 gives a clear overview of AEB functionalities of Audi A8 in time sequence. AEB systems are activated in several steps. In the first phase, the brakes and dampers are preconditioned so that their response time can be shorter during emergency. If the situation becomes worse, the driver starts to receive warning, first acoustically, then optically and finally by brake jerking. Till now, if the driver doesn't react properly to decrease the collision threat low enough, the two-phase partial braking come into play. The brake in the first phase of partial braking is relatively weaker - $-3\ m/s^2$ - but it is big enough to alert an attentive driver and decreases the speed of vehicle significantly. The brake in the second phase of partial braking, in this case, is $-5\,m/s^2$. When the criterion of a unavoidable collision is reached, the full braking is activated and the driver is no longer be able to intervene the braking henceforth.

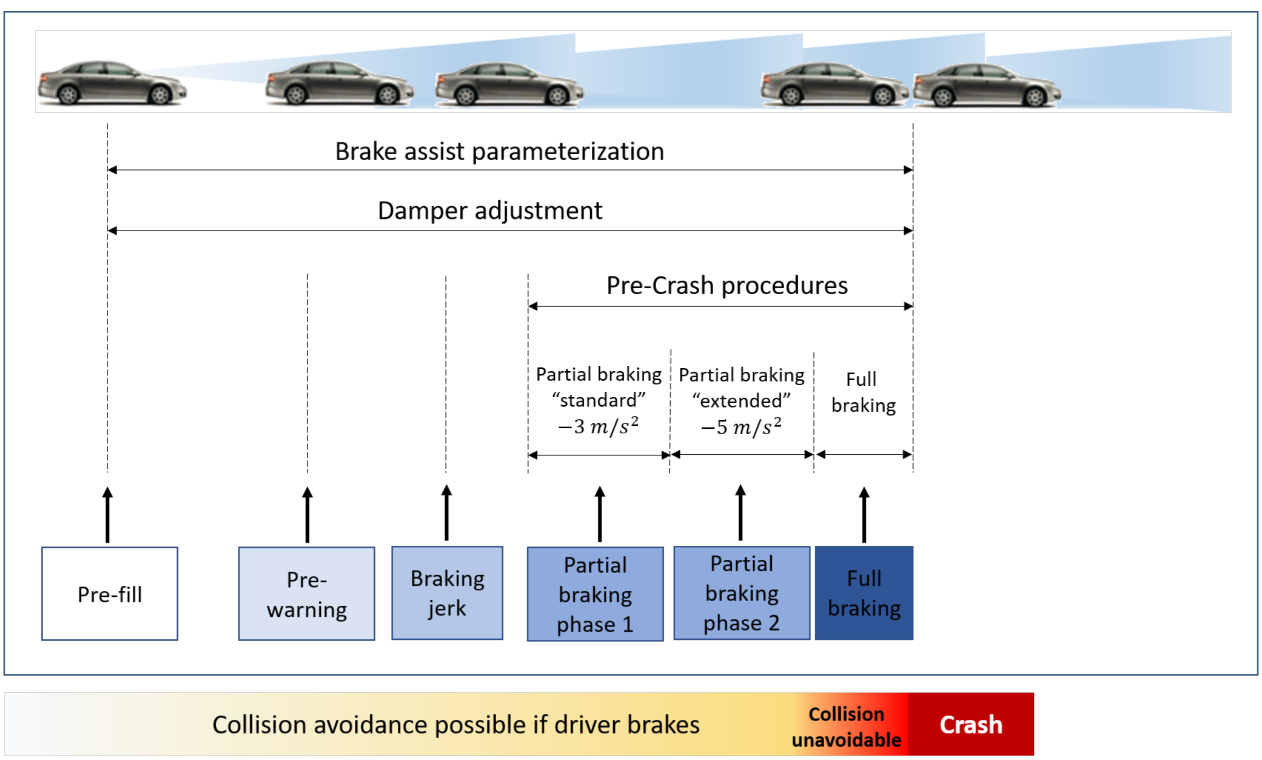


Figure 2.3: AEB braking levels of escalation in the Audi A8 [24].

Volvo City Safe [26] provides a similar collision avoidance functionality but with one phase of partial braking at 50% of maximum braking power and full braking in rapid succession. Mercedes-Benz's latest AEB system

PRE-SAFE Brake [27] also does automatic braking in two stages: around 1.6 s before the calculated impact point – after three audible warning signals – the system initiates partial braking autonomously and decelerates the car with around 40% of the maximum braking power which is approximately $4\,m/s^2$. If the driver fails to react, even after automatic partial braking, the PRE-SAFE Brake activates the maximum braking power around 0.6 s before the now unavoidable collision. The safety benefits of the PRE-SAFE Brake are significant. Realistic tests carried out by the Mercedes engineers have revealed that autonomous PRE-SAFE emergency braking reduces the impact speed by 16 km/h on average.

The characteristics of the state-of-art AEB systems in the commercial passenger cars can be summarized as follows:

1. Oftentimes AEB system functions in parallel with other safety components in the vehicle, such as dampers, belt pretensioner, controllers of sunroof and windows etc. to provide comprehensive protection to the driver.

2. The activation of AEB systems consists of three phases: Warning - partial braking - full braking. The warnings include acoustical, optical and sometimes tactical signs. The tactical warning in some cases is combined with braking, either a braking jerk or a relatively weak but sensible partial braking. The tactical warning is designed to supplement the visual and audible warnings. It gives the driver a further, perceptible signal to act. The partial braking can also be done in more than one phases.

3. The premise of the design of AEB systems is that the driver should bear responsibility of avoiding the collision and AEB systems are only for assistance and support. That's the reason why full braking is only activated when the threat assessment criterion is reached for an unavoidable collision.

The concrete technical details about how AEB is implemented, in other words, the logic behind the three constituent blocks for AEB systems as shown in Fig. 2.1 can not be found from OEMs' public information because they are proprietary. This brings about a need of examination of literature for the latest technology and methodology adopted in the development of AEB systems. Before doing that, we first brief the two important documents in regard to the AEB system - ISO 22839 and UN Regulation No.152. The ISO 22839 standard [28], Intelligent transport systems — Forward vehicle collision mitigation systems — Operation, performance, and verification requirements, specifies the concept of operation, minimum functionality, system requirements, system interfaces, and test methods for Forward Vehicle Collision Mitigation Systems. UN Regulation No.152 [29] establishes uniform provisions for Advanced Emergency Braking Systems fitted to motor vehicles of the Categories M1[1] and N1[2] primarily used within urban driving conditions.

It's worth mentioning that the distinction between standards and regulations lies in compliance. While conformity with standards is voluntary, technical regulations are by nature mandatory. The reasons why ISO 22839 and UN Regulation No.152 are referred to are twofold. Firstly, some valuable insights can be drawn from them about the requirements of AEB systems from the perspectives of standard bodies and regulatory regimes and thus more background information about this graduation project is given. Secondly, these two documents are considered as important references based on which a traditional version of AEB system is implemented and integrated with ACC system to find out the performance and limitations of such an integration.

In the ISO 22839 standard, the formulas for calculating time-to-collision (TTC) and enhanced-time-to-collision (ETTC) are given as below:

$$TTC = -\frac{x_c}{v_{tv} - v_{sv}}$$

$$ETTC^3 = \frac{-(v_{tv} - v_{sv}) - \sqrt{(v_{tv} - v_{sv})^2 - 2 * (a_{tv} - a_{sv}) * x_c}}{a_{tv} - a_{sv}}$$

[1] In vehicle categories according to the Consolidated Resolution on the Construction of Vehicles [30], "Category M1" represents power-driven vehicles having at least four wheels and used for the carriage of passengers and comprising not more than eight seats in addition to the driver's seat.

[2] In vehicle categories according to the Consolidated Resolution on the Construction of Vehicles [30], "Category N1" represents power-driven vehicles having at least four wheels and used for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes.

[3] For the derivation of ETTC, refer to Appendix A

in which x_c is the distance from the target vehicle trailing surface to the subject vehicle leading surface; v_{sv} is the velocity of the subject vehicle; v_{tv} is the velocity of the target vehicle; a_{sv} is the acceleration of the subject vehicle; a_{tv} is the acceleration of the target vehicle.

Three types of countermeasures are introduced in the ISO 22839 standard, which are *Collision Warning*, *Speed Reduction Braking* and *Mitigation Braking*. *Collision Warning* is a warning based on some combination of audible, visual and tactile or haptic sensory modes, meeting the requirements of ISO 15623. *Speed Reduction Braking* is an automatic braking function intending to reduce subject vehicle velocity. *Mitigation Braking* is an automatic braking applied when the collision appears unavoidable.

Besides other performance requirements specified in the ISO 22839 standard, the timing of each of aforementioned countermeasures are of particular interest. The requirements related to this issue are as follows[4]:

5.2.1
: A Collision Warning countermeasure shall occur no later than the initiation of Speed Reduction Braking or Mitigation Braking.

5.2.2
: Speed Reduction Braking will not be initiated if Mitigation Braking is active.

6.3.6.4.1.1
: For light vehicles, the Mitigation Braking shall not be initiated for TTC or ETTC above 3.0 s to achieve the deceleration requirement.

6.3.6.5.1
: The Speed Reduction Braking shall not be initiated for TTC or ETTC above 4.0 s. The activation point shall be decided by the manufacturer.

From UN Regulation No.152. the specific requirements, such as, timing of countermeasures and speed reduction requirement vary based on scenarios, either car-to-car scenario or car-to-pedestrian scenario. For the purpose of this graduation project, we only focus on car-to-car scenario. Some requirements of interest from the regulation are excerpted as follows:

5.2.1.1
: When a collision with a preceding vehicle of Category M1, in the same lane with a relative speed above that speed up to which the subject vehicle is able to avoid the collision, can be anticipated 0.8 s ahead of an emergency braking, the collision warning shall be provided at the latest 0.8 s before the start of emergency braking. However, in case the collision cannot be anticipated 0.8 s ahead of an emergency braking, the collision warning shall be issued immediately after the detection.

5.2.1.2
: When the system has detected the possibility of an imminent collision, there shall be a braking demand of at least 5.0 m/s^2 to the service braking system of the vehicle.

The subject system in question, in both documents, can automatically detect an imminent forward collision and activate the vehicle braking system to decelerate the vehicle, though they are called differently. As far as the braking function, the ISO 22839 standard uses TTC and ETTC to refer to the timing of each countermeasures and specifies the maximum deceleration of Speed Reduction Braking and minimum deceleration of Mitigation Braking. More implementation freedom is left to the manufacturers in UN Regulation No.152. Because it is a regulation by nature. It doesn't explicitly refer to any formulas to indicate how to calculate the timing of the initiation of warning and emergency braking. There is no requirements for the division in terms of the different stages of emergency braking. Furthermore, the maximum and minimum deceleration requirements are not as detail as those in ISO 22839.

Because no specific techniques or methods for the design of an AEB system has been mentioned yet, therefore a literature study is necessary to explore what are the latest trend in the design of AEB systems, for both stand-alone ones and those integrated with ACC systems.

[4] The number in front of each requirement is the clause number in the original document.

2.1.2 Research Work about AEB Systems

In AEB systems, modern intervention strategies obey several partly contradicting principles [31]:

- The vehicle should intervene in time so that the driver can avoid the accident.
- The impact of interventions at the wrong time is to be minimized so that traffic safety is not endangered.
- The level of assistance should be appropriate in the sense that the driver is supported but neither he nor the passengers and other traffic participants are irritated by exaggerated reactions.

These basic principles have led to different designs of AEB systems. There are two research directions on this topic. The first one is to come up with a novel AEB control strategy by including environmental factors, such as tire-road friction, or human factors, such as driving habits. Another research direction is to investigate various scenarios which could possibly lead to a collision. Because accidents in real traffic are complex occurrences, at present it is only possible to address particular accident scenarios by systems designed to avoid collisions or reduce their severity [32]. Though the scope of this graduation project limits the AEB systems in discussion are only for rear-end car-to-car driving scenario, some research extend this scenario by taking the following vehicle into consideration.

In [12], an AEB system is developed in which the human factors and the tire-road friction are considered. The indicator for the threat assessment is the distance to the target vehicle. Braking distance d_b and warning distance d_w are derived from kinematic analysis of the subject vehicle (SV) and the target vehicle (TV). A non-dimensional warning value w is therefore defined based on these two variables to evaluate driving situations:

$$w = \frac{d - d_b}{d_w - d_b}$$

where d the the measured distance between the subject vehicle and target vehicle.
The system alarms the driver by an audio warning or a visual (a red light) and audio warning, depending on the situational threat. If the distance between the front of the SV and the rear of the TV is smaller than the critical braking distance a, the system brakes the SV automatically, see Fig.2.4.

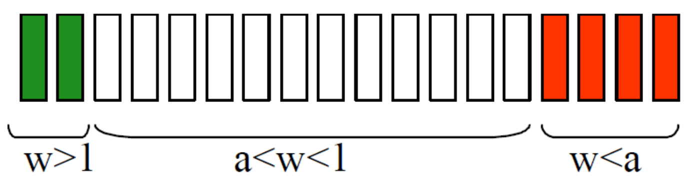


Figure 2.4: The visual warning in the proposed AEB system [12].

Two scaling factors are introduced in the calculation of the scaled warning distance and the scaled braking distance. One accounts for tire-road friction and the other for driving habit.

$$d_{w,scaled} = d_w * f(\mu) * g(driver)$$

$$d_{b,scaled} = d_b * f(\mu) * g(driver)$$

All tunable parameters in the proposed algorithms have to be tuned according to driver test data. Although the simulations showed the benefit of the inclusion of the variation in tire road friction and driving styles, the assumption made in the research that the full knowledge of road conditions is available is the obvious limitation of the proposed algorithms.

In [13], an AEB system considering the effect of different road friction on the braking threshold of TTC is developed. First, a combined-slip tire model is used to estimate peak road friction. The estimated peak road friction is then used to obtain braking threshold of TTC. A simplified dynamic vehicle model consisting of longitudinal and later model is used in the proposed system. The proposed AEB consists of three parts:

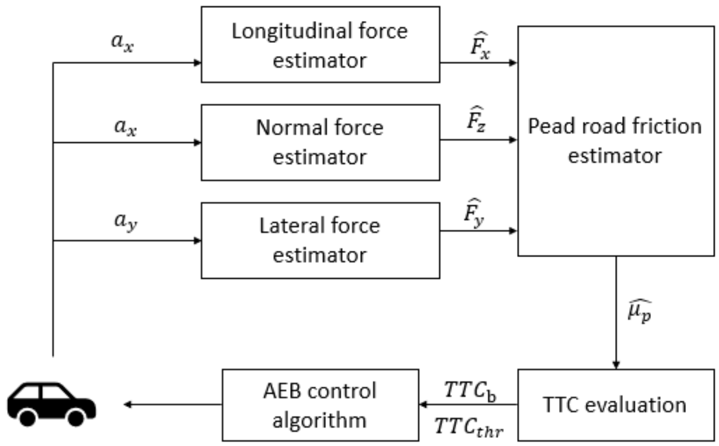


Figure 2.5: Block diagram of the proposed AEB system in [13].

peak road friction estimation, TTC evaluation, and AEB control algorithm, as shown in Fig 2.5.

The AEB control strategy proposed in [13], in comparison with the one from [12], is more practical because the peak friction could be identified by road friction estimator approximately. The adaptive TTC threshold is makes AEB activate more adequately in various friction conditions.

Further more, the work in [33] present a novel AEB system that exploits friction information ahead of the ego-vehicle that is predicted using on-board vehicle sensors as well with cloud services. Instead of taking the road friction as a constant which could lead to inefficient operation under slippery road conditions, researchers in [33] considered the dynamic of the actual road friction profile in the presented AEB system. The proposed algorithm utilizes the predicted dynamic friction profile and calculates the last braking point to prevent a collision. The performance of the proposed algorithm and controller are simulated and evaluated in terms of the braking distance metric that evaluates the relative distance between the ego-vehicle and the threat vehicle at a standstill. The proposed system achieves an improvement of up to 95.8% for varying friction profiles when compared to braking error obtained by constant friction profiles. However, the proposed AEB system doesn't have different stages of braking and warning function.

Besides road friction, road curvature is another environmental factor being taken into account in the design of AEB system. An AEB system incorporating the geometrical information about curved roads is proposed by Lee *et al.* in [34]. The curve coordinate transformation is used to consider the geometric elements of the curved road. The validity of the proposed method was verified by analyzing the collision avoidance performance through the relative distance and TTC.

As mentioned before, basically there are two research directions in the development of AEB system, one of which is related to specific driving scenarios. For example, an adaptive AEB control strategy for collision avoidance including rear vehicles was proposed by Shin *et al.* in [14]. The proposed algorithm adaptively calculates the deceleration that can prevent collision by predicting front and rear collisions. The driving scenario is depicted in Fig.2.6.

The collision prediction with rear vehicle is performed assuming a normal driver model. When a front collision with a obstacle is predicted, emergency braking is performed at a deceleration that can prevent rear collision, thereby preventing front and rear collision. The indicators for situational risk are TTC and the lateral position of the pedestrian.

Although the majority of AEB systems development research view AEB systems as stand-alone and do not interact with the other ADAS (e.g. ACC systems) much, AEB systems and ACC systems are closely

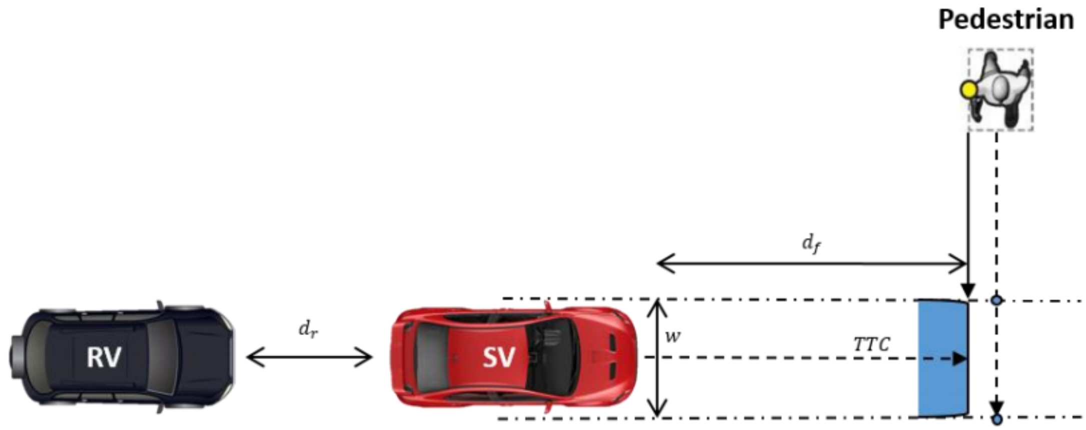


Figure 2.6: Collision situations involving cars and a pedestrian [14].

connected by their technology and their effects on accidents [31]. With the prevalent introduction of ACC systems in series production cars, the research of integration of both systems should attract more and more attention.

An enhanced ACC system is proposed in [15]. The enhanced ACC system has three driving mode, namely, speed tracking, ACC and AEB. The switch logic among these three driving modes is determined by the velocity of the TV and the spacing rate between the SV and TV. The longitudinal vehicle motion control is realized by the use of model predictive control (MPC). For each driving mode the MPC model established is changeless, but the cost function, constraints, weighting coefficients and initial values of the model may be different. According to [15], an unified design of ACC and AEB system is advantageous in two aspects: first, a more intelligent longitudinal vehicle motion control is realized by the inclusion of multiple driving modes based on the level of situation risk; second, the reduction on the complexity of the code and therefore a higher efficiency of operation can be achieved.

An unified design of an ACC and AEB system is proposed in [16], in which different tyre-road friction conditions are considered. A state machine diagram is used to control the switch of driving mode between ACC and AEB. TTC is the single criteria for the transition between ACC and AEB. The execution of AEB consists of four phases. In the first phase, a warning is given and AEB doesn't brake automatically. Thereafter, two partial braking phases are activated with each their own deceleration profile to avoid a collision without the need to decelerate with its maximum deceleration,which leads to a more comfortable experience. If the TTC continues decreasing till the minimum threshold, then the AEB system exerts its maximum deceleration.

In [15] and [16], the integration of ACC and AEB is accomplished by sharing the information from some common modules, like an unchanged MPC model for the control of vehicle motion in [15] and the peak tyre-road friction estimation in [16]. However, the ACC system has little influence on the way how AEB system works. In other words, the AEB system has the same performance regardless of whether the vehicle is controlled by the ACC system or the driver before AEB system is actuated.

A comprehensive longitudinal driving assistance system, including functions of ACC and AEB, is developed in [17]. The purpose of this longitudinal driving assistance system is to imitate the driver's manual driving behaviour. During the manual driving mode, the system identifies the TTC as a characteristic value when driver is likely to start braking. Algorithms for the activation of collision warning and AEB are designed based on the TTC and real-time driver's pedal deflection. The brake pressure is determined by the desired brake pressure during manual driving operation.

2.2 Impact Evaluation of Mixed Traffic

In this section, the literature about impact evaluation in a mixed traffic system has been outlined. First some representative work on the impact assessment of mixed traffic will be laid out. Then the focus is moved towards the impact evaluation on the traffic safety in mixed traffic system because this is where the main concern of this graduation project is.

Fa Zhang *et al.* in [35] presented a microscopic model of longitudinal driving, and investigate the characteristics of mixed traffic of two types of vehicles with different accelerations on a single lane. The traffic flow efficiency indicators adopted in the research are flow-density and velocity-density relationships of the traffic. The impact of different mix ratios of low-acceleration vehicles on the traffic system has been investigated. The longitudinal movement of each type of vehicles are based on decision tree as proposed in [36]. The difference of two types of vehicles is in one parameters - the normal acceleration - of the longitudinal movement model. Due to the simplicity of longitudinal movement model and the single-lane roadway scenario, the impact of such a mixed traffic in the real world traffic is hard to deduce from this work, though the valuable insights gained are useful.

J.Chen *et al.* adopted the traffic simulation platform PTV-VISSIM9 to validate the proposed variable time headway spacing strategy for ACC and CACC vehicles [37]. Different mix ratios of ACC, CACC and conventional human-driven vehicles are used in the simulations. The results illustrated that introducing the ACC/CACC vehicles into mixed traffic can improve traffic flow stability, enhance road capacity and alleviate the increasingly serious traffic congestion problem.

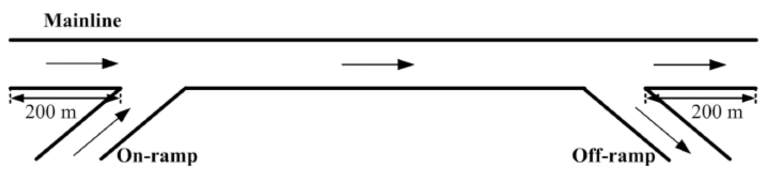


Figure 2.7: Schematic illustration of the road in the simulation [37].

A.J. Pauwels [38] did an extensive work on the traffic efficiency and safety evaluation of automated driving in mixed-traffic urban areas. A framework was proposed in which virtual autonomous vehicles can be injected in the microscopic traffic simulator SUMO and be assessed in terms of safety and operational efficiency. What distinguishes this research from comparable microscopic traffic studies is the Occlusion Aware Driving principle which takes the occluded sensorial view of autonomous vehicles caused by objects into consideration. The safety scenario was assessed by first identifying potential accidents using The Swedish Traffic Conflict Technique and many other surrogate safety indicators. The results showed strong evidence that there is a trade-off between safety and efficiency when varying the car-following parameters. Fig. 2.8 shows the use case adopted in the [38] to validate the proposed framework which is a combined urban microscopic simulation framework with autonomous vehicles, human-driven vehicles and vulnerable road users, such as bikes and pedestrians.

