Heavy-Duty Vehicle Platooning
– Modeling and Analysis

QICHEN DENG

Licentiate Thesis
Stockholm, Sweden 2016
Abstract

Coupled with the growth of world economy, the demand of freight transport has escalated and will continue to do so. As the traffic intensity increases, the pressure on infrastructure, energy usage and environment becomes higher than ever. Meanwhile, the number of traffic accidents is also increasing year by year as a result. Heavy-duty vehicle (HDV) platooning makes a group of HDVs driving closely after each other. It is one potential solution to improve transport efficiency, traffic safety and fuel economy. Even though there have been extensive studies on platooning system and corresponding fuel saving, some of the research areas, such as coordination strategies of platooning, platoon operations and the impacts of HDV platooning on traffic flow are still left open. Under a futuristic scenario where a large number of HDVs will be operating in one or several platoons on highway, how to group HDVs into a platoon and how to select spacing policies for HDV platooning are essential for automobile manufacturers, fleet operators and transport planners. Therefore, the formation strategies and operations of HDV platoons, as well as the impacts of HDV platooning on traffic flow have to be carefully investigated.

This thesis presents contributions to the modeling of HDV platooning and simulation of HDV platoon operations. The focus lies mainly on analytical formulation of speed-density relation of mixed traffic flow and development of simulation framework for study of HDV platooning. On the one hand, a three-regime speed-density relation is proposed to describe the mixed traffic flow consisting of HDVs and passenger cars. The proposed speed-density relation incorporates percentage of HDVs, traffic density and spacing policy of HDV platoons as input variables and delivers aggregate highway velocity as output. By comparing the traffic throughput of no HDV platooning scenario, grouping HDVs into platoon using constant vehicle spacing policy or constant time gap policy results in significant improvement on highway capacity. On the other hand, a simulation framework is developed for implementation of different HDV platoon operations. The platoon formation of two HDVs and disaggregation of a five-HDV platoon at off-ramp are simulated on a two-lane highway. The simulation outcomes show that HDV platoon formation is more favorable in light and medium traffic; disaggregation of a long HDV platoon at off-ramp improves the average speed of passenger vehicles considerably at high traffic flow rate.
To my father, my mother and my friends.
Acknowledgements

There are many who have contributed to the work presented in this thesis. First of all, I would like to give my sincere gratitude to my supervisors Gunnar Flötteröd and Wilco Burghout at KTH for guidance and feedback during the final stage of this project, and also for invaluable insights and recommendations on papers. Then I would like to thank Erik Jenelius for your support during my study in KTH. Bibbi Albania Nissan deserves many thanks for her great enthusiasm and help. I would also give my gratitude to Kuo-Yun Liang at Scania for your help, successful collaboration and for our fruitful discussions that I enjoyed immensely.

My deepest gratitude goes to my colleagues, Mahmood Rahmani, Athina Tympakianaki, Jiali Fu, Ary Pezo Silvano, Anders Lindfeldt, Chengxi Liu, Godfrey Mwesige, Hans Sipilä, Behzad Kordnejad, Jayanth Raghothama, Jennifer Warg, Junchen Jin, Wei Zhang, Beichuan Hong, Zifei Yan, Qiuchen Wang, Tong Shen and Ding Luo. Thank you all for your support and for the strength you have given me during the toughest period in my study.

Many gratitude to all my classmates in National ITS School, Azreena Kamalud-din, Gerasimos Loutos, Stefan P G Jacobsson and Nikita Lyamin for the inspiration and help during the course ITS Basic and Evaluation Basic.

Special thanks to Peter Yeung, Tina Yeung, Hong-Yin Tang, Liwen Wu, Jingtian Chen, Yan Zhou, Martin Tran, Ting Meng, Hao Wu, Wei-Ting Chen and Vivian Liang for your enthusiasm, inspiration and support in my life.

Last but not least, I would like to thank my parents for your patience, love, support, and believing my potential. Without you, I would never have reached this point of success in my life.

Qichen Deng
List of Papers

Papers:


II Deng, Q. and Burghout, W., 2015. The Impacts of Heavy-Duty Vehicle Platoon Spacing Policy on Traffic Flow. Accepted for presentation in the Transportation Research Board 95th Annual Meeting and submitted for publication to Transportation Research Record.

Contribution

The work presented in this thesis initiates simulation modeling and implementation of heavy-duty vehicle (HDV) platooning. It starts with development of simulation framework, the concept and operations of HDV platoon are first defined and later implemented in microscopic traffic simulation environment. The simulation framework is designed to implement different HDV platoon operations in various traffic scenarios, such as HDV platoon acceleration, deceleration, formation and disaggregation. Meanwhile, the impact analysis of HDV platooning is further extended from microscopic traffic simulation to macroscopic mixed traffic flow modeling. The effects of HDV platooning to traffic throughput are investigated through the corresponding macroscopic speed-density relation. There are six papers produced during the licentiate study (Paper 1-3 are not included in this thesis):

In this paper, the Pontryagin Minimum Principle is implemented numerically on speed planning for heavy-duty vehicle (HDV) platoons. The results from Pontryagin Minimum Principle and Dynamic Programming are compared.