In [39] Oussama Derbel *et al.* did a safety assessment of a platoon consisting of two types of vehicles, one of which is human-driven and another one is autonomous. Two Velocity Difference Model (TVDM) is used to model human driver's behaviour and Intelligent Driver Model (IDM) is used to model automated driving vehicles. For safety assessment, the Equivalent Energy Speed for crash gravity and collision number descriptors are used in simulation phases. However, there is no validation presented in [39] to prove the validity of the crash modelling method used in the research.

Similar to the Oussama Derbel *et al.*'s work, Ramin Arvin *et al.* did a safety assessment of mixed traffic at intersections [40]. The composition of the mixed traffic consists of ACC, CACC and human-driven vehicles. The Wiedemann car-following model was used to model human driving behavior for conventional

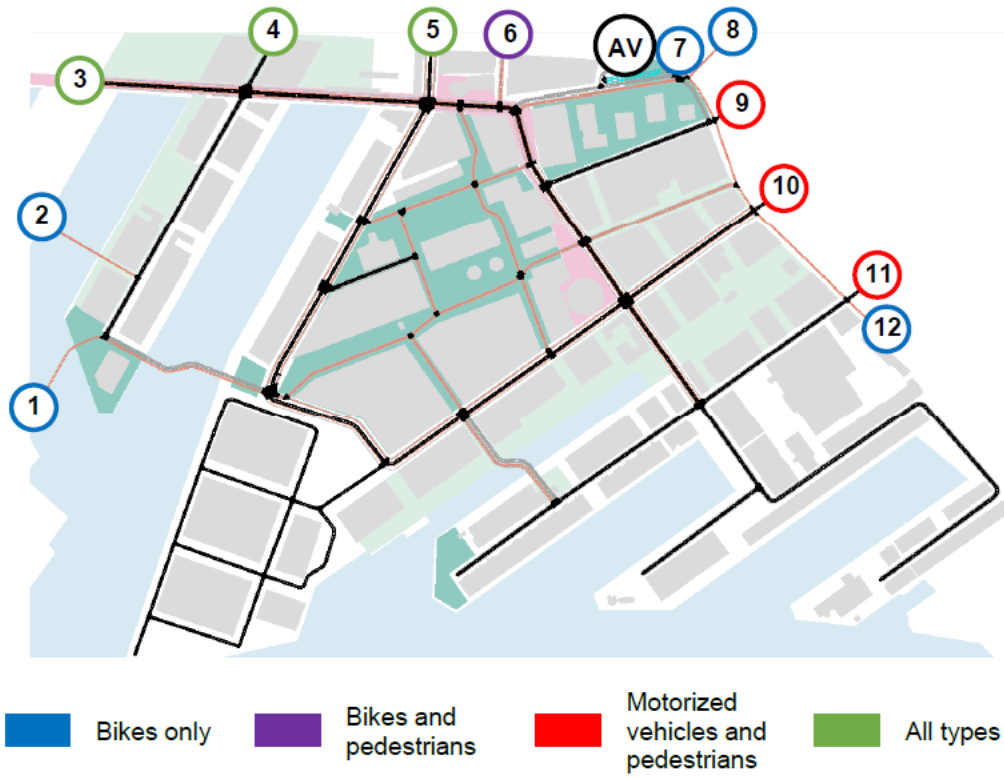


Figure 2.8: The complete network of M4H in 2035, with entrance and exit points indicated [38].

vehicles. This study utilizes the ACC and CACC car-following model developed and validated with real-world AV data. As for the results, two surrogate safety measures are used to evaluate the safety performance of a representative intersection under different market penetration rate of Connected and Automated Vehicles: the number of longitudinal conflicts and driving volatility.

Unlike the microscopic modelling approach used in [35] and [37] -[39], Yao-Ming Yuan *et al.* uses a hybrid modelling approach to investigate traffic flow characteristics in a traffic system consisting of a mixture of ACC vehicles and human-driven vehicles [41]. The human-driven vehicles are described by a cellular automaton model, which can reproduce different traffic states (i.e., free flow, synchronised flow, and jam) as well as probabilistic traffic breakdown phenomena. The ACC vehicles are simulated by using a car-following model. The hybrid modelling approach has, as claimed, two advantages: firstly the three traffic states and the probabilistic traffic breakdown of manual vehicles could be reproduced; secondly the other hand, there is no artificial velocity fluctuations with ACC vehicles. The traffic breakdown probability from free flow to congested flow, and the transition probability from synchronised flow to jams are the traffic characteristics of interest.

2.3 Summary and Identified Gaps

In this chapter, the development of AEB systems and of impact evaluation of mixed traffic system are introduced. In section 2.1 the state-of-art implementation of AEB systems on commercial passenger cars and the performance requirements from standards and regulations are presented, followed by the literature review about the development of AEB systems. In section 2.2 the literature about the traffic impact evaluation is reviewed.

The review of the literature reveals main research gaps which are listed as follows:

1. There is no combined speed controller framework for AV equipped with ACC system and AEB system where the state of one system affects another.
2. There is no overview of the performance of a traditional AEB system designed under the assumptions and principles mainly for HDV in an AV equipped with any type of velocity controller, such as an ACC system.
3. There is no research about the traffic impact assessment, from the perspective of traffic efficiency and safety view, considers the AVs equipped with an ACC system and an AEB system at the same time in the traffic flow composition.

These research gaps are filled by the following work done in this graduation project: firstly, examining the limitations on the collision avoidance performance of ACC systems, with and without the integration with traditional AEB systems; secondly, proposing an integrated ACC+AEB system designed to mitigate those identified limitations. Furthermore, microscopic traffic simulation is used to assess the traffic impact of the proposed ACC+AEB system in a highway scenario with a merging bottleneck.

Chapter 3

Methodology

In this chapter, the methodology followed by this graduation project is described. Then, the traffic simulation techniques are introduced and the justification of the choice for microscopic simulation method is offered.

3.1 Model-Based Systems Engineering

This graduation project bases its methodology on Model-Based Systems Engineering (MBSE). Starting from a succinct description of systems engineering, this section aims to familiarize the readers with the key concepts and buttressing principles of MBSE. After that, the SYSMOD approach - a general-purpose methodology - will be introduced and how it is applied to this graduation project will also be described.

Today's world is becoming ever more complex. As we address the growing complexity propelled by the advanced technologies, a holistic way of thinking is a good complement to the traditional reductionist approaches of the Industrial Age. The term systems engineering can be traced back to Bell Telephone Laboratories in the 1940s [42]. Systems engineering as a practice and a profession is less than 100 years old, quite young compared with formal engineering disciplines [43]. The International Council on Systems Engineering (INCOSE) [44] defines systems engineering as a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods. In concise, systems engineering requires a holistic perspective to see the big picture, systematic thinking to understand the interconnections and interactions, and an act upon the resulting insights and deliver the right solution [43].

To better fulfill the goals of systems engineering, MBSE emerged about 20 years ago. It has been an INCOSE initiative since 2007 [45]. MBSE, as a relatively new practice in comparison with document-based systems engineering, transforms the systems engineering from document-centric to model-centric paradigm. According to INCOSE [44], MBSE is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases [54].

SYSMOD is a MBSE toolbox for pragmatic modeling of systems. It begins with the project context, looking at our system as a black box, studying the environment, and then successively delves into the details [46]. A good scalability is one of its characteristics, and therefore it can be used both for large and small systems. Based on the specific purpose of this graduation project, the following steps are derived from the entire SYSMOD approach (Appendix B) and their relationship with the chapters of the thesis is shown in the Table 3.1. Notice that the term *system* here refers to the integrated ACC+AEB system.

The general methodology of this graduation project is described. When it comes to traffic impact assessment, there are several techniques available and can be used in this graduation project. In the next section, those traffic simulation techniques are introduced and the justification of the choice for microscopic simulation method is offered.

SYSMOD steps	Chapters
1. Describe the project context	Chapter 1. Introduction
2. Determine system requirements 3. Model system context	Chapter 4. Requirements and System Context of AEB system
4. Model system structure	Chapter 5. ACC System Structure and Performance Analysis Chapter 6. Integrated ACC+AEB System: Functions, Architecture and Performance
5. Realize system behavior	Chapter 6. Integrated ACC+AEB System: Functions, Architecture and Performance
6. Test	Chapter 6. Integrated ACC+AEB System: Functions, Architecture and Performance Chapter 7. Traffic Impact Assessment

Table 3.1: The correspondence between SYSMOD steps and the chapters devoted to realize each step.

3.2 Traffic Simulation Techniques

Traffic simulation is a way to model and simulate the traffic flow dynamics that occur in the real world. Traffic simulation can be classified into three types: macroscopic, microscopic and mesoscopic.

Macroscopic simulation uses macroscopic models describing the collective phenomena of traffic flow. As an analogy, macroscopic models sometimes are called hydrodynamics models. Because the locally aggregated variables, such as traffic density, flow and mean speed, are used to describe the traffic flow dynamics just as the hydrodynamic equations to the motion of liquids or gases. Conversely, microscopic models focus on modelling the behaviour of individual particle of such a system and use variables such as vehicle positions, speeds and accelerations. Microscopic traffic simulation is a way to simulate the traffic flow dynamics from the perspective of vehicle-driver unit. It uses microscopic models to describe the behaviour of individual vehicle-driver units which collectively form the traffic flow, such as car-following, lane-changing and human factors of driving behaviour. Mesoscopic traffic flow models were developed to fill the gap between the microscopic models that describe the behavior of individual vehicles and the macroscopic models that describe traffic as a continuum flow [50]. It utilizes the aggregate terms to describe the traffic flow, while in the meantime, defines the behavioral rules for individual vehicles.

The comparison of microscopic models and macroscopic models is shown in Table 3.2.

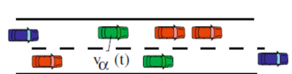
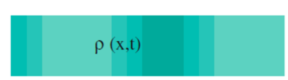
	Microscopic model	**Macroscopic model**
Schematic representation		
Typical model equations	$\frac{dv_\alpha}{dt} = a_\alpha(s_\alpha, v_\alpha, \Delta v_\alpha)$	$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho V_e(\rho))}{\partial x} = 0$
Order of time scale	$1\,s$	$1\,min$

Table 3.2: Comparison of microscopic model and macroscopic model [47]

Microscopic traffic simulation is chosen to conduct this research because the purpose of this graduation project is to investigate how individual vehicles equipped with the proposed ACC+AEB system affect traffic flow. To this end, microscopic simulation is particularly suitable because the individual vehicles' behavior can be adjusted and controlled either by the embedded driver model in VISSIM[1] or by the driver model developed by the researchers.

However, there are some downsides of microscopic traffic simulations which should considered when employing this technique:

- Calibration and verification of model requires extensive traffic data. The simulation model may not necessarily reflect the traffic in reality if it is not calibrated and validated with field data.
- Traffic safety assessment can't be carried on in the simulation model itself. Unlike the traffic flow characteristics, such as average speed and acceleration of the vehicles at a data collection location during the simulation time, the surrogate traffic safety indicators have not be incorporated into the simulation model in VISSIM yet.

In this graduation project, the road network set up in the microscopic simulation model is hypothetical which means there is no field data can be used to calibrate and validate the simulation model. Because we want to compare the traffic flow characteristics and traffic safety for different traffic compositions, a hypothetical simple road network is acceptable for this purpose. The simulation results will give an indication of the impact of the proposed ACC+AEB system on the traffic. The parameters of the simulation model is chosen empirically and by referring to the literature. As for the calculation of surrogate safety indicators and other traffic state indicators which can not be retrieved from the simulation model directly, the vehicle record data at each time step during simulation is exported and processed in Matlab.

3.3 Summary

In this chapter, the MBSE methodology is introduced and the tailored SYSMOD approach is applied. The relation between the adopted SYSMOD steps and the chapters of thesis is shown. Microscopic traffic simulation technology is also addressed.

[1] For more information about VISSIM, please refer to Chapter 7. Traffic Impact Assessment.

Chapter 4

Requirements and System Context of AEB system

In this chapter, the elicited requirements for AEB system system are listed and system context of the integrated ACC+AEB system is modelled.

4.1 Requirements Elicitation for AEB System

As an important step in the system analysis, getting clear and consistent requirements helps develop the system more efficiently and less error-prone. The AEB system shall meet the following requirements:

1. It shall help subjective vehicle avoid the collision with the preceding target in common highway driving scenarios without driver's action.
2. It shall be integrated into the existing ACC system.
3. It shall be implemented in the Simulink.
4. Its implementation shall be imported to microscopic traffic simulation model.
5. It shall assess the collision threat.
6. It shall transfer the vehicle control back to the ACC system when the collision threat is below a specified criterion and when driver has no input.
7. All listed requirements shall be proved to be met at the simulation frequency of 10 Hz.

4.2 System Context

As shown in Fig.4.1, there are three external systems directly interacting with the integrated ACC+AEB system. Because the developed AEB system is going to be integrated into the existing ACC system, so when modelling the system context this integrated ACC+AEB system is viewed as a whole black box and is separated from the external systems which exchange the signals with the ACC+AEB system.

- The **perception module** is responsible for sensing and processing the input signals and then sending them to ACC+AEB system.
  The four input signals from perception module to ACC+AEB system are:
  - v_{target}: the velocity of the target vehicle
  - a_{target}: the acceleration of the target vehicle
  - *mode_choice*: the indicator of the different speed control modes of the ACC system.

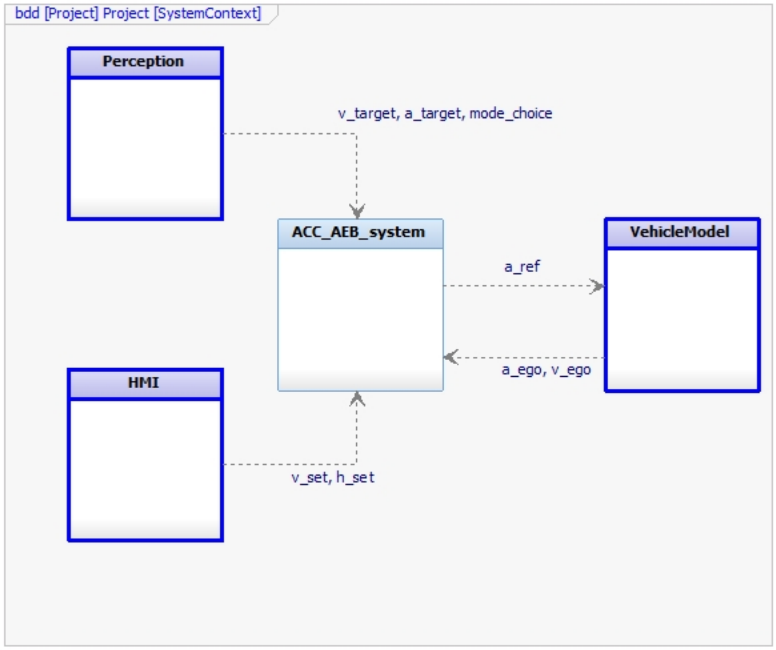


Figure 4.1: The external systems interacting with the integrated ACC+AEB system and the information flow between them.

- **HMI** module is the human-machine interface. Driver can set the desired cruise speed v_{set} and desired time gap h_{set} for the ACC system.
- **Vehicle model** is for modeling the vehicle dynamics. It models the behavior of low-level actuators, such as gearbox and engine. It receives the a_{ref} as desired reference acceleration and sends the actual executed acceleration a_{ego} and actual current velocity v_{ego} of ego vehicle back to the ACC+AEB system.

4.3 Summary

This chapter first lists the elicited requirements for AEB system which is going to be built and integrated into ACC system. Then the external view of the ACC+AEB system is presented. Fig.4.1 shows which external systems are interacting with the ACC+AEB system and what are the information flow between them.

Chapter 5

ACC System Structure and Performance Analysis

To design an AEB system dedicated for ACC vehicles, first we introduce the structure of the existing ACC system. Then we investigate the limitations of the ACC system in the emergency situations. Although ACC system is a driver assistance system for driving comfort and not for safety purpose, this chapter tells us how ACC vehicles behave when encountering the common highway emergency situations. Furthermore, we extend the ACC system with a traditional AEB system to see how it can help improve the collision avoidance ability of the ACC vehicle.

5.1 ACC System Structure

After having the external view of the ACC+AEB system and knowing which systems it interacts with, we next show the structure of ACC system in Fig.5.1.

Five blocks are directly connected with the ACC system by $\longmapsto$,which means they are the subsystems of the ACC system. The functions of each of them are described below.

1. **Cruise controller**: The cruise controller calculates the acceleration needed for reaching or maintaining the desired cruise speed v_{set} set by the driver.
2. **Error calculator**: The error calculator calculates two errors:
   (a) distance error: the error between the desired distance with the target and the actual measured distance.
   (b) velocity error: the error between the desired velocity and the current actual velocity.

   The calculated distance error and velocity error then are transmitted to distance controller.
3. **Gap closing controller**: The gap closing controller is a proportional controller. It maintains a constant acceleration of the ego vehicle.
4. **Distance controller**: The distance controller is where the ACC control method is applied. A proportional–derivative controller serves its core function to follow the target vehicle at a certain distance specified by the desired time gap h_{set}.
5. **Coordination module**: The coordination module synthesises the outputs from cruise controller a_{cc}, gap closing controller a_{gcc} and distance controller a_{dc}. It generates the desired reference acceleration a_{ref}. It consists of two subsystems as shown at the bottom of Fig.5.1:
   (a) **Mixing block**: The mixing block selects the minimum acceleration from a_{cc}, a_{gcc} and a_{dc} as the acceleration which should be executed at the current time step.

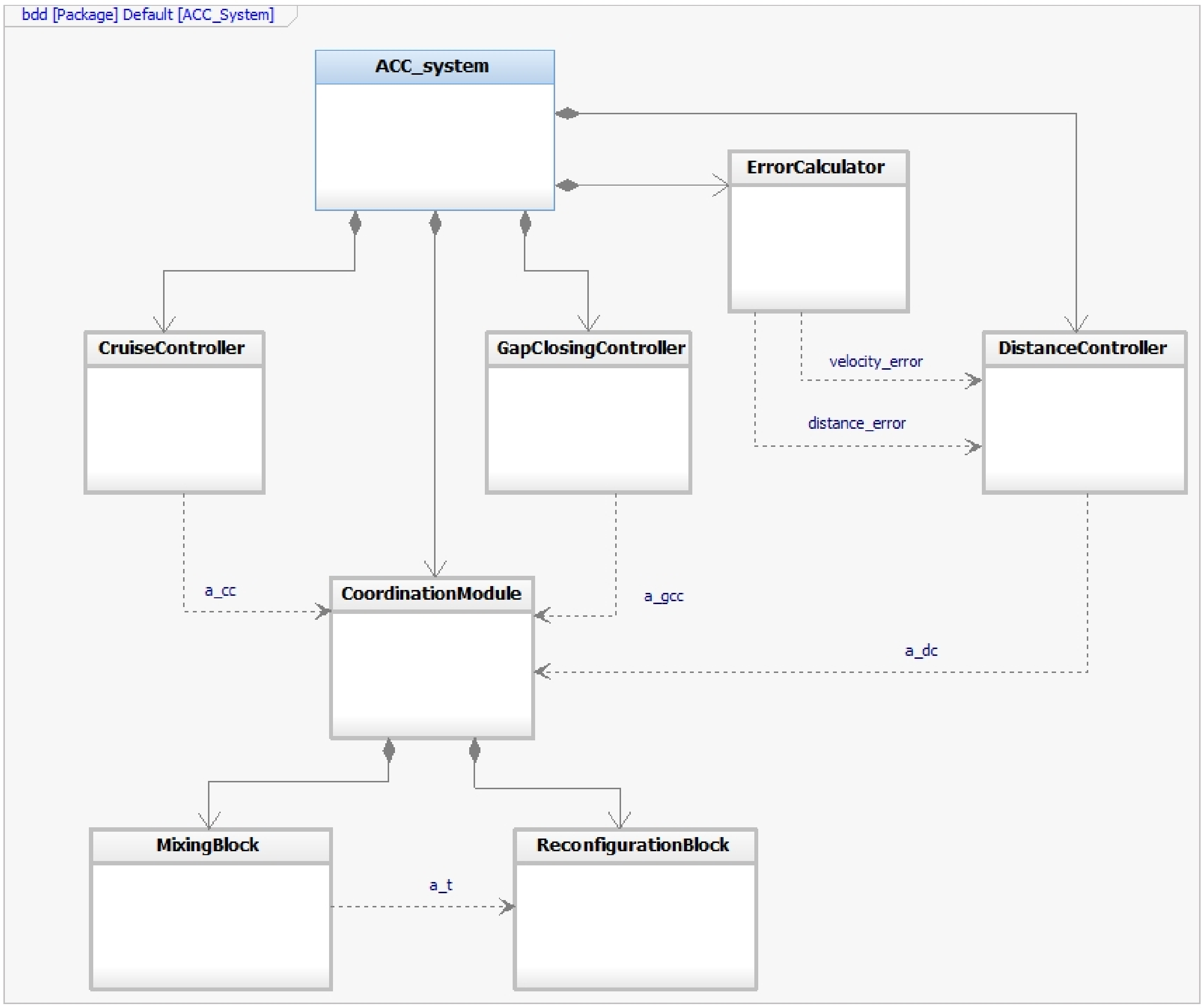


Figure 5.1: ACC system structure. ◆⟶ represents the composition relationship between the system and its subsystems, ⇢ represents the information flow between components.

(b) **Reconfiguration block**: The reconfiguration block make sure there is a smooth transition from the acceleration selected from the last time step to the acceleration determined at the current time step.

5.2 ACC System Performance Analysis

5.2.1 Single Vehicle

To test the collision avoidance performance of ACC system, two critical driving scenarios are come up with. Based on the common sense and the dangerous traffic situations mentioned in the literature for ACC vehicles, the descriptions of two critical driving scenarios are as follow:

Scenario 1 - Following a decelerating target vehicle.

Because the maximum deceleration of ACC vehicle is $-3.5\ m/s^2$, so if the leading vehicle's deceleration exceed a certain limit then the collision between the ego vehicle and the target vehicle may happen. The maximum deceleration of the target vehicle which can cause collision depends on the ACC system's performance.

Scenario 2 - Approaching a low-speed target.

It is common for the following two scenarios to occur in the highway:

- The ego vehicle is driving towards the traffic jam. The vehicles lining in the queue usually move slowly, or even stop fully.
- Due to lane change of the original target vehicle, a new target suddenly appears in the view of the ego vehicle. This new target could be a slowly moving vehicle stuck in the traffic jam or just an obstacle on the road.

The above-mentioned two driving scenarios are grouped together as **scenario 2 - Approaching a low-speed target**.

The following five velocity controllers are tested:

1. **ACC**: The ACC system with structure shown in Fig.5.1 is one type of the velocity controller under examination.

2. **ACC+AEB**: An integration of ACC system and a traditional AEB system is one type of the velocity controller under examination. Its structure is shown in Fig.5.2. In comparison with the ACC system in Fig.3.2, an additional module **TraditionalAEB** is in place to improve the collision avoidance capability of the whole system.

   The **TraditioanlAEB** controller uses TTC to evaluate the situational emergency and sends corresponding acceleration signal a_{aeb} to **CoordinationModule**. Because the **CoordinationModule** will choose the minimum acceleration to execute for each time step, so an extremely large value of a_{aeb} makes sure that AEB system don't intervene the working of ACC system when there is no emergency.

   - If $TTC > 2\,s$, $a_{aeb} = 99\ m/s^2$;
   - If $1\,s < TTC <= 2\,s$, do a partial braking, $a_{aeb} = -4\ m/s^2$;
   - If $TTC <= 1\,s$, do a full braking, $a_{aeb} = -9\ m/s^2$;

   The calculation of TTC is as below:
   $$TTC = -\frac{x_c}{v_{tv} - v_{sv}}$$

3. **CACC**: The CACC system - Cooperative Adaptive Cruise Control system - is a special case of ACC system. In CACC system, the acceleration of the target vehicle is transmitted via V2V communication and incorporated into the **DistanceController** as a feed-forward input in the control loop. This will

make the vehicle respond quicker to the driving state change of the target vehicle and provide a better string stability of a platoon. Whether this adaption of CACC system will show a better capability to protect the subjective vehicle under emergency circumstances is unknown and therefore we single the CACC system out for analysis.

4. **CACC+AEB**: As normal ACC system, CACC system can be integrated with AEB system as well.
5. **CACC+CAEB**: As long as the acceleration of the target vehicle is available, which is the case for CACC system, the TTC calculation formula can be extended to ETTC formula as below:

$$ETTC^1 = \frac{-(v_{tv} - v_{sv}) - \sqrt{(v_{tv} - v_{sv})^2 - 2 * (a_{tv} - a_{sv}) * x_c}}{a_{tv} - a_{sv}}$$

Using the ETTC as threat indicator, CAEB system has the control algorithm as same as traditional AEB system. CAEB system is integrated with CACC system as one type of velocity controller under examination, with the same structure as the one shown in Fig.5.2.

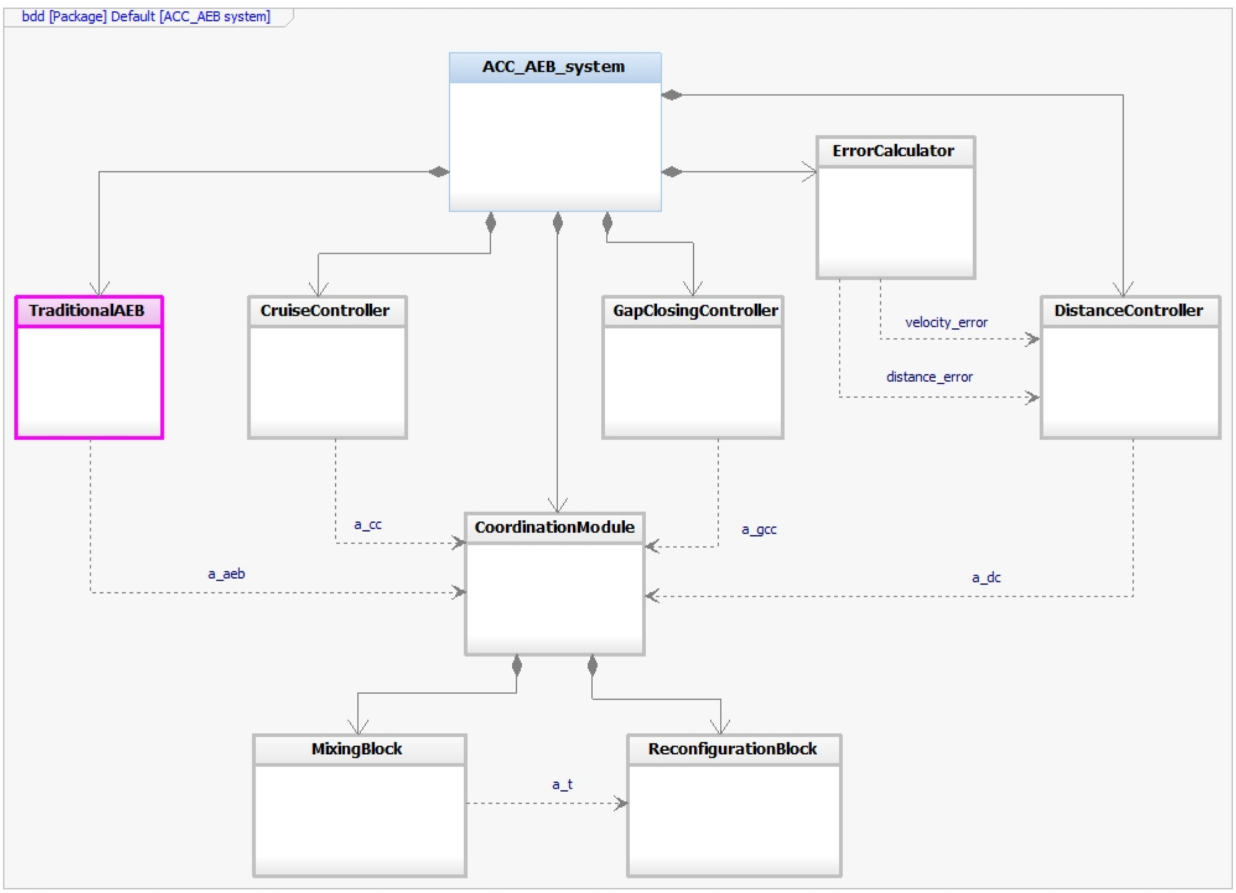


Figure 5.2: ACC+AEB system structure. A traditional AEB system is integrated into ACC system, in parallel with cruise controller, gap closing controller and distance controller.

For the Scenario 1, the critical time gap and the critical deceleration of the target vehicle are the two variables of the most interest in delimiting the collision avoidance capability of five different types velocity controllers.

Fig.5.3 shows the critical time gap with different initial velocities in the Scenario 1 for five velocity controllers. A concrete description of scenario 1 used to produce Fig.5.3 is as follows: The subject vehicle is

[1]For the derivation of ETTC, refer to Appendix A

following a target vehicle with a constant speed in ACC mode or CACC mode, depending on the type of the velocity controller in question. The target vehicle does a hard brake suddenly at certain point of time. The deceleration of target vehicle starts from 0 m/s^2 and then reaches its maximum deceleration -8 m/s^2 within 1.5 s. After that, it maintains the maximum deceleration until standstill. From Fig.5.3 two conclusions can

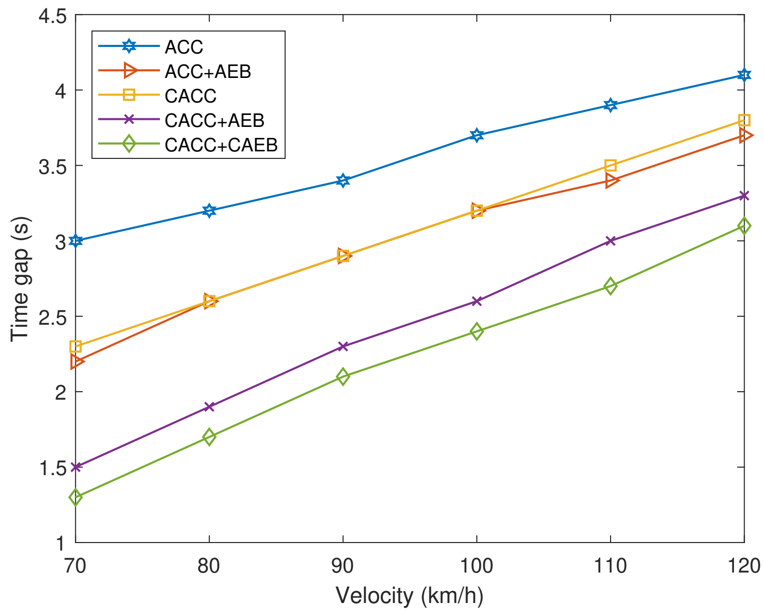


Figure 5.3: The collision-free critical time gap with different initial velocities in the Scenario 1.

be drawn: firstly, AEB system helps the subject vehicle keep a smaller time gap to the target vehicle while guaranteeing the safety. CAEB system contributes to this even more; secondly, the implemented traditional AEB system and CAEB system can't help avoid the collision if the ACC vehicle and CACC vehicle use normal time gaps - 1.5 s for ACC vehicles and 1 s for CACC vehicles when human driver doesn't response to the danger.

The critical deceleration of the target vehicle without causing the collision with an ACC vehicle with TG 1.5 s is shown in the Table 5.1. The critical deceleration of the target vehicle without causing the collision with an CACC vehicle with TG 1 s is shown in the Table 5.2. From Table 5.1 and Table 5.2 it can be concluded that the AEB system and CAEB system do help increase the collision avoidance capability of the ACC and CACC system but not enough to avoid the collision when driver doesn't respond. The maximum deceleration of a vehicle in the emergency situation can be as large as $0.8\,g \sim 1\,g$ which far exceeds the collision avoidance capability of the current implemented systems.

velocity [km/h]	ACC [m/s^2]	ACC+AEB [m/s^2]
70	-2	-3
80	-2	-3
90	-2	-3
100	-2	-3
110	-2	-3
120	-2	-3

Table 5.1: The critical deceleration of the target vehicle without causing the collision.

For Scenario 2, when subject vehicle is approaching a low-speed target, Fig.5.4 shows the relationship between the critical detection range and the relative velocity. The critical detection range shown in the Fig.5.4 is the minimum distance between the subject vehicle and a constant-speed target vehicle required to avoid a collision. The relative velocity is the velocity of subject vehicle subtracted by the velocity of the

velocity [km/h]	CACC $[m/s^2]$	CACC+AEB$[m/s^2]$	CACC+CAEB$[m/s^2]$
70	-3	-4	-4
80	-3	-4	-4
90	-3	-4	-4
100	-3	-3	-4
110	-3	-3	-3
120	-3	-3	-3

Table 5.2: The maximal possible deceleration of the target vehicle for different subject vehicles without collision.

target vehicle. In this driving scenario, the target vehicle has no acceleration so the ACC system and CACC system both behave the same performance. The reason why the red line is below yellow line is because in the TTC calculation of CAEB system, the acceleration of the subject vehicle is taken into account which leads to a larger TTC value in this specific scenario where the target vehicle has no acceleration and the subject vehicle has a negative acceleration value.

There are two conclusions can be drawn from Fig.5.4. Firstly, the upward trend of three curves are in line with the expectation: The larger the relative velocity, the longer the required detection range. Secondly, the required detection range for a collision-free scenario is too large because most of the ACC systems now available have a detection range of 120 m to 150 m.

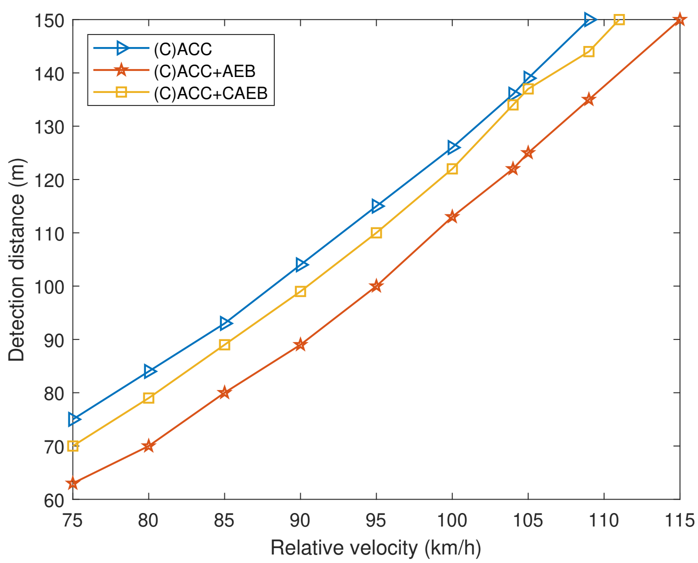


Figure 5.4: The collision-free detection distance threshold under different initial velocities for different types of velocity controllers.

Fig.5.5 shows the acceleration profile, velocity profile and distance with the target vehicle during the approach of a low-speed target. From top to bottom, a_sv is the acceleration of the subject vehicle, v_sv is the velocity of the subject vehicle, and dx is the distance between the subject vehicle and the target vehicle. The subject vehicle is originally in cruise mode at a constant speed of 118 km/h and then at $t = 100s$, it detects the target moving with a constant speed of 5 km/h at the distance of 150 m. At $t = 105.1\,s$, the AEB system activates with two consecutive braking phases - partial braking and full braking. After a short period of time when the v_sv is zero, the subject vehicle starts to accelerate and follow the target vehicle whose velocity is merely 5 km/h. Which type of velocity controller of the subject vehicle has, ACC or CACC, doesn't matter in this case because the target vehicle doesn't accelerate or decelerate.

Fig.5.6 shows the acceleration profile, velocity profile and distance with the target vehicle during the

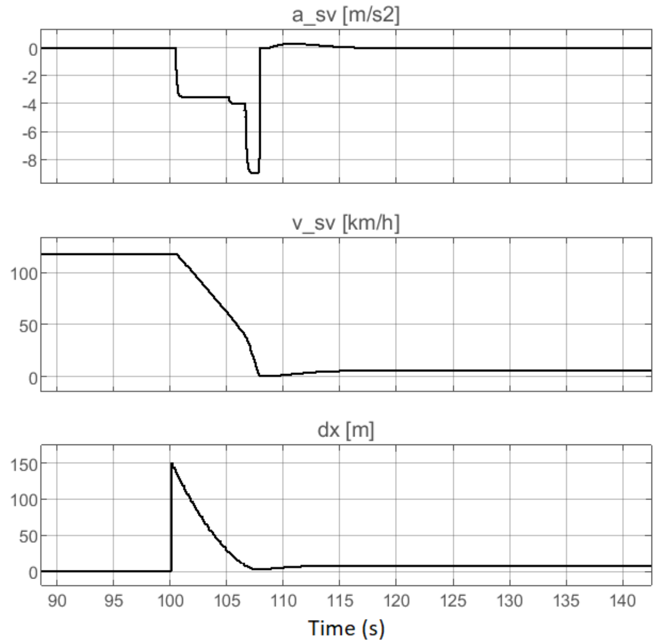


Figure 5.5: The acceleration, velocity and the distance when the subject vehicle (ACC+AEB) is approaching a low-speed target vehicle.

approach of a stationary target. From top to bottom, a_sv is the acceleration of the subject vehicle, v_sv is the velocity of the subject vehicle, and dx is the distance between the subject vehicle and the target vehicle. The subject vehicle is originally in cruise mode at a constant speed of 112 km/h and then at $t = 100\,s$, it detects a stationary target at the distance of $150\,m$. At $t = 105.3\,s$, the AEB system activates with two consecutive braking phases - partial braking and full braking. Then the subject vehicle stops at a distance from the target vehicle.

An unwanted vehicle behavior was observed when running the simulation for Scenario 2: There is no full-stop mechanism for the current implemented velocity controllers. Consequently, when the subject vehicle stops safety with the help of AEB system or CAEB system in front of a stationary target with a stop distance larger than the predefined stop distance in the ACC system - 5 m in the simulation - the subject vehicle would accelerate again to move forward further until the predefined stop distance is met. Fig.5.7 shows the acceleration profile and velocity profile of the subject vehicle during this process. At 255.4 s the subject vehicle stops without collision with the target vehicle. Then it remains standstill for a while and moves again at 255.9 s to shorten the standstill distance to a predefined value. Finally it stops permanently from 257.2 s onward. This behavior is undesirable because the subject vehicle is expected to remain stationary if the target vehicle is stationary.

Another undesired behavior is observed when we try to increase the time threshold for partial barking and full braking of traditional AEB system. It's clear from the results which have been shown so far that the current AEB system and CAEB system can't meet the safety requirements for a typical highway critical situation. Because of that, an attempt to increase the TTC threshold for partial braking and full braking is made. The larger time threshold for partial braking and full braking, the earlier and stronger of the braking of the subject vehicle.

Two impacts are resulted from this change. Firstly, the earlier intervention from AEB system makes the probability of a collision lower and thus makes the subject vehicle safer. Secondly, the increase in the TTC threshold for partial braking and full braking results in a more frequent vehicle control authority transition between AEB system and ACC system. From Fig.5.8 it can be seen that the full braking of AEB system is activated twice. The first time happens between 132 $s$and 133 s and the second time happens between around 137 s. At about 143 s, the AEB is engaged again with partial braking. Every time when AEB is deactivated

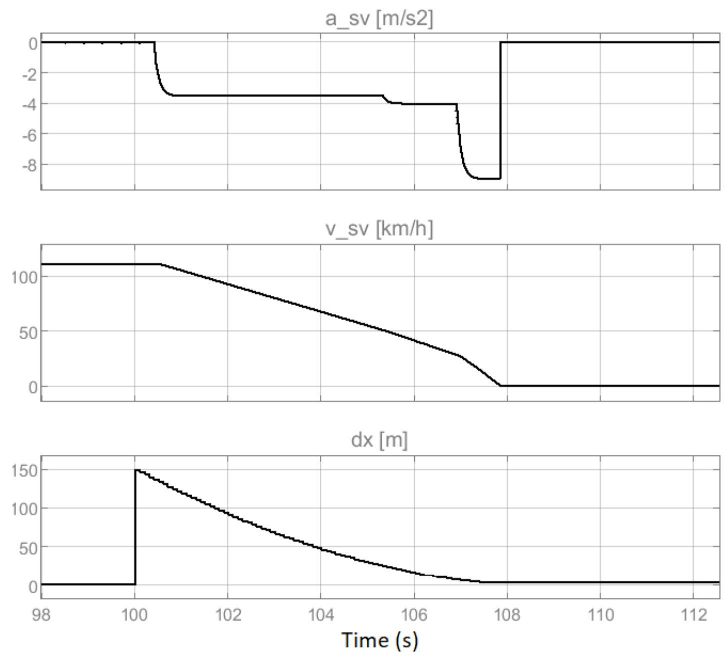


Figure 5.6: The acceleration, velocity and the distance when the subject vehicle (ACC+AEB) is approaching a stationary target vehicle.

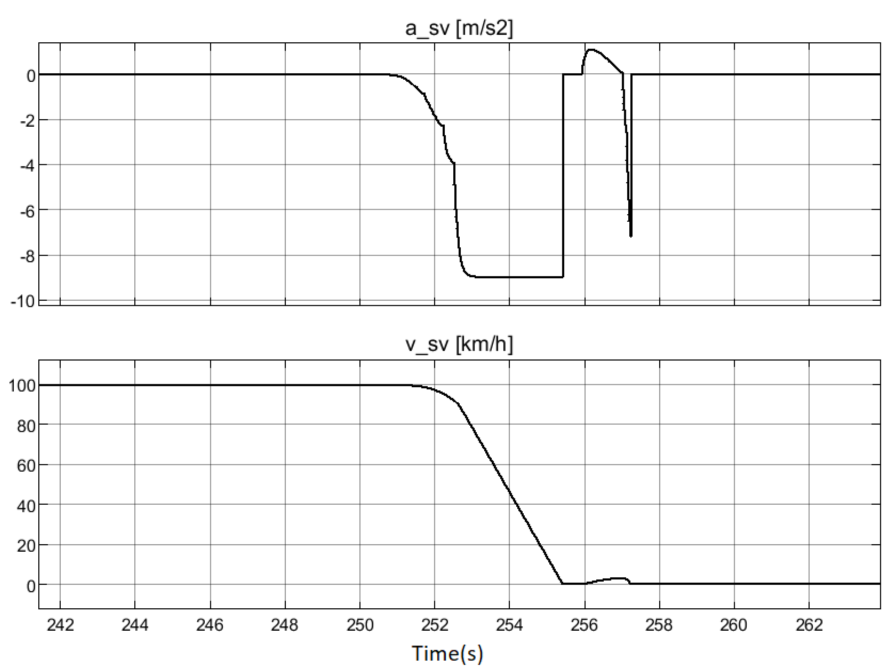


Figure 5.7: The acceleration and velocity of the subject vehicle when approaching a stationary target.

because the calculated TTC is above the TTC threshold, the ACC system takes over and the vehicle begins to accelerate. A disharmonious cooperation between ACC system and AEB system is in place to stop the vehicle safely.

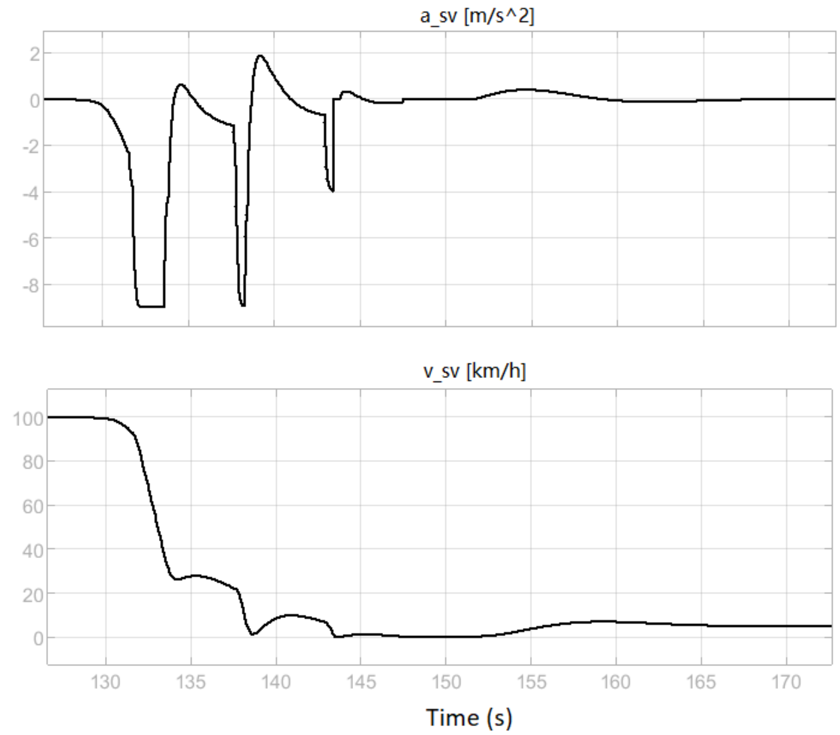


Figure 5.8: The acceleration profile and velocity profile of the subject vehicle in scenario 2 when TTC threshold of partial braking and full braking is increased to 4 s and 3 s, respectively.

5.2.2 Platoon

In this subsection the performance of all five velocity controllers in a platoon formation, as shown in Fig.5.9, during emergency situations are described. The platoon in simulation consists of ten vehicles and the first vehicle is referred to as VEH1, and the second vehicle is referred to as VEH2 and so on. The target vehicle is assumed to be a HDV and therefore can't communicate with VEH1 via V2V communication channel.

Figure 5.9: A platoon consisting of 10 vehicles.

For a platoon consisting of ACC vehicles, the deceleration of the front vehicles is amplified along the platoon and brings about large deceleration on the latter platoon members. Such a string instability may cause collision.

Fig.5.10 shows this phenomenon. This figure shows the acceleration and velocity of VEH1, VEH2 and VEH3 in a simulation run. The scenario is that VEH1 is in cruise mode with a speed of 100 km/h at 0 s and it detects a slowly moving target (5 km/h) at 120 s from a distance of 150 m. VEH2 and VEH3 is in ACC mode with TG of 1.6 s. At detection, the driving mode of VEH1 switches from CC to GCC and then to ACC (TG = 1.6 s). This deceleration is amplified along the platoon, from VEH1 through VEH2 and VEH3. AEB functionality of VEH3 is activated and it helps to avoid the collision between VEH3 and VEH2.