In this paper, a simulation platform is developed based on microscopic traffic simulation software VISSIM. This simulation platform can be used for implementation of HDV platoon operations and analysis of corresponding impacts on traffic flow.

This paper presents a project work in collaboration with Scania and KTH Automatic Control Department. Simulation experiments are carried out using the simulation
platform developed in Paper 2 to study the platoon formation of two HDVs.


In this paper (refer to Paper I in this thesis), the previous developed simulation platform is further extended to a general simulation framework. More simulation experiments are carried to investigate the effects of HDV platooning to traffic flow.


This paper (refer to Paper II in this thesis) presents the modeling of mixed traffic flow consisting of passenger cars and HDV platoons. The speed-density relation of mixed traffic flow is formulated as a function of traffic density, percentage of HDVs and spacing policy of HDV platoons.


In this paper (refer to Paper III in this thesis), a constant spacing policy is applied on HDV platoon disaggregation at highway off-ramp. The impacts of HDV platoon disaggregation on traffic flow are investigated comparing the no HDV platoon disaggregation scenario.

Paper 4-6 (refer to Paper I-III in this thesis) are prepared and drafted by the first author alone. The contribution of supervisor is limited to minor corrections and recommendations.
Contents

Acknowledgements vii
List of Papers ix
Contribution xi
Contents xiii

1 Introduction 1
  1.1 Motivation and Research Objective 2
  1.2 Thesis Outline 3

2 Background 5
  2.1 Development of Heavy-Duty Vehicle Platooning 5
  2.2 Other Related Work 6
  2.3 Summary 8

3 Modeling 9
  3.1 Heavy-Duty Vehicle Platoon Model and Operations 9
  3.2 Platooning Systems 10
  3.3 Fuel Consumption Model 14
  3.4 Summary 15

4 Spacing Policy of HDV Platoon 17
  4.1 Modeling of Steady-State Mixed Traffic Flow 19
  4.2 Numerical Results 25
  4.3 Mixed Spacing Policy 27
  4.4 Summary 28

5 Simulation Framework and Experiments 29
  5.1 Development of Simulation Framework 29
  5.2 Work Flow of Simulation 30
  5.3 A Constant Spacing Policy for Platoon Disaggregation 30
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4</td>
<td>Parameters of CACC System for HDV Platoon</td>
<td>32</td>
</tr>
<tr>
<td>5.5</td>
<td>Simulation Experiments</td>
<td>32</td>
</tr>
<tr>
<td>5.6</td>
<td>Summary</td>
<td>39</td>
</tr>
<tr>
<td>6</td>
<td>Summary and Future Work</td>
<td>41</td>
</tr>
<tr>
<td>Abbreviations</td>
<td></td>
<td>43</td>
</tr>
<tr>
<td>Bibliography</td>
<td></td>
<td>45</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Road freight transport, delivering goods from one location to where they are wanted and useful mainly by heavy-duty vehicles (HDVs), is essential for the world economy. However, together with other traffic on road, freight transport by HDVs holds negative effects such as congestions, traffic accidents, emission pollutions, etc. During the past decades, there was a steady increase in the demand of road freight transport, and the pressure on infrastructure, energy usage and environment became higher than ever. This happened despite continuous efforts from authorities to improve the traffic infrastructure.

While the environmental footprints of transport in European Union correspond to 24% of total greenhouse gases and 28% of CO$_2$ produced by humans from various sources (European Commission, 2009), one of the goals set by European Commission is to cut 60% emissions produced in transport sector by 2050 in order to avert climate change and maintain a sustainable environment (European Commission, 2011). The freight transport by HDVs has been considered as one of the main policy areas for improvement of overall energy efficiency. Therefore, efficiency and sustainability enhancement of freight transport attract extensive attention from public authorities, transport planners, researchers and automotive manufacturers.

Thanks to the rapid evolution of information and communication technology (ICT) and its versatile applications for intelligent transportation system (ITS), it provides an excellent alternative to address these problems by introducing the so called 'cooperative system'. This innovative system utilizes vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication in order to improve the performance of traffic system. Many ongoing research projects have been dedicated to the state-of-the-art development and implementation of cooperative system, due to its positive impact on traffic safety (Farah et al., 2012). Other expected benefits from cooperative system include traffic efficiency improvement and mitigation of the environmental impacts.

Vehicle platooning, also known as convey driving, is a group of vehicles driving closely after each other. In particular, platooning heavy-duty vehicles (HDVs) on highway, as illustrated in Figure 1.1, is a method of reducing fuel consumption
and improving transport efficiency. On the one hand, HDVs traveling in single file with small inter-vehicle distances save space on highway so that the highway section can accommodate more vehicles; on the other hand, HDVs operating in small inter-vehicle distances experience significant air-drag reduction and therefore, reduce fuel consumption. It was shown in a previous study that platooning HDVs may save fuel up to 20% (Browand et al., 2004). According to statistics, freight transport by HDVs in Europe consumes approximately 180 million tons of diesel fuel every year (Energy Balance Sheets, 2013), even modest decrease in fuel usage can result in dramatic savings. Since the demand of freight transport by HDVs is growing steadily year by year, platooning HDVs has already been considered as an effective way of reducing the environmental impacts. Under a futuristic scenario where a large number of HDVs will be operating in one or several platoons on highway, how HDVs should form a platoon and to what extent the HDV platoons improve traffic flow should be carefully analyzed.