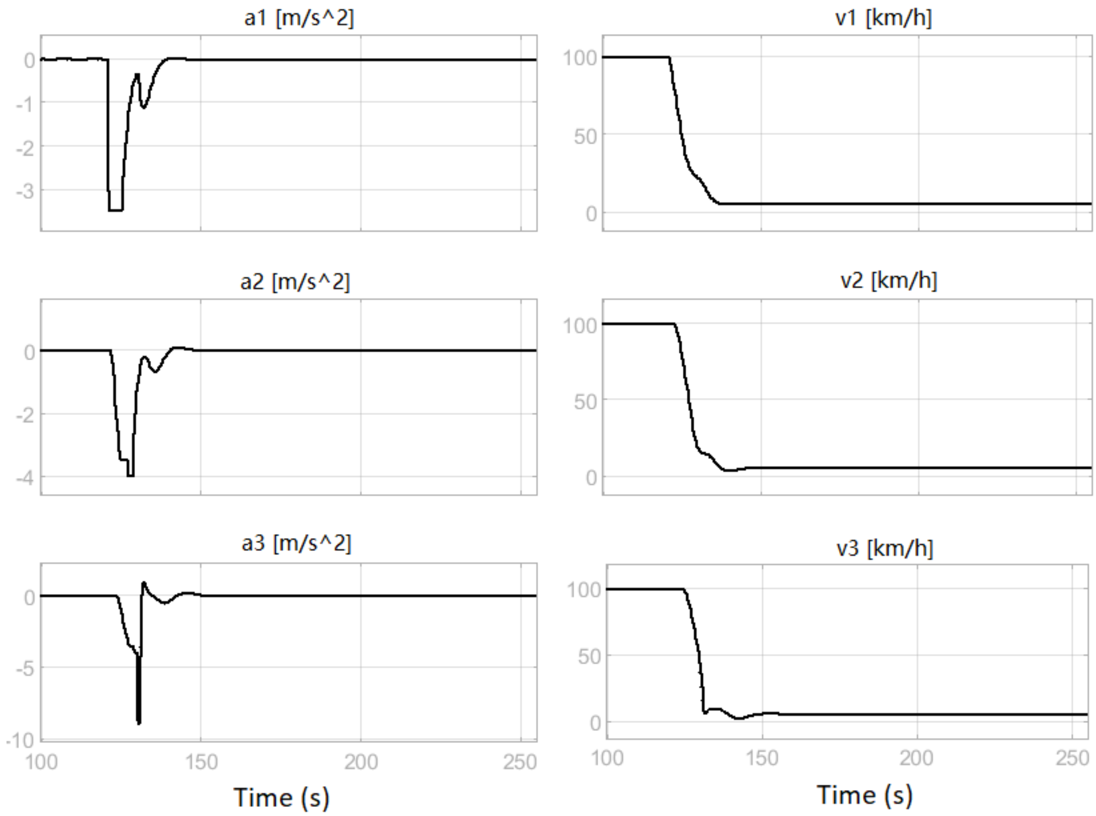


Figure 5.10: String instability of a platoon consisting of ACC vehicles.

Because of this string instability, even a weak deceleration can cause collision among platoon members when the length of the platoon is long enough, no matter how large the time gap is. For a platoon with limited length, for example, a 10-vehicle platoon, collision can be avoided by increasing the time gap. In an exemplar scenario described below, the critical time gap is identified. The target vehicle brakes harshly with the the maximum deceleration of -8 m/s^2. It takes 1.5 s for the target vehicle to reach the maximum deceleration. Then it will maintain the maximum deceleration until it stops. VEH1 to VEH10 are AVs. Before the hard brake of the target vehicle, all vehicles have a constant speed of 120 km/h. VEH1 is an AV equipped with ACC system and its time gap TG_1 is set to 4.1 s in order not to collide with the target vehicle. When VEH2, VEH3...VEH10 are all ACC vehicles then $TG_i(i = 2, 3, 4...10)$ should be larger than or equal to 3.2 s so that no collision occurs among platoon members. When VEH2, VEH3,...VEH10 are equipped with ACC+AEB system, the collision-free TG threshold for $TG_i(i = 2, 3, 4...10)$ is decreased to 2.8 s. If the TG is below the threshold then the collision will occur to some platoon members, for example, when $TG_i(i = 2, 3, 4...10)$ is 2.7 s for ACC+AEB vehicles, VEH1 to VEH6 don't collide with the preceding vehicle but VEH7 collides with VEH6.

For a platoon consisting of CACC vehicles, the deceleration of the front vehicles will not be amplified because a platoon consisting of CACC vehicles has string stability. Fig.5.11 shows the acceleration of VEH1, VEH2, VEH3 and VEH10 from a simulation for scenario 2. VEH1 is an ACC+AEB vehicle and it is in cruise mode with a constant cruise speed of 100 km/h before the target is detected. At 120 s, VEH1 detects the target from 112 m away which is moving with a constant speed of 5 km/h. VEH1 has TG of 1.6 s. VEH2 - VEH10 are in CACC mode with TG of 1s before the detection of target vehicle. It can be observed that the amplitude of the deceleration for each type of velocity controller decreases from VEH1 to VEH10 and CAEB brings less harsh brake than AEB while still guarantee safety.

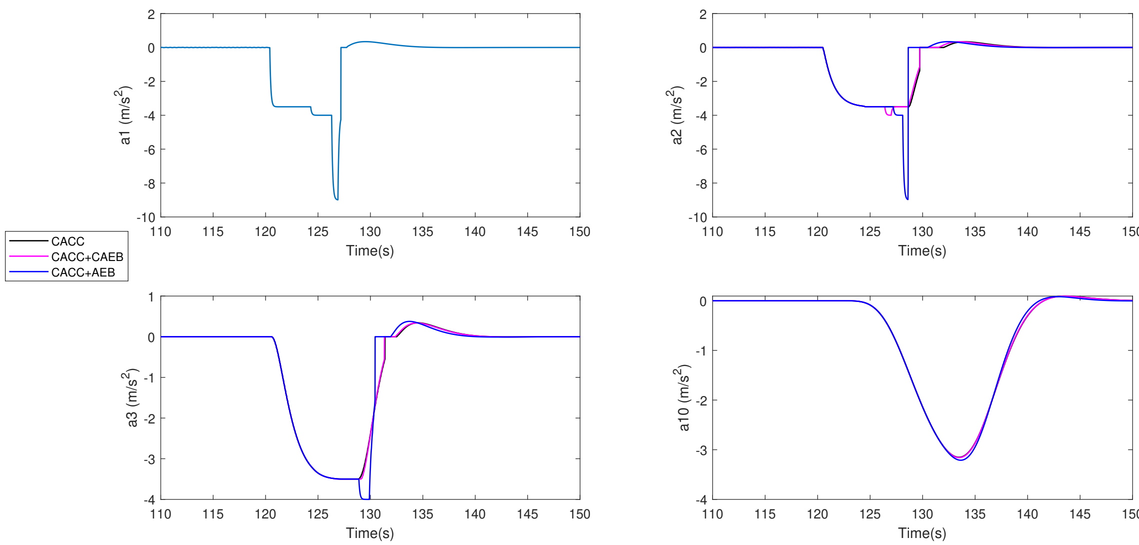


Figure 5.11: The platoon consisting of CACC vehicles are string stable.

For a platoon consisting of CACC vehicles, as long as the time gap is above the critical time gap then the collision can be avoided among platoon members for any length of the platoon. In an exemplar scenario described below, the critical time gap is identified and the results are shown in Table 5.3.

The target vehicle is a HDV and is driving in a constant speed of 120 km/h. It starts decelerating at certain point of time with maximum deceleration of -8 m/s^2. It takes 1.5 s for the target vehicle to reach its maximum deceleration. Then it will maintain the maximum deceleration until it stops.

Type of VEH1	TG_1**(s)**	**Type of VEH2 to VEH10**	**Critical time gap for** TG_i**(i = 2,3,...10)(s)**
ACC	4.1	CACC	0.1
ACC+AEB	3.8	CACC	1.7
ACC+AEB	3.8	CACC+AEB	0.7
ACC+AEB	3.8	CACC+CAEB	0.3

Table 5.3: The critical time gap for a CACC platoon.

When VEH1 is an ACC vehicle whose lower bound of acceleration is limited to $-3.5\ m/s^2$, there is no collision happening to the platoon even if VEH2 to VEH10 are equipped with neither AEB system nor CAEB system and the time gap is set to as small as 0.1 s. When VEH is an ACC+AEB vehicle, then VEH2 to VEH10 need AEB system or CAEB system to make the critical time gap below 1 s.

In summary, for a platoon consisting of CACC vehicles the collision won't be caused by the amplified deceleration among the platoon member and therefore as long as the first CACC vehicle doesn't collide with its target then all the following CACC vehicles are safe. The current implemented AEB can make sure that no crash happens for CACC vehicles with a time gap of 1 s in all tested driving scenarios. CAEB is even safer and causes less harsh brake than AEB.

5.3 Summary

This chapter first presents the structure of ACC system in Fig.5.1. Fig.5.1 shows the architecture of the existing ACC system and the information flow between its subsystems. The basic functions of each component of the ACC system are described. This ACC system is a base system for controlling the velocity of the ego vehicle. It is going to be extended with AEB function so that the integrated ACC+AEB system is realized. Then the performance analysis of the ACC system under critical traffic situations and its integration with a traditional AEB system is conducted. We conclude this chapter with the following findings:

1. Without driver's input, current implemented AEB usually can't avoid collisions in the typical critical road situations for an ACC or CACC vehicle with common time gap setting. The typical critical road situations are, for example, having a harshly braking preceding vehicle or encountering a very slowly moving target. The common time gap setting is referring to $1\,s$ for CACC vehicle and $1.5\,s$ for ACC vehicle.

2. The current way of integration of a traditional AEB system and an ACC system brings about undesirable vehicle movement, such as Stop-and-Go in front of a stationary target vehicle and frequent velocity fluctuation.

3. In a platoon consisting of ACC vehicles, current implemented integration of AEB system and ACC system usually can't avoid collisions for all platoon members when the foremost platoon member reacts to the typical critical road situations.

4. In a platoon consisting of CACC vehicles, current implemented AEB system and CAEB system can help avoid collisions in most cases and the velocity fluctuation caused by the vehicle control authority switch from (C)AEB system to CACC system won't be amplified along the platoon.

Chapter 6

Integrated ACC+AEB System: Functions, Architecture and Performance

In this chapter, an new integrated ACC+AEB system will be introduced. The content of this chapter includes the motivation of the new design, the functions and architecture of the new integrated ACC+AEB system, and the test results of the integrated ACC+AEB system.

The traditional AEB system relies solely on the (E)TTC as its safety indicator governing its output acceleration. From the simulation results in last chapter it's been proven that this design doesn't fit for (C)ACC vehicles well.

Firstly, the fact that TTC thresholds are the only factor to activate and deactivate the AEB controller, as we have seen, results in some undesirable velocity fluctuation during the transition from AEB system to ACC system and vice versa.

Secondly, the threshold values used in the traditional AEB are selected with the following expectation in mind: the driver is attentive and in control of the vehicle when urgent situation comes up. More often than not, this is not the case for drivers when the vehicle is under the control of ACC system. When vehicle is under the control of ACC system, the driver is easier involved in the secondary tasks and the lower mental workload could also lead to lower level of situation awareness. Consequently, the driver may not be fully attentive, even out of the loop. Furthermore, because the driver is not in control of the vehicle, it's quite natural that the driver may have higher expectation for the collision avoidance capacity of the AV than for a HDV.

These are the reasons why a newly designed AEB system dedicated to ACC vehicles is needed.

6.1 Use Cases

Fig.6.1 is the use case diagram of the ACC system. In the diagram, each oval represents a function of the ACC system, so called use case. There are two main use cases shown in the diagram, marked in purple: **Acceleration Calculation** and **Acceleration Coordination**.

1. **Acceleration Calculation** use case calculates the acceleration according to the different control strategies. After processing the input data from *HMI* and *Perception*, **Acceleration Calculation** invokes three use cases - **Cruise Acceleration Calculation**, **Following Acceleration Calculation** and **Gap Closing Acceleration Calculation** - to calculate the acceleration based on the control strategy adopted by each of three use cases.

2. **Acceleration Coordination** use case determines the final acceleration and sends it to the *Vehicle*

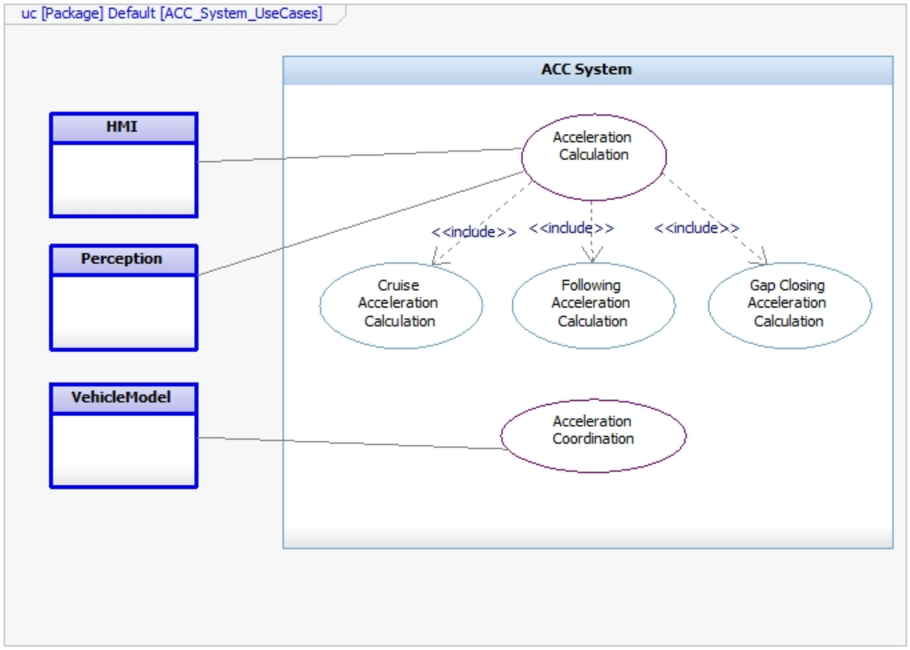


Figure 6.1: ACC system use case diagram.

Model. In Acceleration Coordination use case, the calculated acceleration values from **Acceleration Calculation** use case are merged and the final acceleration which should be sent to the *Vehicle Model* is determined.

Fig.6.2 shows the use case diagram of ACC+AEB system. To enhance the collision avoidance performance of ACC system, the integrated ACC+AEB system is proposed and its functional view is presented in Fig.6.2. In comparison with ACC system, three new use cases are added, marked in pink.

1. **Collision-free Acceleration Calculation** use case calculates the minimum required acceleration for the subject vehicle to stop safely behind the target vehicle without collision.
2. **Driving State Evaluation** use case is included in the **Acceleration Coordination** use case and it is responsible for determining the driving state in terms of safety level and the corresponding acceleration value which should be adopted at the current time step.
3. **Emergency Output Control** use case is an extending use case of **Acceleration Coordination** use case. **Emergency Output Control** sends the acceleration to *Vehicle Model* without taking the driving comfort into consideration, in case of emergency situation is identified by **Driving State Evaluation** use case.

Fig.6.1 and Fig.6.2 give us the functional view of the original ACC system and the newly proposed ACC+AEB system. In the next section, the architecture of ACC+AEB system is presented and system design is explained.

6.2 Architecture

Fig.6.3 shows the structure of the new integrated ACC+AEB system. In this new integrated ACC+AEB system, three subsystems are designed.

- **Threat Assessment** calculates the required minimum deceleration a_{req} that enables the subject vehicle to stop at a safe distance from the target vehicle. When a collision is likely to occur, the formula of

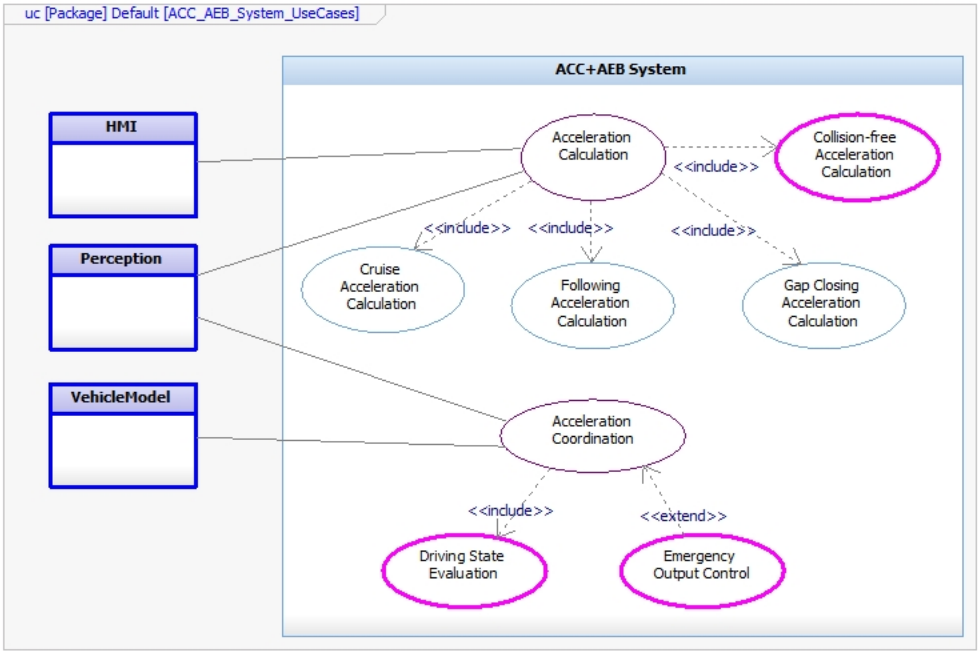


Figure 6.2: ACC+AEB system use case diagram.

calculation of a_{req} is as below:

$$a_{req} = a_{tv} - \frac{(v_{tv} - v_{sv})^2}{2(d_x - d_{stop})}$$

- **Driving State Controller** is responsible for the threat judgement of the situation and the determination of a_{aeb} which is going to be sent to the mixing block and output control block. a_{aeb} is the deceleration that the **Driving State Controller** choose based on the current state of driving situation. The **Driving State Controller** is implemented as a state chart as shown in Fig.6.4.

- **Output Control** functions as a shortcut for a_{aeb} in case of emergency so that the process delay of the signal can be minimized.

The design of the **Driving State Controller** is described below. It is based on a state chart, as shown in Fig.6.4.

The exact meaning of each state and transition is presented as following.

- **States**

  1. **Safe**
     In this state, the AEB system is standby because there is no emergency event detected.
  2. **Braking**
     In this state, the AEB system is activated and the acceleration signal sent by the AEB system to the coordination module is the minimum of the following - the acceleration without the limit of $-3.5\ m/s^2$ from Cruise Controller, Gap Closing Controller and Distance Controller, the acceleration of the target vehicle, and the acceleration needed for the subject vehicle to stop before the target vehicle with the stop distance of $5\,m$ assuming the current velocity and acceleration of the target vehicle prevail.
  3. **Transition to Safe**
     This state is a transitional state. In this state, the AEB system assumes that the emergency situation has finished and after it goes through this state, the ACC system will be in charge again. In this state, the acceleration signal sent from the AEB system to coordination module is a constant value $0.5\ m/s^2$

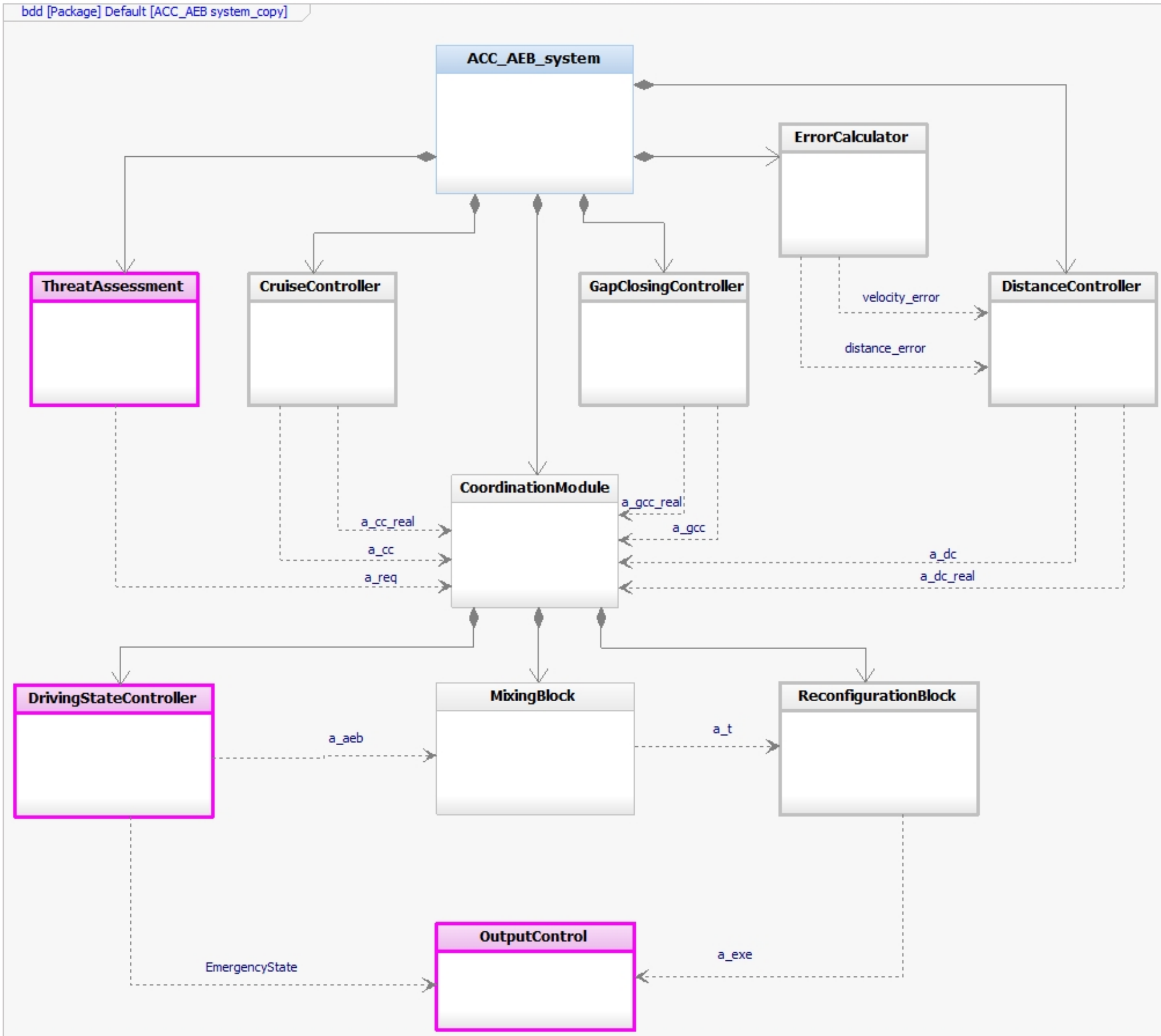


Figure 6.3: ACC+AEB system structure.

with the purpose of limiting the acceleration amplitude during the transition phase from AEB system to ACC system.