1.1 Motivation and Research Objective

While research into vehicle platooning has been ongoing for the past 50 years, the majority of work has been dedicated to the state-of-the-art development of robust platooning system, e.g., Naus et al. (2010b) and Ploeg et al. (2011b), and the impacts of platooning on traffic flow, VanderWerf et al. (2002), Arem et al. (2006) and Schakel and Arem (2010). However, those studies mainly focused on platooning of cars and
assumed that vehicles start as platoons and remain in platoons throughout the trip. The impacts of platooning spacing policy (the desired inter-vehicle distance between vehicles in steady state) on traffic flow still have been inadequately studied (Dharba and Rajagopal, 1999). Apart from fuel saving, there are many open research questions in HDV platooning. Little knowledge has been found regarding the HDV platoon formation or the impacts of HDV platoon operations on traffic flow.

In order to better understand the impacts of HDV platooning on existing traffic system, this thesis aims at modeling and simulation study of HDV platooning. Modeling of HDV platoon includes three different aspects: first of all, the properties, basic operations and advanced operations of an HDV platoon; secondly, the impacts of spacing policy (desired inter-vehicle distances between HDVs) of HDV platoons on traffic flow; thirdly, the HDV platoon disaggregation. On the other hand, after the basic and advanced operations of HDV platoon have been defined, a simulation framework is initialized to implement the platoon operation at certain road facilities, or evaluate the impacts of HDV platooning on traffic flow.

1.2 Thesis Outline

The outline of this thesis is as follows:

Chapter 2: Background

This chapter briefly describes the related work about HDV platooning, such as implementations, studies of fuel saving and coordination for HDV platoon formation.

Chapter 3: Modeling

In this chapter, the modeling of HDV platoon is presented in detail. This includes defining properties and operations of HDV platoon, modeling of ACC/CACC system considering the acceleration capability and modeling of fuel consumption for passenger car and HDV. This chapter is based on the Paper I:


Chapter 4: Spacing Policy of HDV Platoon

This chapter investigates the impacts of different HDV platoon spacing policies on traffic flow. It is considered as complementary study to microscopic traffic simulation.
In this chapter, the speed-density relation of mixed traffic flow is analytically formulated. The spacing policies studied in this chapter includes constant vehicle spacing (CVS) policy, constant time gap policy (CTG) and mixed CVS-CTG policy. The main performance indicator is traffic throughput (highway capacity). This chapter is based on the Paper II:


Chapter 5: Simulation Framework and Experiments

This chapter presents the architecture of simulation framework for the study of HDV platooning. Three simulation experiments are carried out to study the effects of HDV platooning: the first experiment is to investigate the impacts of HDV platooning on traffic flow; the second experiment is to study the influence of traffic on HDV platoon formation; the third experiment is to apply a modified constant spacing policy on HDV platoon disaggregation at highway off-ramp. This chapter is based on the Paper I and Paper III:


Chapter 6: Summary and Future Work

This chapter summarizes the thesis with some concluding remarks and gives an outlook to future work.
Chapter 2

Background

2.1 Development of Heavy-Duty Vehicle Platooning

As mentioned in the previous section, vehicle platooning means a number of vehicles driving closely after each other and being controlled as one unit, i.e., all vehicles in a platoon mimic the lead vehicle. Vehicle platooning has been an attractive topic in ITS research since early 1970s, with some theoretical interest about severe traffic near around major urban centers. In the late 1970s, the concept of fully automated vehicles traveling in platoon using electronic coupling emerged (Caudill and Garrard (1977) and Shladover (1978)). In 1986, the California Partners for Advanced transportation TecHnology (PATH) was established. The objective of PATH program was to develop solutions to the problems of California transportation system and vehicle platooning had become part of the program (Shladover et al., 1991). The project included basic vehicle modeling (Cho and Hedrick, 1989), engine modeling (Moskwa and Hedrick, 1990) and design of longitudinal vehicle controller (Hedrick et al., 1991). PATH was also one of the first to demonstrate vehicle platooning with small inter-vehicle distances. The emphasis of vehicle platooning was specifically for cars in the beginning, and grouping cars into a platoon was considered as an effective way of increasing road capacity. The focus later shifted to HDV platooning and reduction of aerodynamic resistance (PATH, 2010).

The project iQFleet started from 2011 (Sandberg, 2011). The goal of this project was to develop methodologies, technology and test sites for intelligent real-time fleet control and management systems. iQFleet included four major tasks. In the first task, an optimal control specifically for HDV platoon was designed in order to operate HDVs more energy efficiently. The second task was about traffic data fusion, historical and real-time floating car data were combined to predict the traffic. Based on the prediction, HDV platoons will be given a speed guidance so that the platoon can drive in fuel efficient way (Deng and Ma, 2014a). In the third task, a simulation platform was developed based on the microscopic traffic simulator VISSIM (Deng and Ma, 2014b). The impacts of HDV platooning on traffic flow will be studied using this platform. In the fourth task, the optimal vehicle control, traffic data fusion and
simulation platform were integrated into a real-time fleet control and management system.