- **Transitions**

  [1-2] and **[0-2]** : The trigger of these two transitions are same, as following:

$$a_x <= -1.5$$

or

$$min(ACC, GCC) <= -5$$

Here $a_x = a_{tv} - a_{sv}$ and ACC and GCC are the outputs of distance controller and gap closing controller with the minimum acceleration of $-3.5\ m/s^2$ removed.
Because distance controller itself can't avoid a decelerating preceding vehicle with deceleration of at most $-2\ m/s^2$ (see Table 5.1), so here the relative acceleration threshold is set to -1.5 as a sign of a potential collision. The second criteria is come up for the scenario where the subject vehicle encounters

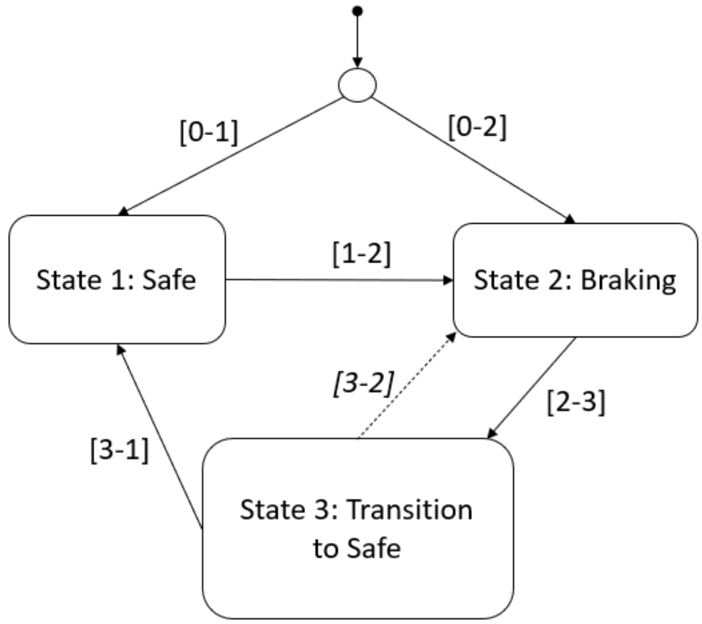


Figure 6.4: The new design of AEB dedicated to ACC vehicles

a target vehicle whose deceleration is negligible but has a slower velocity than the subject vehicle in a quite short distance.

[0-1] : The trigger of this transition is the negation of the trigger of the transition **[0-2]**, as following:

$$a_x <= -1.5$$

and

$$min(ACC, GCC) > -5$$

[2-3] : The trigger of this transition is as following:

$$a_{tv} >= 0$$

and

$$min(ACC, GCC) > -3.5$$

and

$$dx >= 5$$

[3-2] :The trigger of this transition is as following:

$$dataMode == 1$$

and

$$DistanceError <= -1$$

This transition is exclusively designed for ACC system, of which the acceleration of the target vehicle is not included in the control algorithm. Because without this transition, collision still occurs to a platoon consisting of ACC vehicles when the driving state is State 3. Therefore, a fallback transition from State 3 to State 2 is included. $dataMode == 1$ means the distance controller doesn't use the acceleration of the target vehicle in its control loop.

[3-1] :The trigger of this transition is as following:

$$abs(DistanceError) <= 0.1$$

and

$$abs(VelocityError) <= 0.1$$

and

$$min(ACC, GCC) > -1$$

6.3 System Test

This section shows the collision avoidance capability of the new ACC+AEB system. The same driving scenarios from Chapter 5. ACC System Structure and Performance Analysis are used to test the new ACC+AEB system.

- **Single vehicle**
  - Scenario 1: Following a decelerating target vehicle.
    Equipped with the new ACC+AEB system, the subject vehicle will not collide with the decelerating target vehicle in the test scenarios. The maximum deceleration of the target vehicle in the test is $-9\ m/s^2$. The minimum time gap of ACC vehicle in the test is $0.6\,s$ and the maximum initial velocity of the subject vehicle in the test is 120 km/h.
    Fig.6.5 shows the comparison of the acceleration profiles of the subject vehicle and the target vehicle in a test scenario. The delay in the initial of the deceleration between subject vehicle and target vehicle is $0.6\,s$.

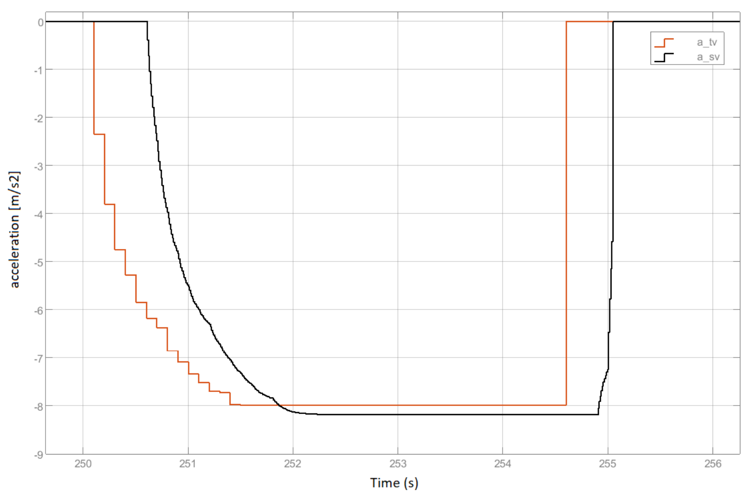


Figure 6.5: Acceleration profiles of the subject vehicle with a new ACC+AEB system as its velocity controller and target vehicle in a test scenario.

Fig.6.6 shows the acceleration profile, velocity profile of the subject vehicle and the distance between the subject vehicle and the target vehicle in this scenario. The subject vehicle is in ACC mode with the TG of $1.5\,s$ and the initial velocity is 120 km/h. At $250\,s$, the target vehicle starts decelerating till standstill.

  - Scenario 2: Approaching a low-speed target.
    Fig.6.7 shows the minimal detection distance for ACC vehicles equipped with traditional AEB and new AEB under different approaching velocities. The required detection range is smaller for the new ACC+AEB system and the increase of the required detection range when the relative velocity increases is also less obvious in comparison with the traditional ACC+AEB system.

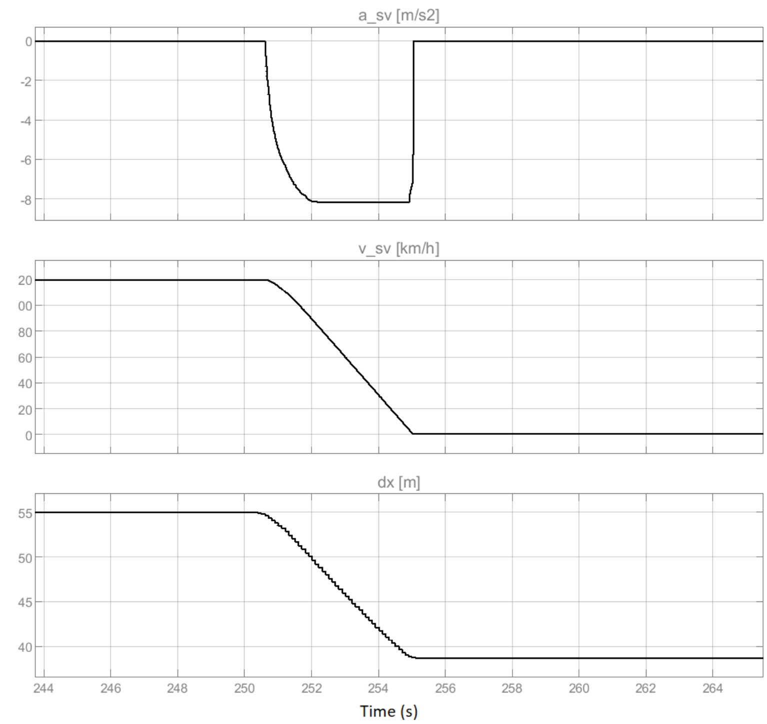


Figure 6.6: The acceleration profile, velocity profile of the subject vehicle and the distance between the subject vehicle and the target vehicle in the test scenario.

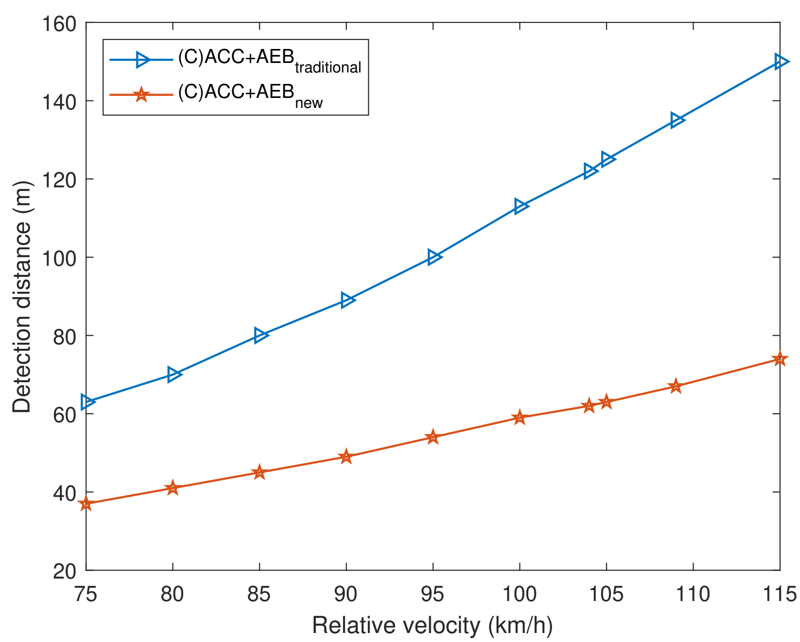


Figure 6.7: The minimal collision-free detection distance under different initial velocities for ACC vehicles equipped with traditional AEB and new AEB. Relative velocity = $V_{sv} - V_{tv}$

- **Platoon**

With the new ACC+AEB system, the can be avoided for all platoon members in both scenarios. Fig.6.8 shows the acceleration profile and velocity profile of VEH1, VEH3 and VEH5 in the scenario 1. All platoon members, from VEH1 to VEH10 have ACC+AEB system as velocity controllers. They are all in the ACC mode with TG of 1.5 $s$before the target vehicle starts to decelerate. The initial velocity of the platoon is 120 km/h. At 250 s the target vehicle decelerates to 10 km/h with the maximal deceleration of $-8\ m/s^2$.

Fig.6.9 shows the acceleration profile and velocity profile of VEH1, VEH3 and VEH5 in the same scenario but the platoon members, except VEH1, have CACC+CAEB system as their velocity controllers and the time gap is set as 1 s. When integrated with CACC system, the new AEB system will use the acceleration of the target vehicle in its **Threat Assessment** block and **Driving State Controller**. Therefore, it is referred as CAEB system. With the CACC+CAEB system as the velocity controller, the platoon will not have collisions and the crash caused by string instability of the ACC platoon is avoided.

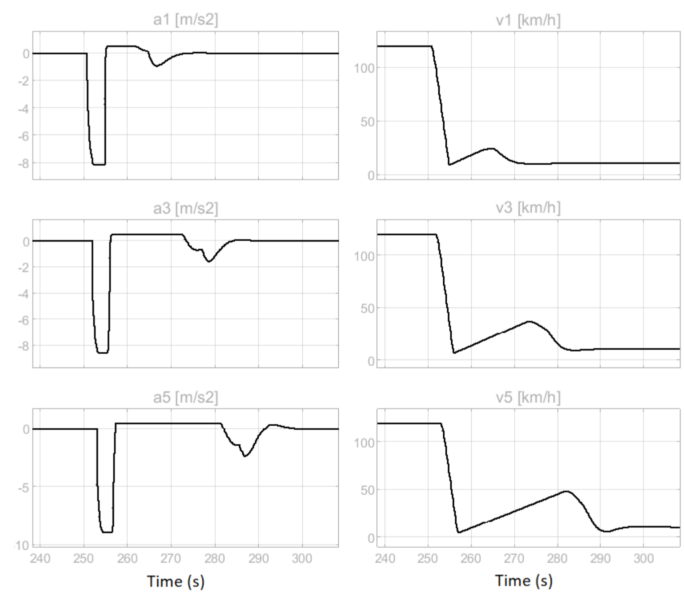


Figure 6.8: The acceleration profile and velocity profile of VEH1, VEH3 and VEH5 (ACC+AEB) in the scenario 1.

Fig.6.10 shows the acceleration profile and velocity profile of VEH1, VEH3 and VEH5 in the scenario 2. Before detecting a target vehicle, VEH1 is driving with a constant cruise speed of 120 $km/h$and VEH2 to VEH 10 are in ACC mode with TG of 1.5 s. All platoon members, from VEH1 to VEH10 have ACC+AEB system as their velocity controllers. At 150 s VEH1 detects the target vehicle which is driving with a constant velocity of 5km/h at the distance of 80 m. Notice that the causes of the two great deceleration of VEH5 are different. The first huge deceleration is a reaction for the sudden detection of the target vehicle. The second time, another great deceleration between 180 s and 190 s is to avoid the collision with the preceding vehicle, in this case, VEH4, due to the string instability of ACC platoon.

Fig.6.11 shows the acceleration profile and velocity profile of VEH1, VEH3 and VEH5 in the same scenario but the platoon members, except VEH1, have CACC+CAEB system as their velocity controllers and the time gap is set as 1 s.

6.4 Summary

This chapter proposes a new integrated ACC+AEB system and presents its improved collision avoidance capability over the traditional ACC+AEB system. The new ACC+AEB system has improved driving safety

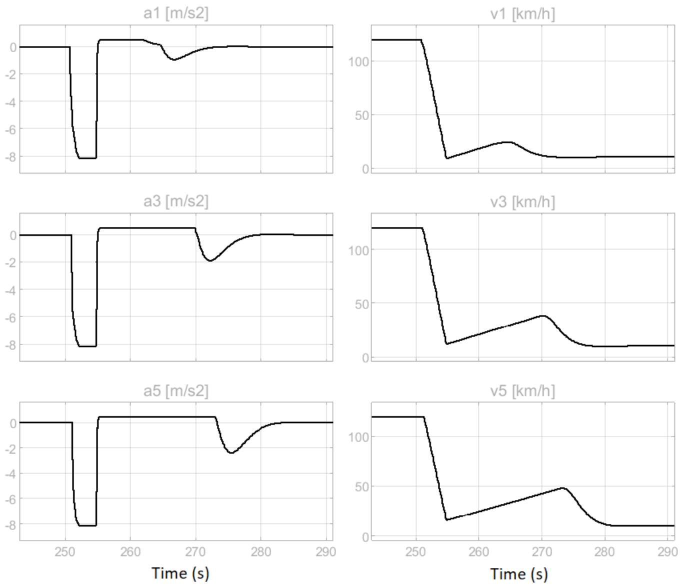


Figure 6.9: The acceleration profile and velocity profile of VEH1, VEH3 and VEH5 (CACC+CAEB)in the scenario 1.

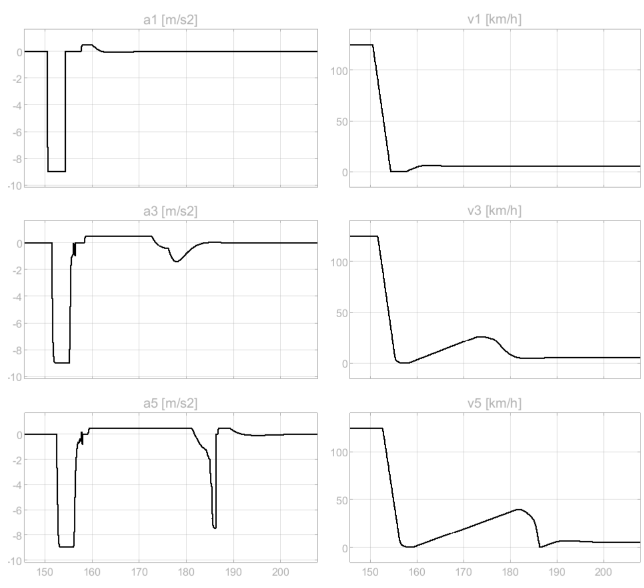


Figure 6.10: The acceleration profile and velocity profile of VEH1, VEH3 and VEH5 (ACC+AEB)in the scenario 2.

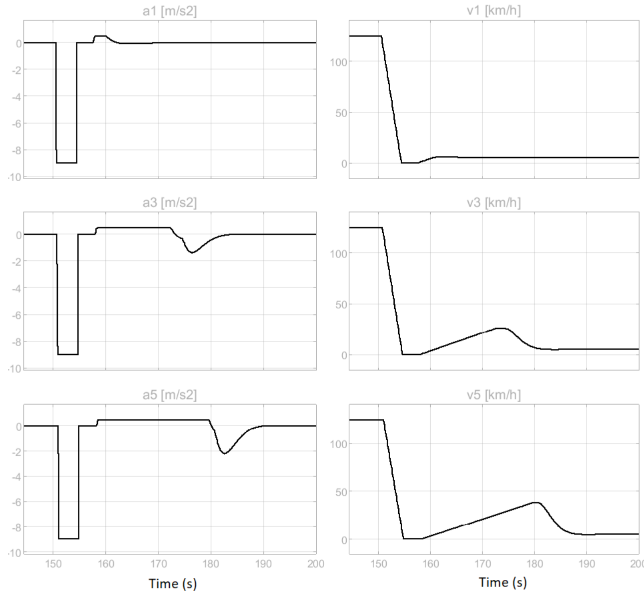


Figure 6.11: The acceleration profile and velocity profile of VEH1, VEH3 and VEH5 (CACC+CAEB)in the scenario 2.

for AV in both single vehicle test scenarios and platoon test scenarios. It helps avoid rear-end collisions in the typical critical road situations with common time gap setting. The typical critical road situations are, for example, having a harshly braking preceding vehicle or encountering a very slowly moving target. The common time gap setting is referring to $1\,s$ for CACC vehicle, which is considered as a special case of ACC vehicle when the V2V communication is in place, and $1.5\,s$ for ACC vehicle. In the new ACC+AEB system, the interaction between AEB system and ACC system is coordinated so that no undesirable velocity fluctuation is observed.

Chapter 7

Traffic Impact Assessment

In this chapter the microscopic traffic simulation is conducted to assess the impact of the new integrated ACC+AEB system and CACC+CAEB system on the traffic flow. Section 7.1 gives an overview of the traffic simulation workflow and defines the input parameters. Section 7.2 shows the network in the simulation and introduces the set up of the simulation model. Finally, Section 7.3 presents the observations and findings from traffic simulation.

7.1 Simulation Workflow and Input Parameters

We use VISSIM as a software to conduct the microscopic traffic simulation. VISSIM is a time step and behavior based microscopic traffic simulation model developed at the University of Karlsruhe, Karlsruhe, Germany, in the early 1970s [51]. The workflow of the simulation conducted in VISSIM for this project is shown in Fig.7.1.

To run the simulation, we need to define the input parameters for the simulation model. Four key parameters in the simulation model are explained as follows:

- **Traffic composition**

  Traffic composition defines the type of the vehicles in the simulation model. In this project, we assume that the vehicles in the simulation model are all passenger cars. The longitudinal behavior model of these passenger cars are either the car-following model from VISSIM itself or the user-defined model, such as the ACC+AEB system developed in this graduation project. The different traffic composition is reflected by the different Market Penetration Rate (MPR) of AVs. The MPR of AVs varies from 0% to 100% by a 20% interval. For example, the traffic composition of a simulation run can be 20% MPR of ACC+AEB vehicles. This means in this run of simulation, the vehicles generated by VISSIM at the entrance of the traffic network consisting of 20% automated vehicles which have ACC+AEB system as their velocity controllers and 80% of vehicles generated are HDV.

  The lateral behavior model of the HDVs is defined by VISSIM and AVs don't have lateral movement during simulation.

  In terms of size, the traffic composition adopts the distribution as shown in Table 7.1.

  In terms of velocity controller for each type of vehicles, the car-following model in VISSIM is used to model the velocity controller for HDV, and the ACC system and AEB system are implemented to model the velocity controller for AV.

  ■ **HDV: Car-following model in VISSIM**

  The car-following model in VISSIM is used to model the behavior of HDV in the simulation. There

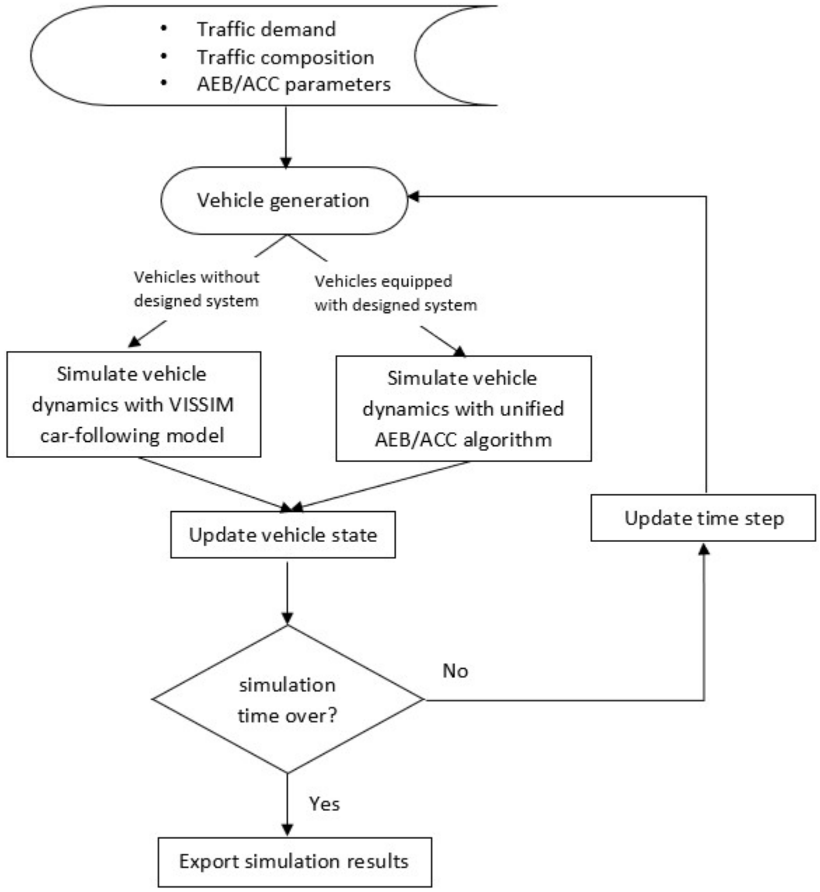


Figure 7.1: The workflow of traffic simulation in VISSIM.

2D model name	Share
Volkswagen Golf	0.24
Audi A4	0.18
Mercedes CLK	0.16
Peugeot 607	0.16
Volkswagen Beetle	0.14
Porsche Cayman	0.02
Toyota Yaris	0.10

Table 7.1: Vehicle size distribution

are two car-following models in VISSIM: Wiedemann 74 and Wiedemann 99. Between these two car-following models, Wiedemann 99 is more suitable for modelling highway driving [51]. There are 9 parameters driving the Wiedemann 99 model [52]. Their meanings and values adopted in the simulation are shown in Table 7.2.

Parameters	**Explanation**	**Value**
CC0	Standstill distance: The desired standstill distance between two vehicles.	$5\,m$
CC1	Time headway: The desired time headway between the lead and following vehicle.	$1.5\,s$
CC2	Longitudinal oscillation: Restricts the distance difference a driver allows for before he intentionally moves closer to the car preceding him.	$4\,m$
CC3	Perception threshold for following: Defines the beginning of the deceleration process. At this stage the driver recognizes a preceding slower vehicle.	-8 s
CC4	Negative speed difference: Defines negative speed difference during the following process.	$-0.35\,m/s$
CC5	Positive speed difference: Defines positive speed difference during the following process.	0.35 m/s
CC6	Influence speed on oscillation: Influence of distance on speed oscillation during the following process.	$11.44\,/(m\cdot s)$
CC7	Oscillation acceleration: Minimum value for absolute acceleration/deceleration used by a driver when following another vehicle.	$0.25\,m/s^2$
CC8	Acceleration starting from standstill: Desired acceleration when starting from standstill.	$3.50\,m/s^2$
CC9	Desired acceleration at 80 km/h.	$1.50\,m/s^2$

Table 7.2: Key parameters in Wiedemann 99 car-following model.

- **AV: Implementation of (C)ACC system and (C)AEB system**

VISSIM provides an external driver model interface enabling the replacement of the default car-following model by the user-defined model. To use the external driver model interface, the existing (C)ACC system and the proposed (C)ACC+(C)AEB system are implemented in a DLL written in C++ and imported into the traffic simulation model. During a simulation run, VISSIM calls the DLL code for each affected vehicle in each simulation time step to determine the behavior of the vehicle. VISSIM passes the current state of the vehicle and its surroundings to the DLL and the DLL computes the acceleration of the vehicle and passes these values back to VISSIM to be used in the current time step [53].

Key parameters used for (C)ACC system and (C)AEB system in the traffic simulation are shown in Table 7.3.

- **Traffic demand**

Traffic demand is the number of vehicles generated at the entrance of the simulation network in a pre-defined time interval. Its unit usually is ”veh/hr/lane”. To determine the traffic demand used for the simulation, first we find out the pipeline capacity of the traffic network under different traffic compositions, i.e. different MPRs for AVs. Then two values for the traffic demand are chose to run the simulations, one of which is relatively small, representing the sparse traffic flow and another is relatively large, representing a more crowded traffic flow. Refer to Section 7.2 for more information regarding this.

Parameters	Explanation	Value
Standstill distance	The desired distance between stopped vehicles.	$5\,m$
Target detection range (ACC)	The longest distance that can be detected by the ACC system of the subject vehicle.	$100\,m$
Target detection range (CACC)	The longest distance that can be detected by the CACC system of the subject vehicle.	$150\,m$
Sensor delay	The sensor delay of ACC system in the measurement of distance and target velocity.	0.3 s
Desired time gap (ACC)	The desired time headway between the subject vehicle and the target vehicle for ACC system.	$1.2\,s$
Desired time gap (CACC)	The desired time headway between the subject vehicle and the target vehicle for CACC system.	$1.0\,s$
Acceleration lower limit of (C)ACC system	The minimum acceleration of the (C)ACC system.	$-3.50\,m/s^2$
Acceleration upper limit of (C)ACC system	The maximum acceleration of the (C)ACC system.	$2.00\,m/s^2$
Acceleration of full braking of (C)AEB system	The minimum acceleration of the (C)AEB system.	$-9.00\,m/s^2$

Table 7.3: Key parameters used for (C)ACC system and (C)AEB system in simulation.

7.2 Traffic Network Setup

The simulation is conducted on a 8km-long road section with an on-ramp located at $5\,km$ downstream from the beginning, as illustrated by Fig.7.2. An acceleration lane of $250\,m$ connects on-ramp with the mainline. In the first $1.5\,km$ of the simulated network, the individually generated (C)ACC vehicles will naturally form strings via the join manoeuvre. Thus the first $1.5\,km$ is used as a warm-up section in the simulation. Around the on-ramp location, at different positions in the mainline there are 12 data collection points are placed to detect the average speed at these locations within the simulation interval. They are $100\,m$ apart from each other. The marks of these data collections points range from -5 to 6, as shown in Fig.7.2.

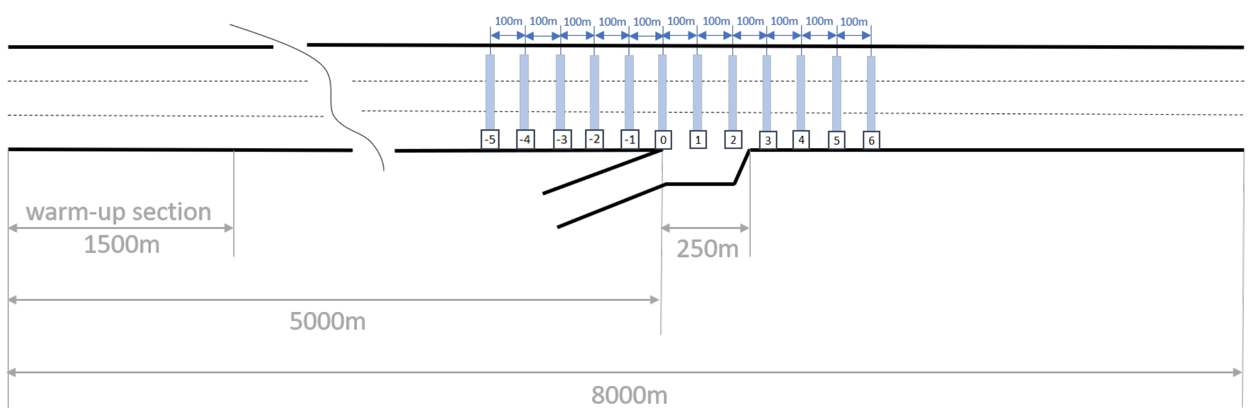


Figure 7.2: Road sketch of a simple merging network.

In order to set a proper traffic demand for the simulation model, first we need to estimate the pipeline capacity of the traffic. To this end, we conducted simulations on an 8km-long section with three lanes, identical to the network in Fig.7.2 except the on-ramp. The pipeline capacity was estimated by setting a traffic demand large enough to make the generated vehicles pile up at the beginning of the network. A data collector is put at $5\,km$ downstream to count the throughput. Fig.7.3 shows the pipeline capacity under different MPR of ACC vehicles and CACC vehicles.

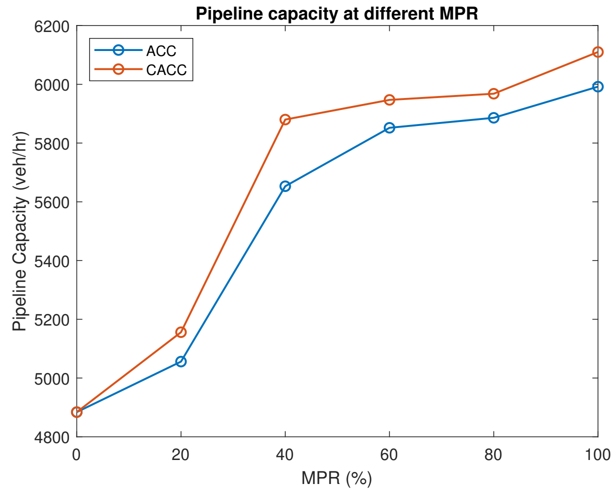


Figure 7.3: The pipeline capacity with different penetration rates for ACC and CACC vehicles.

In the simulations, three traffic demand values are picked - 2000 veh/hr at mainline entrance for a sparse traffic flow, 4000 veh/hr at mainline entrance for a crowded traffic flow, 500 veh/hr at on-ramp entrance for both cases. The vehicle composition at mainline entrance varies with different MPR. The vehicle composition at on-ramp entrance is always 100% HDV.

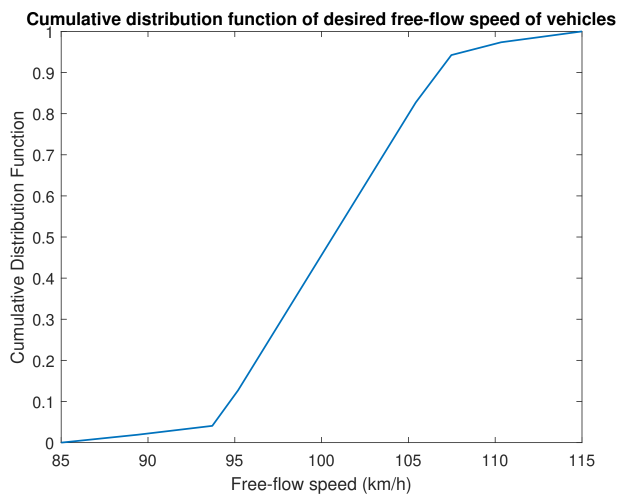


Figure 7.4: The probability distribution function of the desired speed

As for the speed of vehicles at the entrance, for both mainline and on-ramp, Fig.7.4 shows the cumulative distribution function of the desired free-flow speed for all vehicles generated by VISSIM.

For each simulation of a MPR value, five repetitions have been done with different random seed each time. The random seed assigns desired speed and the arriving interval between two vehicles at the simulation vehicle generators. Each run of simulation lasts for one hour with a $0.1\,s$ time step and the first $10\ min$ is taken as a warm-up period.

7.3 Traffic Impact Assessment Results

In this section, the impact of (C)ACC+(C)AEB system on traffic safety is first addressed. To do that, three indicators are chose to evaluate the traffic safety. Then, the average speed at data collection points and the acceleration value distribution of all vehicles are also investigated.

The traffic safety indicators are as follows:

1. **Time Integrated Hard Brake Time (TIH)**
   The TIH indicator is designed to evaluate the traffic safety from the perspective of hard brake times. Its visual representation is shown in Fig.7.5.

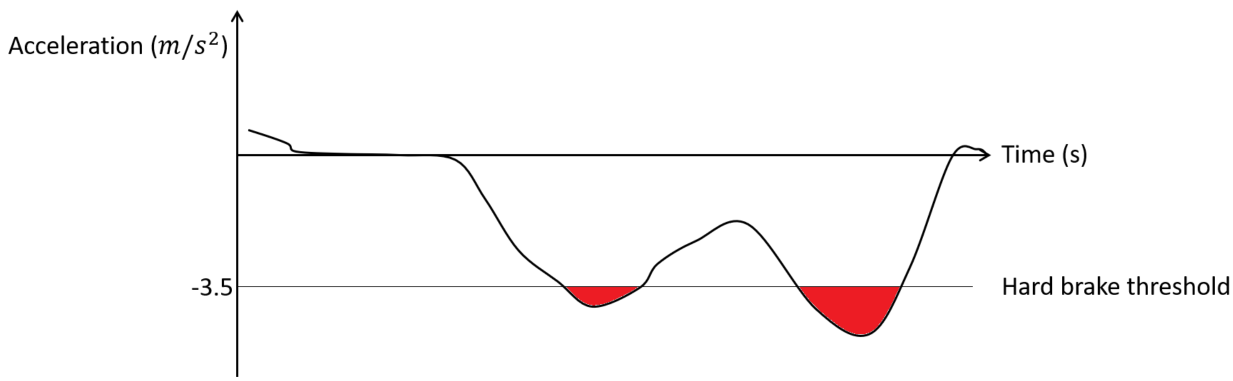


Figure 7.5: Acceleration profile with TIH indicated.

   For the i^{th} vehicle, its TIH_i is calculated as below:

$$TIH_i = \sum_{t=0}^{T}[Brake_{th} - Acc_i(t)]\Delta t, \forall Acc_i(t) \leq Brake_{th}$$

   Acc_i is the acceleration value of i_th vehicle, $Brake_{th}$ is the hard brake threshold and Δt is the time step. The hard brake threshold is set as $-3.5\ m/s^2$ because this value is the lower acceleration limit of ACC system. There is no consensus found from literature about exact value of the brake threshold when evaluating the traffic safety level, so the lower acceleration limit of ACC system is taken as hard brake threshold to indicate the traffic safety.

   After getting TIH_i for each vehicle passing through the simulated road section, we divide TIH_i by the travel time T_i of i^{th} vehicle and calculate the average for all vehicles passing the road section at one-hour time interval:

$$TIH = \frac{\sum_{n=1}^{N}(TIH_i/T_i)}{N}$$

2. **Time Integrated Time-to-Collision (TIT)**
   The TIT indicator, introduced by Minderhoud et al.[49], takes the integral of the TTC profile to evaluate the level of traffic safety. Its visual representation is shown in Fig.7.6 and its calculation formula is as below:

$$TIT_i = \sum_{t=0}^{T}[TTC^* - TTC_i(t)]\Delta t, \forall 0 \leq TTC_i(t) \leq TTC^*$$

   TIT_i is the TIT value of i_th vehicle, TTC^* is the TTC threshold and Δt is the time step.

   After getting TIT_i for each vehicle passing through the simulated road section, we divide TIT_i by the travel time T_i of i^{th} vehicle and calculate the average for all vehicles passing the road section at one-hour time interval:

$$TIT = \frac{\sum_{n=1}^{N}(TIT_i/T_i)}{N}$$

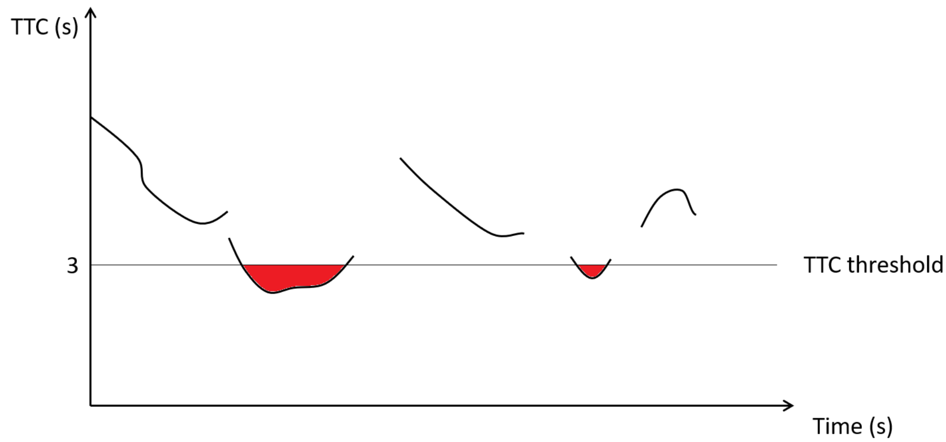


Figure 7.6: TTC profile with TIT indicated, adapted from [49].

The TTC threshold is chose as 3 s because this TTC value is the earliest initiation time of collision avoidance countermeasures according to ISO 22839, as mentioned in Chapter 2. Literature Review.

3. **Minimum Time-to-Collision**
   Although the TIH and TIT demonstrate the level of traffic safety, they are both related to the average traffic safety level in a defined amount of time. An indicator which can give us the insight about the most dangerous moment occurring to an individual vehicle is needed, and therefore we take the average of minimum TTC of 30 vehicles with the smallest minimum TTC values to represent the danger level of the most critical conflicts happening on the road section in the defined amount of time.

Fig.7.7 and Fig.7.8 shows above-mentioned three safety indicators with different MPR of AV in the sparse and crowded traffic condition, respectively.

The observations from Fig.7.7 and Fig.7.8 are as follows:

1. **Time Integrated Hard Brake Time (TIH)**
   - When the traffic demand is low, AEB doesn't influence TIH much at some MPRs (ACC: 20%,40%,100%; CACC: 20%,40%,60%) but will increase TIH at other MPRs (ACC: 60%,80%; CACC: 80%,100%).
   - When the traffic demand is high, AEB will decrease TIH at low MPR ($< 50\%$), and increase TIH at high MPR ($> 50\%$) for ACC vehicles and CACC vehicles.
2. **Time Integrated Time-to-Collision (TIT)**
   For both low traffic demand and high traffic demand situations, AEB system decreases the TIT for ACC vehicles and doesn't have much influence on TIT for CACC vehicles except at MPR 40% where AEB decreases TIT for CACC to a larger extent in comparison with other MPR values.
3. **Minimum Time-to-Collision**
   - When the traffic demand is low, AEB system increases the Minimum TTC for ACC vehicles at any MPR and increases the Minimum TTC for CACC vehicles when MPR is larger than 60%.
   - When the traffic demand is high, AEB increases the Minimum TTC for ACC vehicles when MPR is larger than 20% and the larger MPR, the larger increment. For CACC vehicles, AEB system doesn't influence much on Minimum TTC. Only a little increment observed at MPR 20%, 40% and 100%.

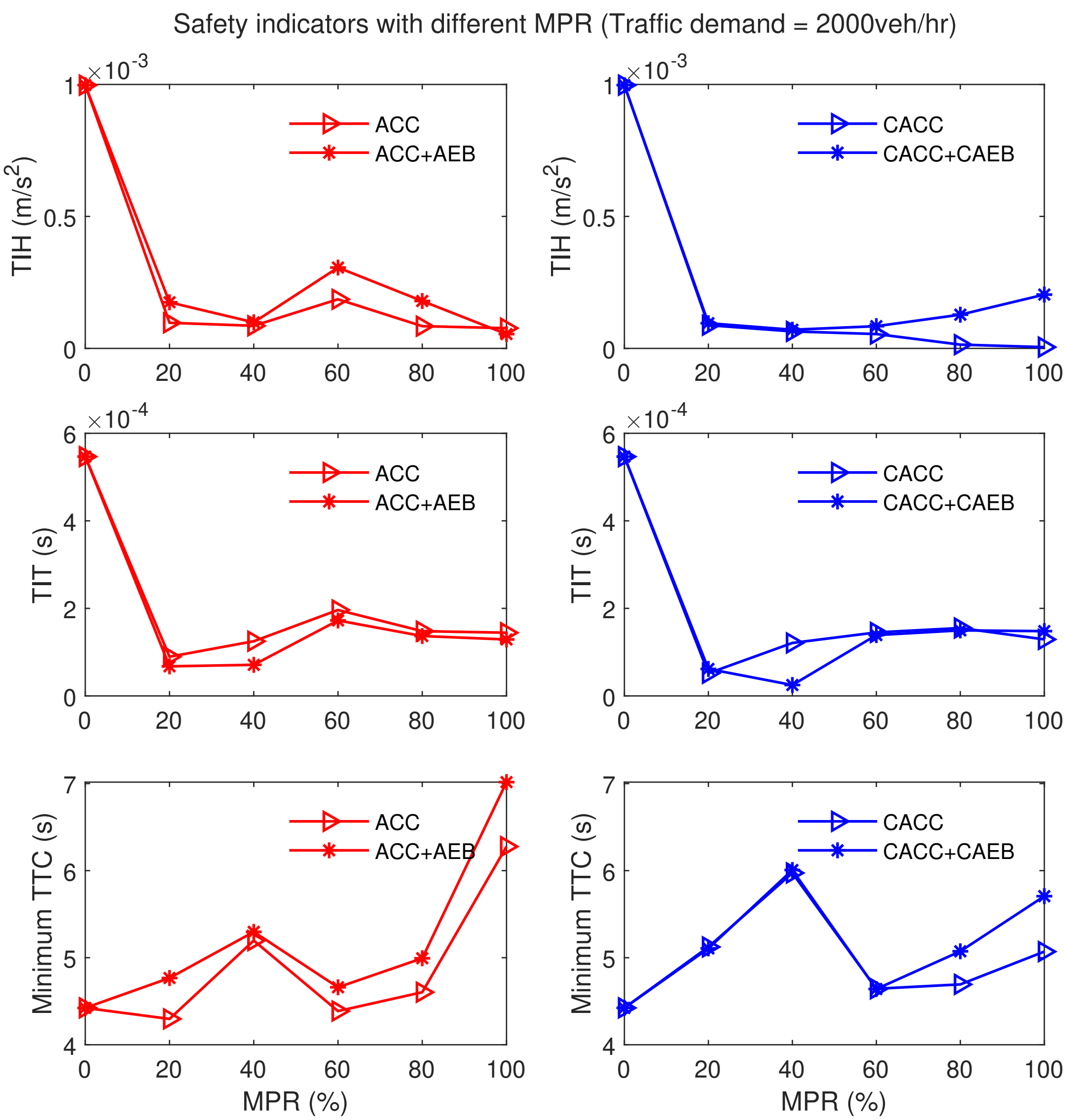


Figure 7.7: Safety indicators with different MPR of AV in the sparse traffic condition.

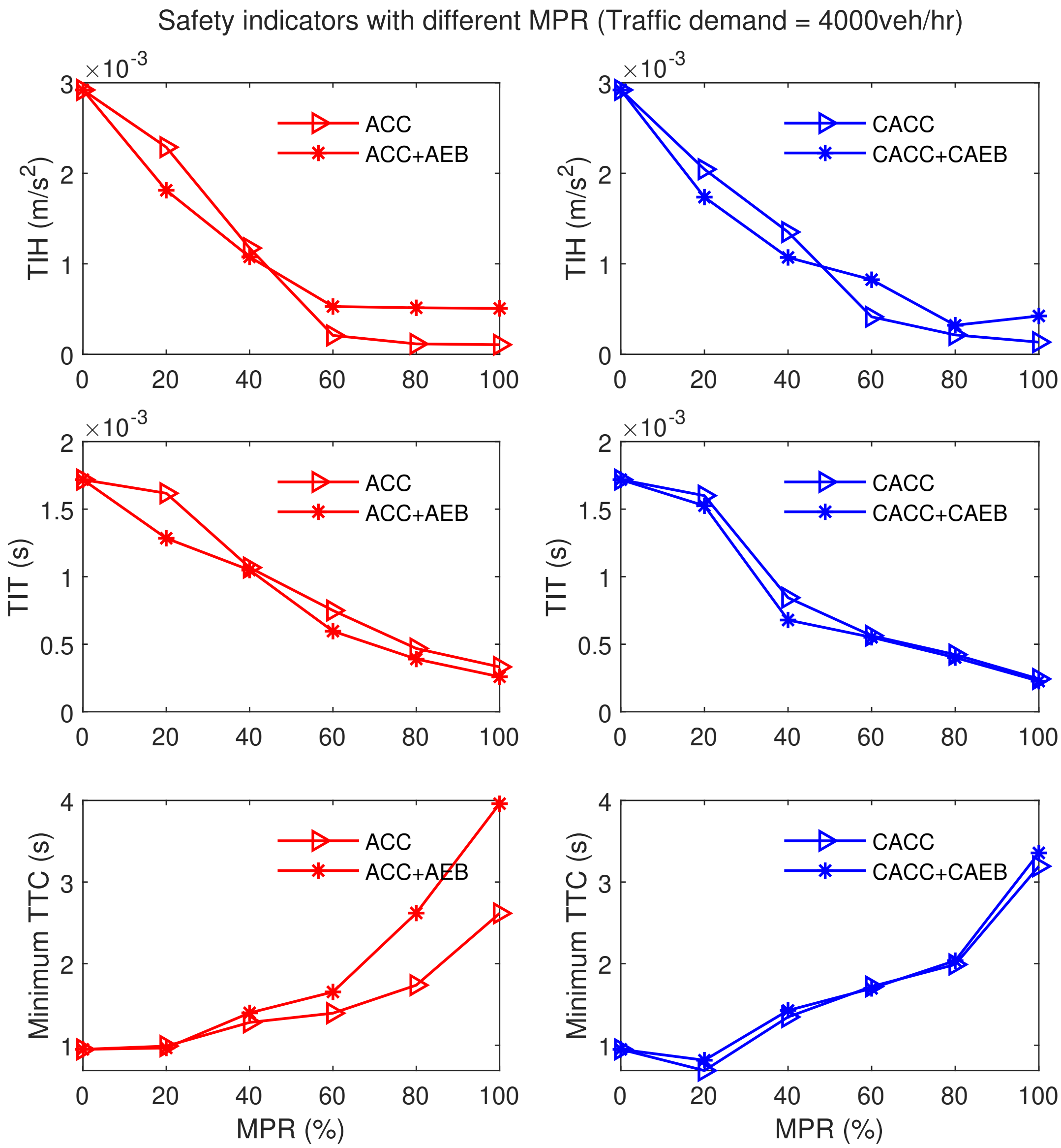


Figure 7.8: Safety indicators with different MPR of AV in the crowded traffic condition.

Fig.7.9 shows the average speed at the data collection points with different MPR of AV in the sparse traffic condition. Two observations can be made from it:

- The higher MPR of AV, the lower average speed at all data collection points.
- AEB system decreases average speed for ACC vehicles at MPR 40% and 80%; for CACC vehicles at MPR 20% , 40% and 80%. With other MPR values, AEB system doesn't change average speed much.