In 2013, the project COoperative dynamic forMation of PlaToons for sAfetY and energy-optImized goods transportatioN (COMPANION) was initiated (COMPANION, 2013). This project is funded by the European Commission under the 7th Framework programme. The objective is to develop a dynamic coordination system by taking into account traffic information and weather condition. In COMPANION, the HDVs in the platoon do not necessarily have the same origin or destination. A platoon will be formed dynamically by merging vehicles or sub-platoons that share subparts of their routes. Moreover, the project will also examine how the human machine interface (HMI) should be presented to the drivers. The purpose is to suggest common regulations for EU that would permit shorter distances between HDVs in the platoon.

2.2 Other Related Work

This section is divided into two parts, one focuses on study of air-drag reduction, fuel saving, control system development and implementation of HDV platooning. In this part, it is assumed that the HDV platoon maintains its structure all the time, no other HDV will join the platoon or no HDV will leave the platoon. The other part reviews the platoon formation, where HDVs are not necessary in the platoon but there are incentive to coordinate those HDVs to form a platoon.

2.2.1 Implementation of HDV Platooning

While HDV platooning has become increasingly important for the automobile industry, the conclusive results with respect to the fuel reduction possibilities of platooning remain unclear, since fuel saving in HDV platoon is related to many factors, such as road topology, mass of HDV and time gap between HDVs in the platoon. This issue had been studied by KTH and Scania in 2010 (Alam et al., 2010). Experimental results showed that by using preview information of the road ahead from the lead vehicle, the adaptive cruise controller can reduce the fuel consumption. Whether a heavier HDV or lighter HDV should be the platoon leader depends on the desired time gap between HDVs in the platoon. If the HDV platoon leader is 10\% lighter than the followers, fuel saving 3.8\%–7.4\% can be achieved depending on the time gap. On the contrary if the lead vehicle is 10\% heavier than the followers, a corresponding 4.3\%–6.9\% fuel reduction can be achieved.

On the other hand, Alam et al. also worked on the design of suboptimal decentralized controller (Alam et al., 2011). A systematic design methodology was presented over the class of linear quadratic regulators (LQR) for chain graphs. The proposed controller was for the subsystems with interconnected dynamic in the HDV platoon and evaluated with physical constraints. The results showed that the decentralized controller gives good tracking performance. Moreover, the proposed controller was possible to maintain string stability in the platoon even for an arbitrary number of
2.2. Other Related Work

vehicles. The proposed control design methodology can most likely be implemented in real life applications.

Meanwhile, an automated truck platoon was developed and demonstrated with respect to energy saving (Tsugawa et al., 2011). A platoon of three fully-automated trucks with 10 m inter-vehicle distance was tested on an expressway. The test consisted of not only steady-state driving but also lane changing of the whole platoon. The longitudinal control was implemented using radar, lidar and wireless communication. The lateral control was implemented based on the lane marker detection by the computer vision. The test outcomes showed that fuel saving about 14% can be achieved. Moreover, simulation showed that under 40% heavy truck platooning percentage, CO$_2$ can be reduced by 2.1% when the inter-vehicle distance is 10 m and 4.8% when the inter-vehicle distance is 4 m.

A recent study presented more details about the impact of HDV platooning specifically on fuel reduction over a range of speeds, following distances, and mass (Lammert et al., 2014). The steady-state speeds ranged from 55 mph to 70 mph, the following distances ranged from 20 ft to 75 ft, and the gross vehicle weights were about 65 klbs to 80 klbs. This study showed that 2.7% to 5.3% fuel savings can be achieved if the gross vehicle weight of platoon leader is 65 klbs, and 2.8% to 9.7% for the trailing HDV. A best combination for fuel saving was also given, 55 mph vehicle speed, 30 ft inter-vehicle distance, and 65 klbs gross vehicle weights yielded 3.7% to 6.4% fuel saving for a two-HDV platoon.

In fact, smaller inter-vehicle distances between HDVs yield more significant fuel savings. This however requires a robust controller to guarantee stability. Otherwise the followers need to accelerate and brake in order to maintain a safe distance to the vehicle ahead, which incurs additional fuel costs. This can be seen in the KONVOI project, which showed fuel saving on the test sites but no fuel savings achieved during the test on public highway (Shladover, 2012). Moreover, a small gap also requires a more aggressive controller to ensure driving safety and avoid collision. This topic had been studied by several researchers, e.g., Alveraez and Horowitz (1997), Seiler et al. (1998), Horowitz and Varaiya (2000) and Alam et al. (2014).

2.2.2 Coordination for HDV Platoon Formation

It can be seen that most of the conducted work in HDV platooning assumes that the HDV platoon maintains its structure, the HDVs will start as a platoon and remain in the platoon throughout the trip. However, in real life, HDVs are usually assigned with different transport missions, have different origins or destinations, meaning that HDVs will be scattered on the highway. How HDVs should form a platoon is also an open research question, little knowledge has been found regarding platoon formation.