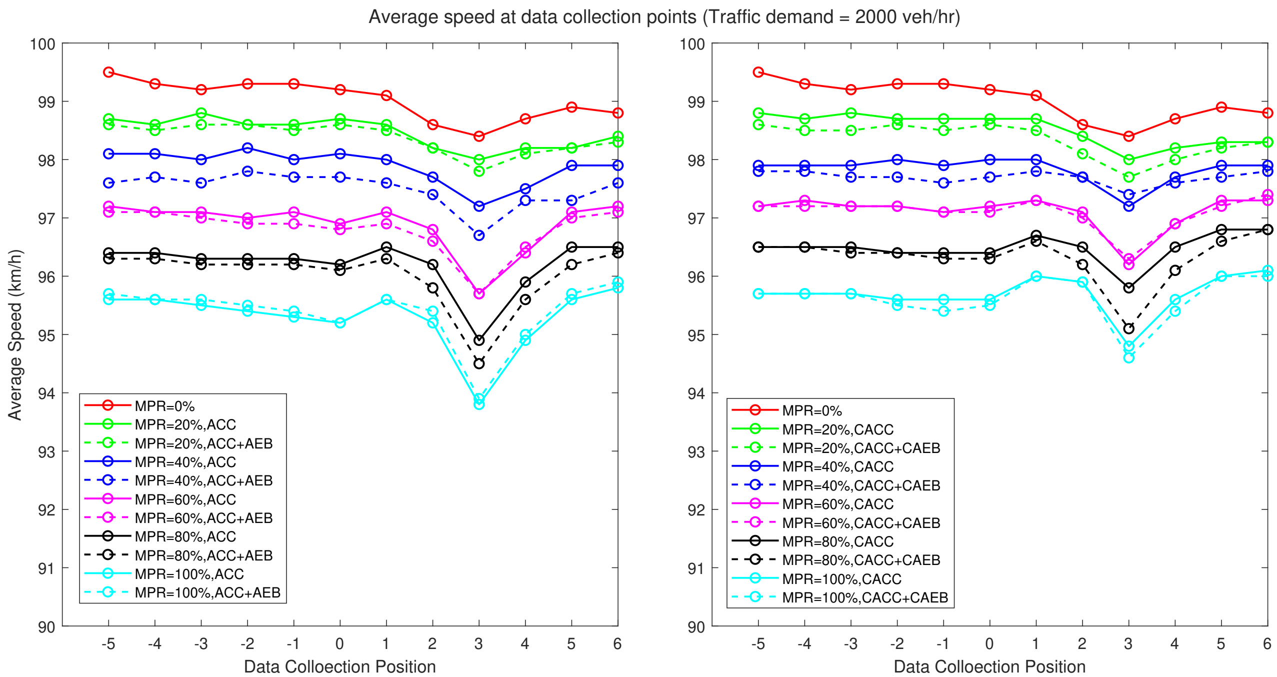


Figure 7.9: Average speed at data collection points in the sparse traffic condition.

Fig.7.10 and Fig.7.11 show the average speed at data collection points with different MPR of ACC/ACC+AEB vehicles and CACC/CACC+CAEB vehicles in the crowded traffic condition, respectively. Observations obtained from these two figures are as follows:

- In the crowded traffic condition, when MPR is larger than 20%, the larger MPR, the slower average speed at the upstream of on-ramp.
- AEB system doesn't influence the average speed at the upstream of on-ramp.
- The influence of AEB system on average speed near on-ramp (data collection points 0-4) depends on the vehicle type (ACC or CACC) and the MPRs. No consistent phenomenon are observed from Fig.7.10 and Fig.7.11.

Fig.7.12 and Fig.7.13 shows the acceleration distribution with different MPR of ACC vehicles and ACC+AEB vehicles in the sparse traffic condition, respectively. The figures are double y-axis bar chart. The left y axis marked in blue are the scale for two blue bars in the chart - acceleration value between $-1\ m/s^2$ and $0\ m/s^2$ and between $0\ m/s^2$ and $2\ m/s^2$. The right y axis marked in red are for the rest bars in the chart. It's can be seen from Fig.7.12 and Fig.7.13 that When the traffic demand is low, for ACC vehicles, AEB system increases the frequency of acceleration smaller than $-6\ m/s^2$ when MPR is larger than 20% and makes the frequency of acceleration between $-6\ m/s^2$ and $-1\ m/s^2$ reach the maximum at MPR 20%. AEB system doesn't have much impact on the frequency of acceleration larger than $-1\ m/s^2$.

Fig.7.14 and Fig.7.15 shows the acceleration distribution with different MPR of CACC vehicles and CACC+CAEB vehicles in the sparse traffic condition, respectively. Just as in the AEB+ACC case (Fig.7.12

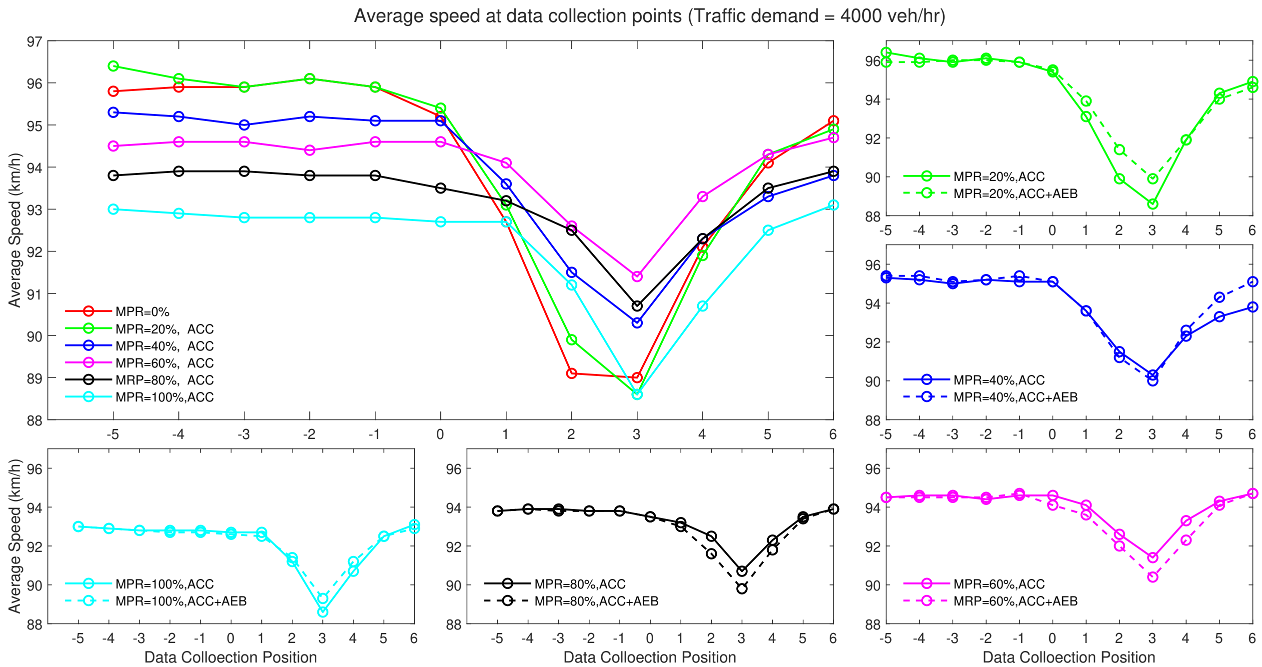


Figure 7.10: Average speed at data collection points in the crowded traffic condition for different MPR of ACC vehicles and ACC+AEB vehicles.

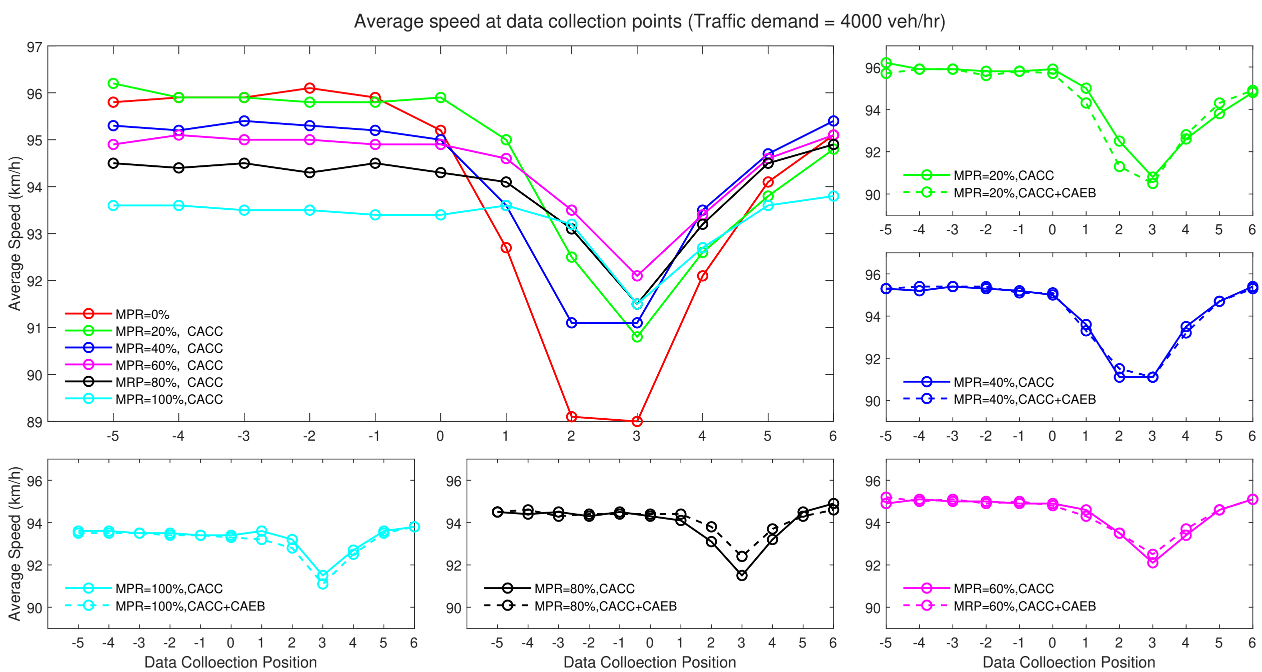


Figure 7.11: Average speed at data collection points in the crowded traffic condition for different MPRs of CACC vehicles and CACC+CAEB vehicles.

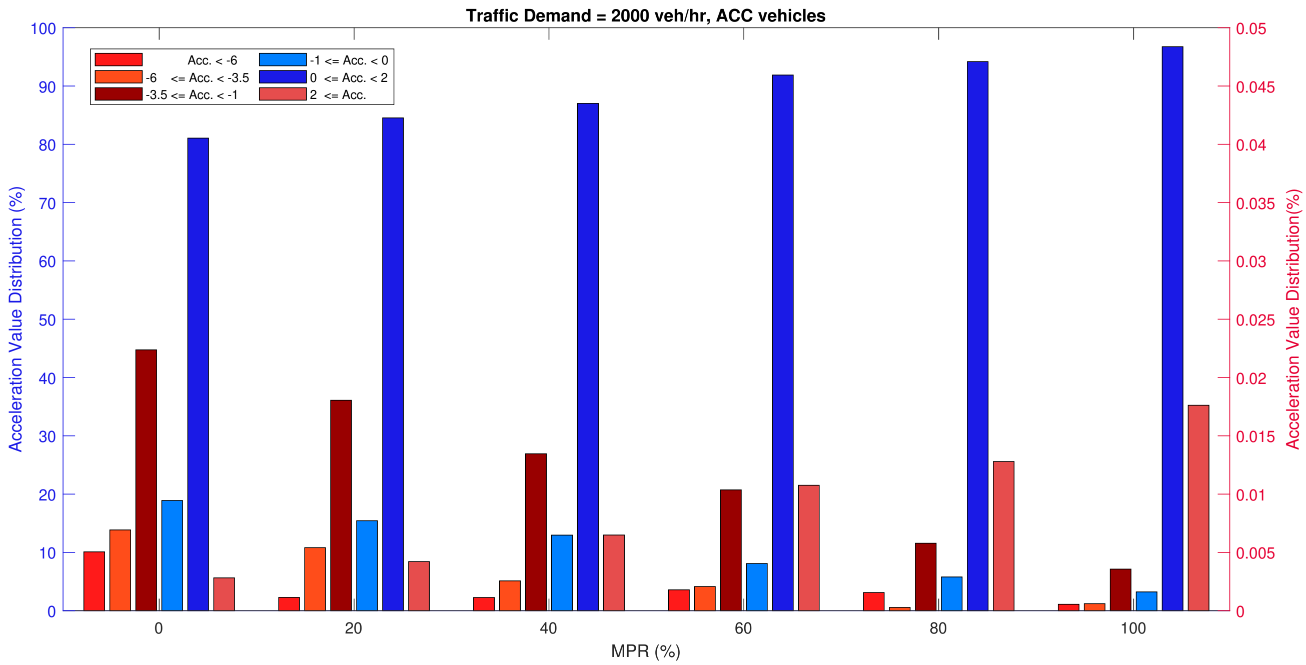


Figure 7.12: Acceleration distribution in the sparse traffic condition for different MPRs of ACC vehicles.

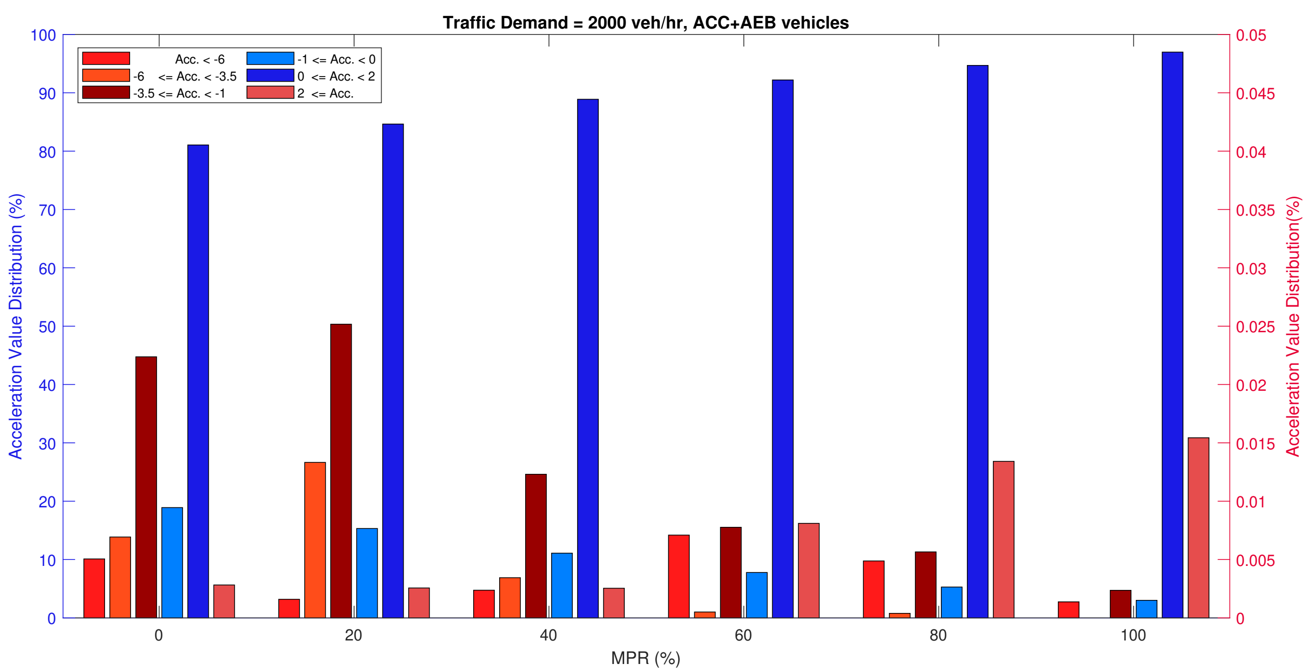


Figure 7.13: Acceleration distribution in the sparse traffic condition for different MPRs of ACC+AEB vehicles.

and Fig.7.13), CAEB system doesn't have much impact on the frequency of acceleration larger than $-1\ m/s^2$ in the sparse traffic condition. When the traffic demand is low, for CACC vehicles, CAEB increases the frequency of acceleration smaller than $-6\ m/s^2$ when MPR is larger than 60%, and makes the frequency of acceleration between $-6\ m/s^2$ and $-1\ m/s^2$ higher than CACC vehicles at MPR 20% but lower than CACC vehicles when MPR is larger than 40%.

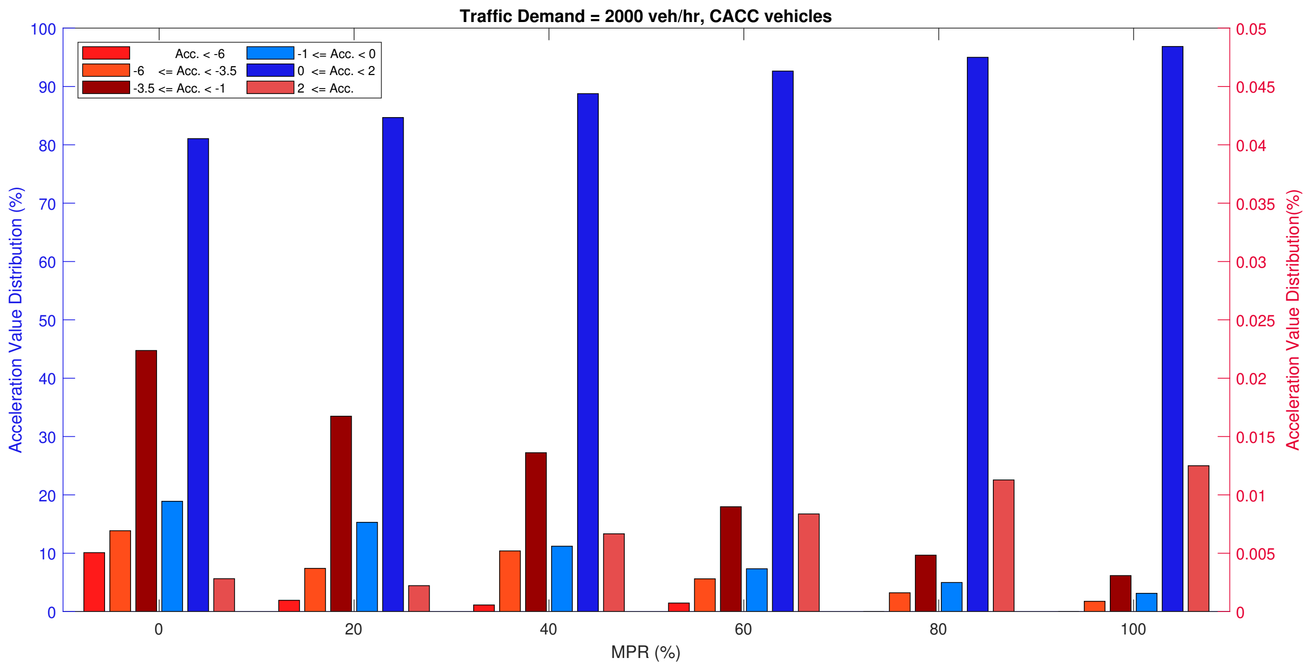


Figure 7.14: Acceleration distribution in the sparse traffic condition for different MPRs of CACC vehicles.

Fig.7.16 and Fig.7.17 shows the acceleration distribution with different MPR of ACC vehicles and ACC+AEB vehicles in the crowded traffic condition. Fig.7.18 and Fig.7.19 shows the acceleration distribution with different MPR of CACC vehicles and CACC+CAEB vehicles in the crowded traffic condition. One common thing can be observed from Fig.7.16 $\sim$ Fig.7.19 is that when the traffic demand is high, AEB system and CAEB system have no impact on the trend of acceleration distribution for acceleration larger than $-6\ m/s^2$.

Besides that, for ACC vehicles, AEB system increases the frequency of acceleration smaller than $-6\ m/s^2$ when MPR is larger than 20%. At MPR 60%, the frequency of acceleration smaller than $-6\ m/s^2$ is the smallest for ACC+AEB vehicles. ACC+AEB system also decreases the frequency of acceleration between $-6\ m/s^2$ and $-1\ m/s^2$ much more in comparison with ACC vehicles when MPR increases from 0% to 20%.

For CACC vehicles, CAEB system has almost no influence on the acceleration distribution when MPR is lower than 40%. When MPR at 60% and 100%, CAEB makes frequency of acceleration between $-3.5\ m/s^2$ and $-6\ m/s^2$ higher but when MPR at 80%, CAEB system makes it lower in comparison with CACC vehicles.

7.4 Summary

This chapter presents the microscopic traffic simulation and the results of evaluating the impact of AEB system on the traffic flow.

First the workflow of simulation, the key parameters used in the simulation model: velocity controllers - (C)ACC system and (C)AEB system - and traffic network are presented.

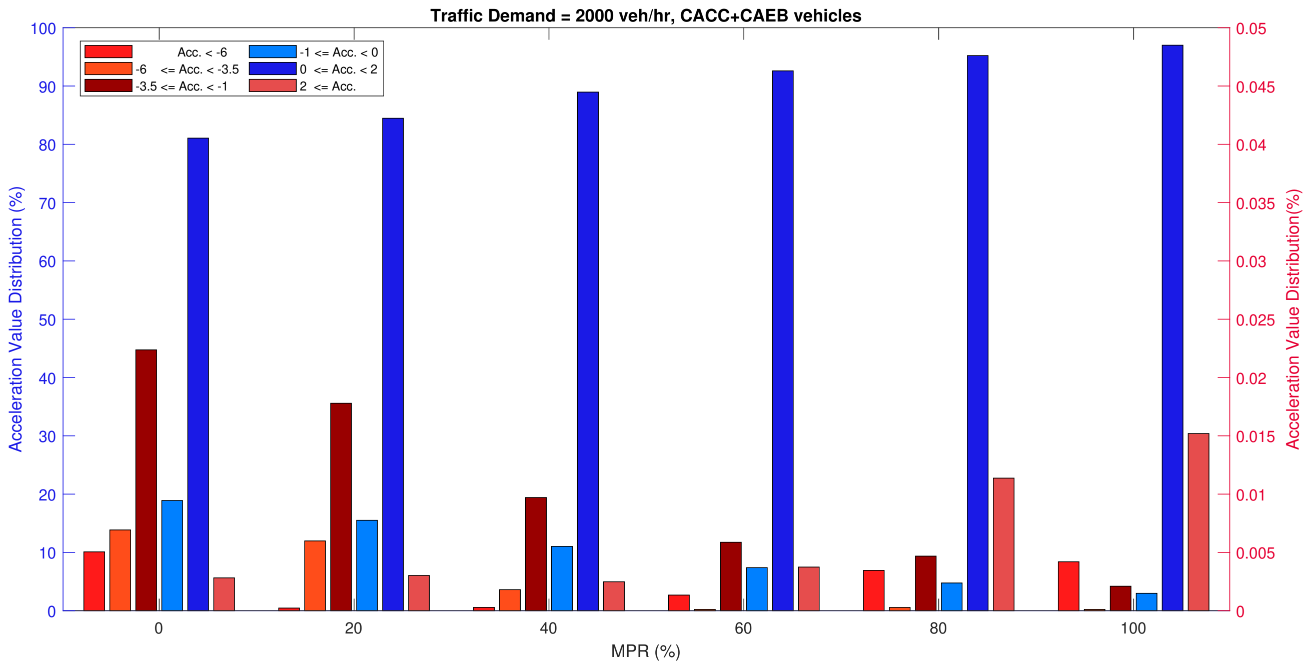


Figure 7.15: Acceleration distribution in the sparse traffic condition for different MPRs of CACC+CAEB vehicles.