The idea of fuel-efficient HDV platoon formation was proposed by KTH and Scania (Liang et al., 2013). The aim of the study was to investigate when it is beneficial for a HDV to accelerate and catch up another HDV or platoon to form a longer platoon. A formula was derived based on flat road and no vehicle accelerations.
This formula can be used to calculate whether or not two HDVs should form a platoon, whether HDVs operating in a platoon can reduce fuel usage compared with driving individually. The fuel savings vary depending on the distance between the target vehicle and the distance to the destination. It was observed that for a trip of 350 km and a distance of 10 km to the vehicle ahead, the fuel saving could be up to 7% if the follower vehicle decides to increase the speed from 80 km/h to 90 km/h in order to catch up and form a platoon.

However, the above study addressed a single HDV increasing its speed to catch another HDV or platoon ahead. In this case, it only benefits the trailing HDV to speed up if the travel distance is sufficiently long. Larson et al. (2015) extended the HDV platoon formation to highway network level. A distributed network of controllers was proposed to maximize the amount of fuel saved by possible HDV platoon formation. The proposed controllers are placed at major intersections in a road network. They help coordinate the velocity of approaching vehicles so that HDVs arrive at the junction simultaneously and then merge into a platoon. This control is initiated only if the cost of forming the platoon is smaller than the savings incurred from platooning. In a large scale simulation of the German Autobahn network, it was observed that fuel savings surpassing 5% when only a few thousand vehicles participate in the system. If more HDVs participate the system, fuel saving can be increased considerably.

2.3 Summary

In this chapter, the relevant literature about HDV platooning is reviewed, including the development of HDV platooning and HDV platoon formation. The work of this thesis extends HDV platooning on detailed modeling in microscopic simulation and formulation of macroscopic speed-density relation, in particular, HDV platoon formation and disaggregation considering traffic condition, and the impacts of HDV platoon spacing policy on traffic flow.
Chapter 3

Modeling

This chapter is based on Paper I (Deng, 2015a). Heavy-duty vehicle (HDV) platooning means a group of HDVs driving closely after each other and being controlled as one unit, i.e., all vehicles in the platoon mimic the lead vehicle. In HDV platoons, the following vehicles are operating with assistance of (cooperative) adaptive cruise control (ACC/CACC) system. The concept of HDV platooning has gained worldwide recognition especially in automobile industry. It is developed specifically for fuel saving due to reduction of aerodynamic resistance. This chapter presents the modeling of HDV platoon (Section 3.1), cooperative adaptive cruise control (Section 3.2) and instantaneous fuel consumption (Section 3.3).

3.1 Heavy-Duty Vehicle Platoon Model and Operations

The HDV platoon is modeled as Platoon class/structure, which represents a group of HDVs with platooning capability. It defines and implements driving behaviors (operations) of a platoon, including acceleration, deceleration, desired inter-vehicle distance adjustment and other advanced operations. Figure 3.1 illustrates the concept of HDV platoon model.

Each platoon should have one platoon leader and one or several followers. Like other vehicles in traffic, the platoon leader is operated completely by a human driver and interacts with other vehicles. When an HDV joins a platoon and becomes a follower, an autonomous driving system will take over the longitudinal driving task and change the HDV from manually driving to (semi-)autonomous driving.

A Platoon object is created whenever a platoon of HDVs is formed. It manipulates HDVs and carries out operations as one unit. The HDV platoon has three main properties: platoon ID, platoon speed and a list of HDV platoon members. The HDV platoon ID and platoon speed is the ID and vehicle speed of lead HDV (platoon leader). The list of HDV platoon members includes information and vehicle states of each HDV operating in the platoon. In addition to basic platoon acceleration and deceleration, inter-vehicle distance adjustment is defined for different traffic scenarios and road facilities. For example, large inter-vehicle distances would be
required when a platoon approaches ramp areas to enhance safety for other vehicles. After passing the ramp area, the inter-vehicle distances in platoon can be reduced to enhance air-drag reduction and fuel saving. Advanced operations are speed planning, platoon aggregation and disaggregation etc. All platoon operations are initiated and controlled by the platoon leader.

3.2 Platooning Systems

3.2.1 ACC System

When an HDV is operating in platoon mode, an autonomous driving system takes over the longitudinal driving task. Adaptive cruise control (ACC) system is a type of radar-based autonomous driving system, it automatically adjusts vehicle speed and maintains a safe distance to the vehicle ahead. One commonly used ACC provides acceleration demand based on the linear combinations of relative speed and deviation of current distance from desired vehicle gap (VanderWerf et al., 2001):

\[ a_{acc} = k_v(v_1 - v_2) + k_r(r - r_{des}) \]  

(3.1)
where $v_1$ and $v_2$ are the speeds of front vehicle and following vehicle respectively; $r$ is the inter-vehicle distance and $r_{\text{des}}$ is the desired inter-vehicle distance; $k_v$ and $k_r$ are control parameters that have to be empirically configured. In fact, ACC is primarily designed for driving comfort (Vahidi and Eskandarian, 2003), relatively large inter-vehicle distance is required with minimum time headway of one second (International Organization for Standardization, 2003). Previous research showed that ACC could reduce the variance of acceleration by 44% - 52% (Marsden et al., 2001). However, if the target headway is too large, introducing ACC systems in mixed traffic leads to capacity decrease (Zwaneveld and Aren, 1997). Meanwhile, low penetration ($\leq 10\%$) of ACC vehicles is insufficient to prevent jams (Davis, 2004).

On the other hand, decreasing inter-vehicle distances in an HDV platoon yields dramatic fuel saving due to reduction of aerodynamic resistance (See Figure 3.2). But Naus et al. (2010a) argued that application of ACC system with small desired headways could amplify the disturbances to traffic upstream. This is often induced by speed variance between a platoon leader and the followers when the followers need to accelerate or brake frequently in order to maintain a safe distance. While disturbance attenuation across a string of vehicles could not be addressed by ACC system, V2V communication facilitates HDV platoon maintaining a stable vehicle string. The resulting functionality is cooperative adaptive cruise control (CACC).

**Figure 3.2:** percentage of air-drag reduction in a three-HDV platoon from various inter-vehicle distance: short inter-vehicle distance results in great air-drag reduction (Wolf-Heinrich and Ahmed, 1998).
Relative speed and vehicle gap can be measured by on-board radar and sensors (ACC/CACC System).

Vehicle acceleration of preceding HDV can be obtained through wireless vehicle-to-vehicle communication (CACC System).

**Figure 3.3:** An example of 2-HDV platoon: relative speed and inter-vehicle distance can be measured by the on-board radar and sensors, vehicle acceleration of preceding HDV can be obtained via V2V communication.

### 3.2.2 CACC System

Cooperative adaptive cruise control (CACC) is an extension and further improvement of ACC by taking advantages of information exchange via V2V communication. In addition to relative speed and vehicle spacing, CACC system could obtain acceleration of preceding vehicle (see Figure 3.3) to achieve small desired time headway while maintaining a stable vehicle string. Ploeg et al. (2011a) proposed and evaluated a CACC on a fleet of six vehicles. The results showed that with support of V2V communication, the desired time headway can be reduced to 0.5 second while preserving string stability. One commonly used CACC was proposed by VanderWerf et al. (2001), the algorithm extends previous ACC algorithm with the acceleration of preceding vehicle:

\[
a_{\text{cacc}} = a_1 + k_v(v_1 - v_2) + k_r(r - r_{\text{des}})
\]  

(3.2)

where \(a_1\) is the acceleration of preceding vehicle. The design of (3.2) is based on (3.1), hence even if no communication is present (\(a_1\) is not known to the following vehicle), the functionality of ACC is still available, namely, \(v_1 - v_2\) and \(r - r_{\text{des}}\) can still be measured from on-board radar and sensors, in this case the CACC system will degrade to ACC system.
3.2. Platooning Systems

3.2.3 Acceleration Capability

It is worth mentioning that ACC/CACC generates acceleration demands without considering the properties of vehicle type. However, HDV is distinguished from passenger car of its acceleration and deceleration capabilities. For this reason, the following HDV enabled by ACC or CACC is expected to track its desired vehicle acceleration imperfectly. In practice, each HDV platoon follower is modeled with limited acceleration and deceleration capabilities:

\[
a_{\text{min}} \leq a_2 \leq a_{\text{max}}(v_2)
\]  

(3.3)

The maximum acceleration of HDV is the ratio of maximum net force acting upon HDV \((F_{\text{net}}^{\text{max}})\) to mass of HDV \((M)\). Figure 3.4 shows that maximum net force is the vector sum of maximum engine force \((F_{\text{engine}}^{\text{max}})\), air resistance \((F_{\text{air-drag}})\), rolling friction \((F_{\text{rolling}})\) and the force due to gravity \((F_{\text{gravity}})\):

\[
a_{\text{max}}(v_2) = \frac{F_{\text{net}}^{\text{max}}(v_2)}{M} = \frac{F_{\text{engine}}^{\text{max}} - F_{\text{air-drag}}(v_2) - F_{\text{rolling}} - F_{\text{gravity}}}{M}
\]  

(3.4)

\[
F_{\text{air-drag}}(v_2) = \frac{1}{2} \rho_a A_c D (1 - \varphi) v_2^2
\]  

(3.5)

\[
F_{\text{rolling}} = \mu M g \cos \theta
\]  

(3.6)

\[
F_{\text{gravity}} = M g \sin \theta
\]  

(3.7)

Detail of parameters are summarized in Table 3.1. The maximum engine force exactly maintains HDV driving at constant maximum speed on level road:

\[
F_{\text{engine}}^{\text{max}} = F_{\text{air-drag}}^{\text{max}} + F_{\text{rolling}}\big|_{\theta=0} = \frac{1}{2} \rho_a A_c D v_{\text{max}}^2 + \mu M g
\]  