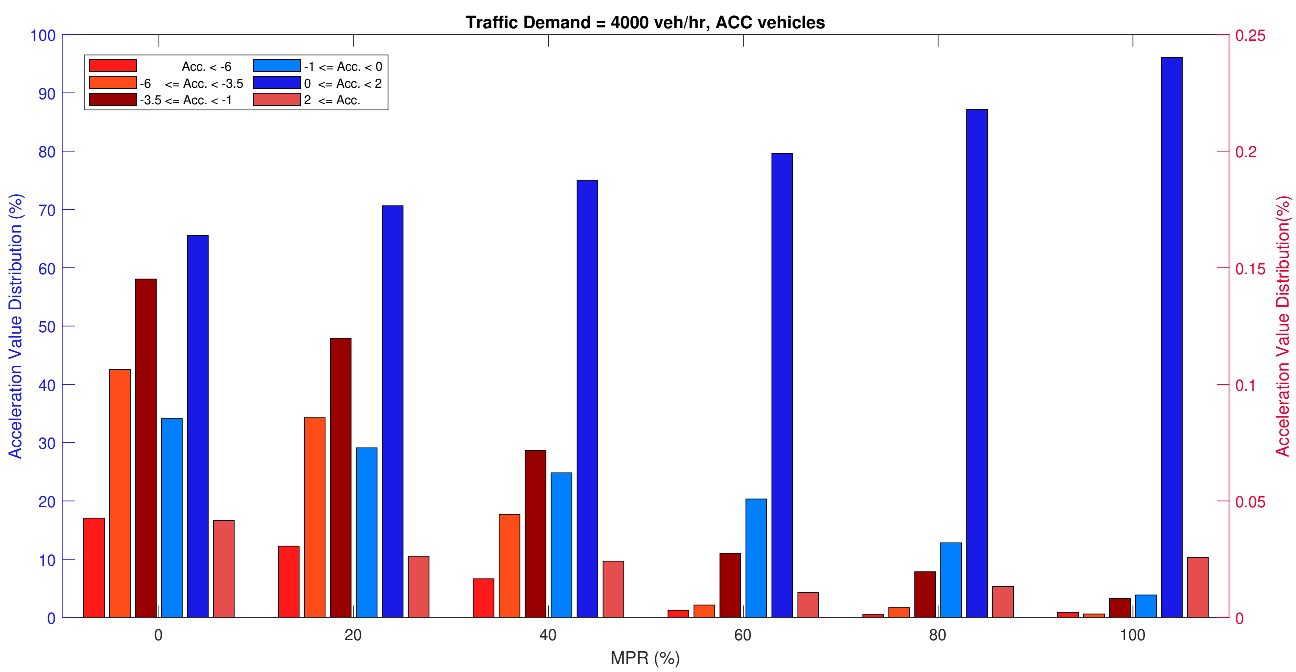


Figure 7.16: Acceleration distribution in the crowded traffic condition for different MPRs of ACC vehicles.

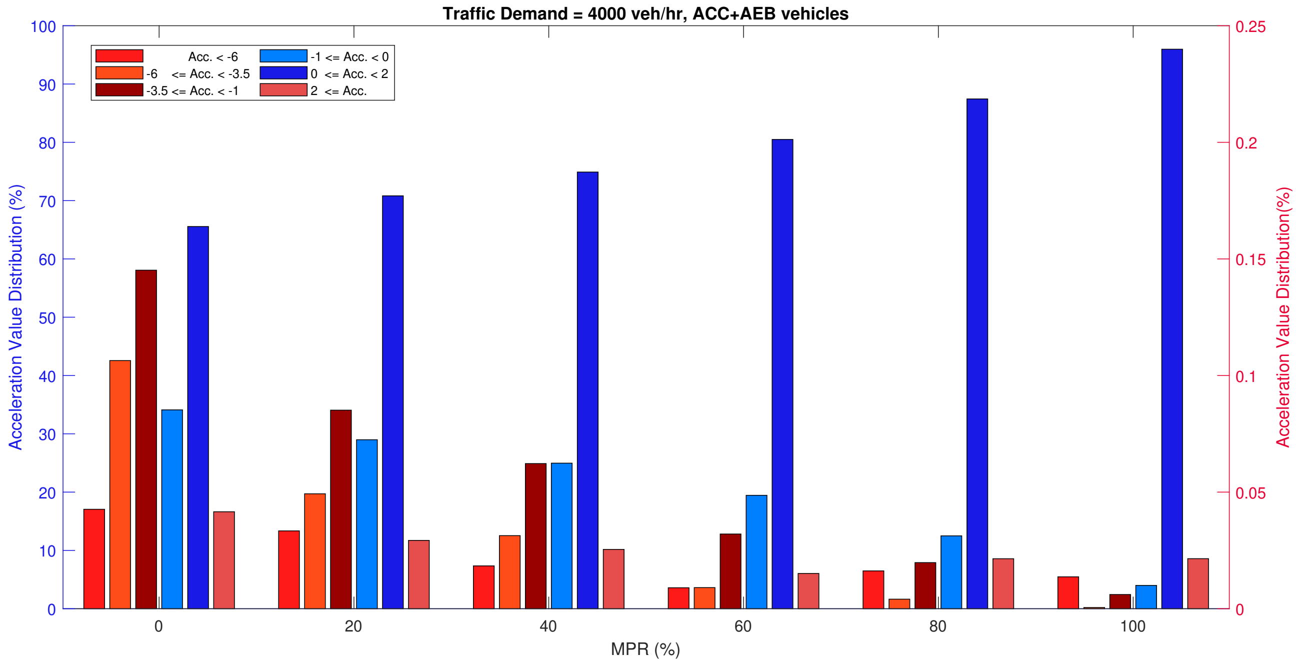


Figure 7.17: Acceleration distribution in the crowded traffic condition for different MPRs of ACC+AEB vehicles.

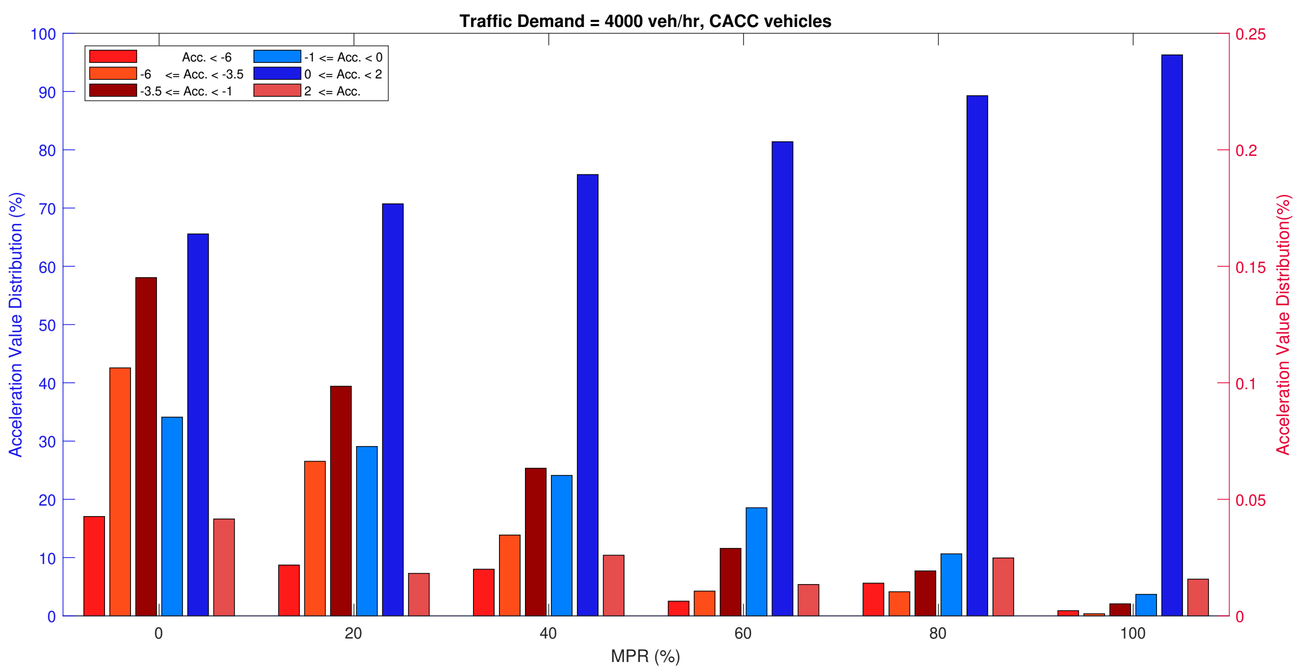


Figure 7.18: Acceleration distribution in the crowded traffic condition for different MPRs of CACC vehicles.

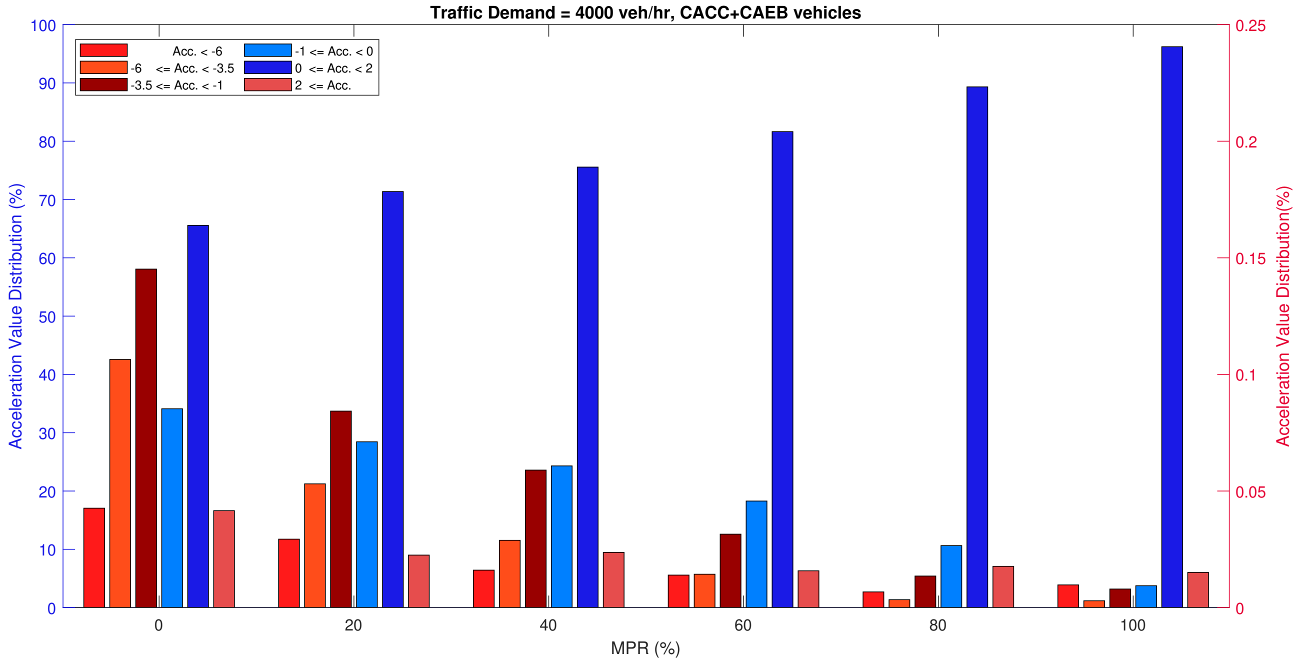


Figure 7.19: Acceleration distribution in the crowded traffic condition for different MPRs of CACC+CAEB vehicles.

The results are discussed from the three perspective: traffic safety, average speed and acceleration distribution. The detailed analysis of the microscopic simulation results are in Section 7.3 and here we conclude this chapter by some general conclusions on the traffic safety:

1. According to TIT, (C)AEB system has a positive impact on the traffic safety.
2. Min.TTC shows that (C)AEB system helps reduce the most dangerous conflicts.
3. The extent of improvements on safety depends on the vehicle type (ACC or CACC), MPR and traffic demand and can't be generalized.

As for the average speed and acceleration distribution, no general conclusions can be drawn for all MPRs.

Chapter 8

Conclusions and Future Work

This chapter will discuss the final conclusions and the future work of this graduation project.

8.1 Conclusions: Research Questions

We discuss the final conclusions of this graduation project by giving answers to the research questions.

What are the limitations of the ACC vehicles in the critical driving situations?

The collision avoidance capabilities of ACC vehicles are tested by simulation in the two typical highway emergency driving scenarios: first, following a decelerating target vehicle and second, approaching a low-speed target vehicle. In both driving scenarios, ACC system and CACC system can't provide a satisfactory collision avoidance capabilities. It is in line with our expectations because ACC system and CACC system are for driving comfort, not for the enhancement of safety.

Furthermore, the integration of a traditional (C)AEB system and (C)ACC system is under test in the same driving scenarios. The traditional (C)AEB system is implemented in the simulation based on the state-of-art (C)AEB system technology available in the commercial passenger cars and the relevant industry standard and international regulation, namely, ISO 22839 and UN Regulation No.152. The collision avoidance capabilities of the integrated systems are improved in comparison with the stand-alone (C)ACC system but still can't avoid the collision in the two typical highway emergency driving scenarios mentioned above without driver's reaction. Besides the lack of collision avoidance capability, the integrated system of the traditional (C)AEB system and (C)ACC system also needs structural change in order not to generate undesired vehicle behaviors, such as big jerk resulted from frequent transfer of vehicle control authority between (C)AEB system and (C)ACC system.

When such an integration is applied in a platoon, the string instability of a ACC-platoon could always introduce the collision to the platoon with unlimited length. Even for a 10-vehicle ACC platoon, the collision-free time gaps for platoon members are too large in comparison with the common time gaps for ACC vehicles. For a CACC platoon, the AEB system can help avoid collisions in the two typical highway emergency driving scenarios and the velocity fluctuation caused by the vehicle control authority switch from (C)AEB system to CACC system won't be amplified along the whole platoon.

How to design an AEB system for ACC vehicles which can avoid rear-end collisions without driver's take-over?

The main differences between the proposed AEB system which is dedicated for (C)ACC vehicles and the traditional AEB system which is mainly for HDVs are as follow.

1. The transitional state between "Brake" state and "Safe" state functions as a buffer when the vehicle control authority is transferred from AEB system and (C)ACC system and provides better indication for

environment threat level for (C)ACC vehicles.

2. More parameters are taken into consideration when assessing the environment threat. In the traditional AEB system, the threat assessment highly relies on the kinematics parameters of the ego vehicle and the target vehicle, such as velocity and acceleration, and the parameters derived from them, such as TTC. Not only these parameters are included in the threat assessment of the proposed AEB system, but also the signals from (C)ACC system, such as the required acceleration of the ego vehicle at the current time step calculated by the distance controller. The inclusion of the signals from (C)ACC system increases the accuracy of the threat assessment, i.e. allows the AEB system to more confidently indicate an imminent danger to the (C)ACC vehicle. The results of the threat assessment in the proposed AEB system are embodied as the transitions between different driving states - "Safe","Braking" or "Transition to safe".

It is worth noting that the threshold values used in the proposed AEB system are derived by trial-and-error and specific for the (C)ACC system used in this graduation project. Therefore they don't generally applicable for other (C)ACC systems.

The proposed (C)ACC+(C)AEB system has improved driving safety for AV in both single vehicle test scenarios and platoon test scenarios. It helps avoid rear-end collisions in the two typical highway emergency driving scenarios with common time gap setting. In the proposed (C)ACC+(C)AEB system, the interaction between (C)AEB system and (C)ACC system is coordinated so that no undesirable velocity fluctuation is observed.

What impacts the integrated ACC+AEB system has on the traffic flow?

As expected, (C)AEB system has a positive impacts on the traffic safety according to TIT traffic safety indicator. In the simulated traffic network with specified traffic demands, the (C)AEB system help lower the safety indicator TIT for every MPR tested which means (C)AEB system help improve the average safety level for all the vehicles passing the simulated traffic network in the predefined amount of time (1 hour). The Min.TTC safety indicator is for indicating the criticality of the most dangerous moments occurring in the simulated traffic network in the predefined amount of time (1 hour). The smaller the Min.TTC, the more dangerous the situation. Simulation results show that (C)AEB system can increase the Min.TTC at some MPRs for (C)ACC vehicles while don't have much impacts at the other MPRs.

In general, there is no negative impact of (C)AEB system on the traffic safety has been identified according to TIT and Min.TTC but the extent of improvements on the traffic safety depends on the vehicle type (ACC or CACC), MPR and traffic demand.

For average speed, when the traffic demand is low the influence of (C)AEB system varies with the vehicle type (ACC or CACC) and MPR; when the traffic demand is high, the influence of (C)AEB system converges towards the locations near the on-ramp and don't affect the average speed of locations far way from the on-ramp, with MPR 40% of ACC vehicles as the only exception.

For acceleration distribution, (C)AEB system has no influence to the acceleration value larger than $-1\ m/s^2$ and has no consistent influence to the acceleration value smaller than $-1\ m/s^2$. The influence of (C)AEB system to the distribution of the acceleration value smaller than $-1\ m/s^2$ depends on the the vehicle type (ACC or CACC), MPR and traffic demand.

8.2 Future Work

This graduation project makes contribution to the understanding of how (C)ACC vehicles behave in the safety critical situations and the limitations of the traditional AEB system when integrated with (C)ACC system. A state-chart based (C)AEB system is designed to be integrated into the existing (C)ACC system architecture and is proved to have better collision avoidance capabilities than the integration of (C)ACC system with traditional AEB system. Furthermore, this graduation project provides insights on the impacts of the (C)AEB system has on the traffic flow. The benefits of integrating (C)AEB system into (C)ACC system on the traffic safety are revealed.

To further explore the benefits of integrating (C)AEB system into (C)ACC system, a congested traffic flow can be created in the microscopic traffic simulation to evaluate the impact of (C)AEB. In this graduation project, two typical highway emergency driving scenarios have been chosen to test the (C)AEB system on the vehicle level - following a decelerating target vehicle and approaching a low-speed target vehicle. However, on the traffic level, in the current simulation model the majority of emergency situations happening to the AVs are the first one. Because the traffic flow has not reached a congested point so it's rare for an AV to encounter a low-speed target driving ahead to trigger an emergency brake.

Additionally, the realistic human reaction to the warnings issued by (C)AEB system should be taken into account. This means firstly, the appropriate warning mechanism should be developed for the (C)AEB system and secondly, the interaction between human and (C)AEB+(C)ACC system should be implemented in the VISSIM simulation model. In this graduation project, we assume that there is no reaction from human drivers when (C)AEB+(C)ACC is active. This assumption is made for the simplicity of the project implementation. It is acceptable because in this way we can still get the indication of the impacts of (C)AEB system has on the traffic flow. But for more realistic traffic simulation, the human driver's reaction should not be ignored.

8.3 Summary

This chapter discusses the final conclusions for the three main research questions. The collision avoidance capabilities of (C)ACC system and traditional AEB system are described. The proposed AEB system and its integration with (C)ACC system are summarized. The impact of the proposed ACC+AEB system on the traffic flow is also concluded. Finally, the future work is suggested.

Appendix A

Derivative of ETTC

The formula for ETTC is derived assuming the relative acceleration between the subject vehicle and the target vehicle remains constant. Using rectilinear kinematics of a particle, position can be expressed as a function of time.

$$\int_{x_0}^{x} dx = \int_{0}^{t} (v_0 + a_c t)\, dt$$

Assuming constant acceleration

$$x = x_0 + v_0 t + \frac{1}{2} a_c t^2$$

Solving using the quadratic equation

$$0 = x_c + (v_{tv} - v_{sv})t + \frac{1}{2}(a_{tv} - a_{sv})t^2$$

$$ETTC = \frac{-(v_{tv} - v_{sv}) - \sqrt{(v_{tv} - v_{sv})^2 - 2 * (a_{tv} - a_{sv}) * x_c}}{a_{tv} - a_{sv}}$$

Appendix B

SYSMOD approach

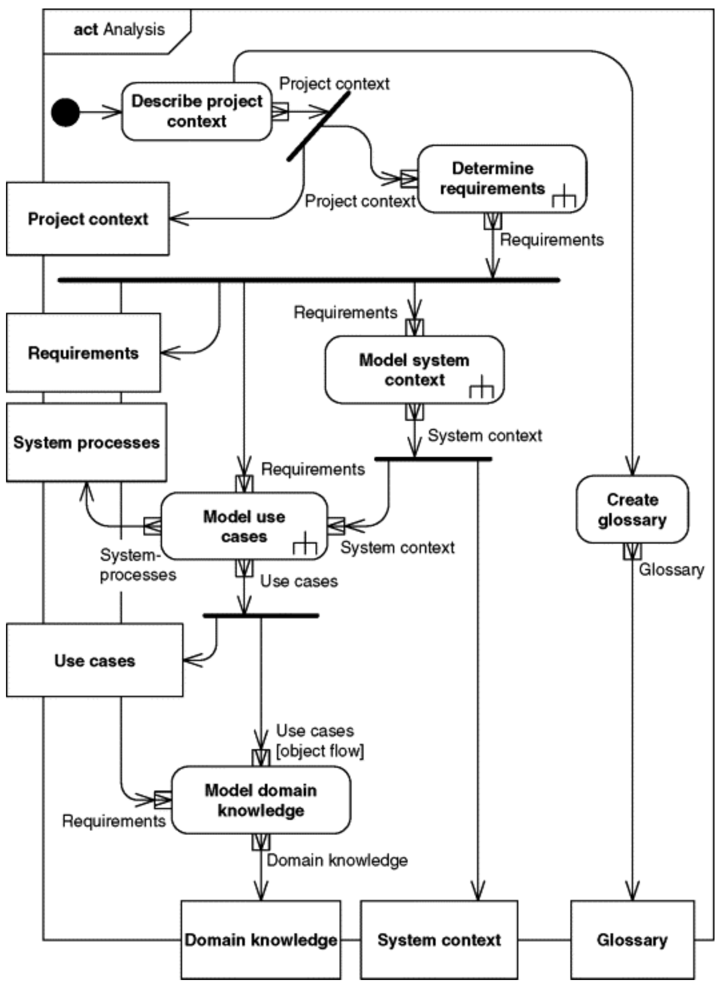


Figure B.1: The SYSMOD approach model for analyses [46].

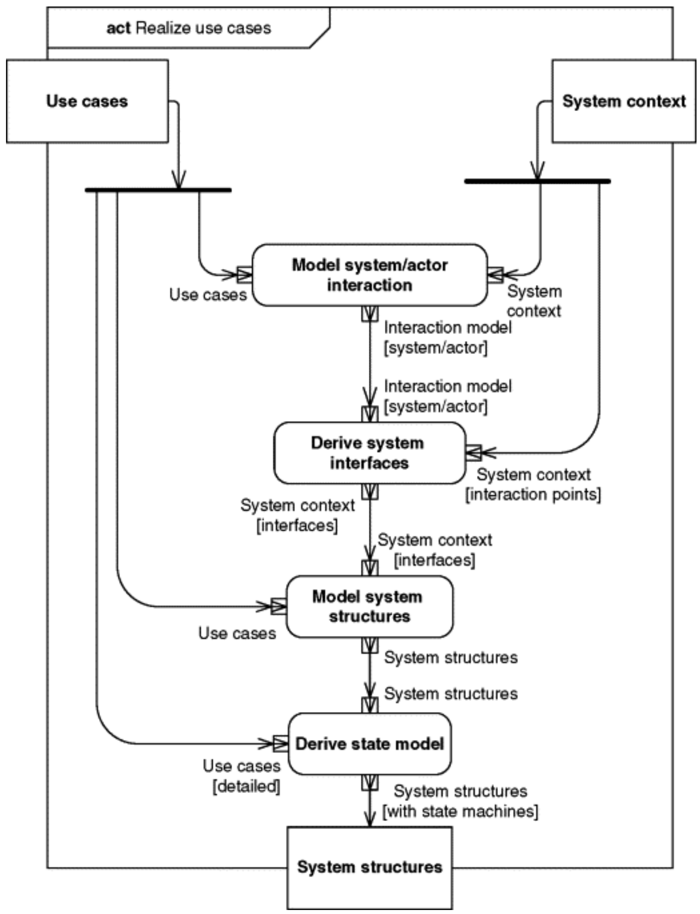


Figure B.2: The SYSMOD approach model for designs [46].

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