(3.8)
Table 3.1: Parameters for HDV and fuel consumption models (Sahlholm, 2011).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>Vehicle Mass of HDV</td>
<td>40000 kg</td>
</tr>
<tr>
<td>$c_D$</td>
<td>Air-Drag Coefficient</td>
<td>0.6</td>
</tr>
<tr>
<td>$A_a$</td>
<td>Vehicle Front Area of HDV</td>
<td>10.26 $m^2$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Rolling Resistant Coefficient for HDV</td>
<td>$7 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\rho_a$</td>
<td>Air Density</td>
<td>1.29 $kg/m^3$</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Road Grade</td>
<td>0</td>
</tr>
<tr>
<td>$g$</td>
<td>Standard Gravity</td>
<td>9.8</td>
</tr>
<tr>
<td>$H$</td>
<td>Energy Density</td>
<td>36 $MJ/L$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Energy Efficiency</td>
<td>0.4</td>
</tr>
</tbody>
</table>

$v_{\text{max}}$ is the maximum possible vehicle speed (about 160km/h-180km/h, or equivalently 44.4m/s-50m/s). The maximum acceleration $a_2$ can be simplified to:

$$a_{\text{max}}(v_2) = \frac{\rho_a A_a c_D}{2M} \left[ \left( \frac{v_{\text{max}}}{3.6} \right)^2 - \left( \frac{v_2}{3.6} \right)^2 \right]$$

Here $v_{\text{max}}$ and $v_2$ are in the unit $m/s$. Moreover, the maximum deceleration for HDV platoon follower is modeled according to driving comfort (Hoberock, 1977):

$$a_{\text{min}} = -3 \text{ m/s}^2 \quad (3.10)$$

Therefore if the acceleration demand generated by (3.1) or (3.2) exceeds the acceleration capability, the vehicle acceleration $a_2$ will be given by (3.9); if the acceleration demand violates deceleration capability, $a_2$ will be determined by (3.10). Although the jerk of HDV (derivative of acceleration) has not been considered when modeling vehicle acceleration of HDV platoon follower, according to Table 3.1, (3.9) and (3.10), the maximum acceleration of HDV platoon follower is about $0.13 m/s^2 - 0.2 m/s^2$, always within driving comfort (from $-3 m/s^2$ to $2 m/s^2$ (Hoberock, 1977)).

### 3.3 Fuel Consumption Model

Since one purpose of HDV platooning is to improve fuel efficiency, an analytical model proposed by Oguchi et al. (2002) is adopted to estimate the instantaneous fuel consumption of HDV. The fuel consumption model can be analytically represented by the following equation:

$$f = \frac{\int_{t_0}^{t_f} \delta \left[ (\mu \cos \theta + \sin \theta) M g v + \kappa v^3 + M a v \right] dt}{H \eta}$$

(3.11)
where \( t_0 \) and \( t_f \) denote the initial and final time instances; \( H \) and \( \eta \) are energy density and efficiency respectively; \( v \) and \( a \) are vehicle speed and acceleration; \( M \) is the mass of vehicle; \( \delta \) indicates if the engine is active:

\[
\delta(t) = \begin{cases} 
1 & \text{if } (\mu \cos \theta + \sin \theta) M g v + \kappa v^3 + M a v > 0 \\
0 & \text{otherwise}
\end{cases}
\]

the air-drag coefficient \( \kappa \) is computed from:

\[
\kappa = \frac{1}{2} \rho_a A c_D (1 - \varphi)
\]

For passenger cars, single HDVs and HDV platoon leaders, the air-drag reduction \( \varphi \) is 0. For HDV platoon followers, \( \varphi \) can be estimated from Figure 3.2. The road grade \( \theta \) is set to 0 in this study for simplicity. Detail of parameters are presented in Table 3.1.

3.4 Summary

In this chapter, the properties and operations of HDV platoon are defined. The ACC and CACC system are also model considering acceleration capability of HDV and driving comfort. An instantaneous fuel consumption model is presented to estimate the fuel usage according to vehicle dynamics. The HDV platoon model is used in the rest of the thesis.
This chapter is based on Paper II (Deng and Burghout, 2015) and could be considered as complementary study to microscopic traffic simulation. In platoons, the vehicle spacing is determined by the spacing policy, which refers to the desired gap a platoon follower wants to maintain from its predecessor in steady state (Santhanakrishnan and Rajamani, 2013). Spacing policy of HDV platoon not only plays an important role in air-drag reduction and fuel savings but also is directly coupled with traffic throughput. Large spacing policy meets safety requirement of HDVs at the cost of decreasing lane capacity; conversely, small desired spacing policy can increase traffic flow rate and reduce air-drag, but it requires strong acceleration and braking capability to maintain safety and control stability. Evidently there is always trade-off between traffic/fuel efficiency and safety/stability in selection of spacing policy for an HDV platoon. The impacts of spacing policy on HDV platoon fuel saving have been extensively studied in many projects, such as PATH (Browand et al., 2004), eCoMove (Vreeswijk et al., 2010) and EnergyITS (Tsugawa et al., 2011). However, the impacts of platoon spacing policy on traffic flow have been inadequately studied (Dharba and Rajagopal, 1999). Since the development of HDV platooning is still in the early stage, the impacts of the HDV platooning on highway traffic flow characteristics need to be carefully analyzed.

In general, the spacing policy of an HDV platoon may be a constant, or typically a function of vehicle speed of HDV platoon follower, or even a function of other variables. A variety of spacing policies have been proposed and studied. Ideally, small spacing policies yield improved highway capacities from a traffic flow point of view. The goal for most HDV platooning policies is thus to achieve smallest spacing as possible. For example, Shladover suggested 1 meter constant vehicle spacing (CVS) for vehicle platoons (Shladover, 1991). This small spacing policy and corresponding tight platoon model increased traffic throughput considerably. However, when it comes to application, particularly for HDV platoons, safety might not be guaranteed. Since HDVs have limited braking capability, a delay in vehicle-to-vehicle (V2V) communication could result in rear-end collisions. The smallest feasible constant spacing policy is 3 meters according to Browand et al. (2004), with such spacing
policies HDVs are still able to operate at 90 km/h in the platoon. At present, the most common spacing policy used by researchers and automobile manufacturers is the constant time gap (CTG) policy, in which the inter-vehicle distances adapt to vehicle speeds according to a predefined constant time gap. The CTG policy has become the baseline spacing policy for development and comparison of new spacing policies. Many researchers have recently developed new spacing policies, such as safety spacing policy (Zhao et al., 2009), variable time gap policy (Wang and Rajamani, 2004), or other nonlinear spacing policy (Petricic and Petrovic, 2012). Comparing the performance of CTG policy on traffic flow stability and capacity, the proposed spacing policies show potential improvement on traffic throughput.

The impacts of platoon spacing policy on traffic flow can be described using speed-density relation. This relation serves as a basis to understand to what extent a particular spacing policy of HDV platoons improves the traffic system. There are several single and multi-regime models proposed to describe speed-density relation. Single-regime models (space mean speed is monotonous decreasing with increasing traffic density) including Greenshields (1935), Greenberg (1959), Underwood (1961), Drake et al. (1967), Drew (1968) and Pipes (1967) attempted to capture the general shape of empirical speed-density relation using as few parameters as possible. However, they show shortcomings in in free-flow and low-density regimes, where the correlation between speed and density is weak. Multi-regime models such as Edie (1961), two-regime model (May (1990)) and three-regime model (Drake et al. (1967) and May (1990)) provide a closer fit to empirical observations, at the cost of increased complexity and number of parameters. However, they are difficult to incorporate with platoon and its spacing policy since no explicit relation between vehicle spacing and traffic density can be seen in these models. In order to emphasize the connection between traffic density and spacing policy of a vehicle platoon, Santhanakrishnan et al. modeled traffic flow based on steady state single regime speed-density relation, which assumes that all vehicles have the same speed and vehicle gap in steady state (Santhanakrishnan and Rajamani, 2013). However, like other single-regime models, it does not accurately describe speed-density relation in free flow, and their study only focused on platooning of cars.

Although the developments of spacing policies are well documented, there is little knowledge on how HDV platoon spacing policies affect traffic flow. HDV platoons are distinguished from car platoons by their acceleration and deceleration capabilities and maximum vehicle speed. HDVs generally have much lower speed and weaker acceleration/deceleration capabilities than passenger cars. Besides, the existing single-/multi-regime macroscopic traffic flow models have several limitations: it is difficult to express the spacing policy of HDV platoon as an input of traffic flow rate explicitly; the maximum benefit from HDV platooning to traffic throughput could not be analytically estimated. To address these limitations, one critical step towards better understanding of how HDV platooning benefits transport efficiency is to derive mixed traffic flow model consisting of HDV platoons and passenger cars.

To sum up the literature study, a multi-regime speed-density model is more appropriate than single-regime model to describe both free flow and congested flow,
since the space mean speed of highway should be independent of traffic density in free flow but affected by traffic density in congested traffic flow. Secondly, in order to analytically derive the impacts of platoon spacing policy on traffic flow, the spacing policy needs to be modeled as an input variable in speed-density relation. Thirdly, vehicle interaction or car-following behavior should be considered in the modeling of speed-density relation if possible.

This chapter mainly focuses on two of the most commonly used spacing policies: constant vehicle spacing (CVS) and constant time gap (CTG). Figure 4.1a depicts the platoon structure and spacing policy. In CVS policy, the desired inter-vehicle distance is constant:

\[ r_{\text{des}} = r_d \]

where \( r_d \) is constant. The CVS policy has many advantages: on the one hand, it guarantees global asymptotic stability and string stability (Liang and Peng, 2000); on the other hand, it is easy to implement in practice. Moreover, different CVS policies can be applied for various traffic facilities, for instance, large CVS policy would be required when an HDV platoon approaches on-/off-ramp to enhance safety of other vehicles. After passing the ramp area, the inter-vehicle distances of HDV platoon will be reduced to enhance air-drag reduction and fuel saving.

CTG is also one of most common spacing policies. Different from CVS policy, the desired inter-vehicle distance adapts to current vehicle speed with constant time gap \( t_d \) in CTG policy, that is:

\[ r_{\text{des}} = v t_d \]

CTG policy is also capable of maintaining a stable vehicle string in an HDV platoon (Liang and Peng, 2000). In order to achieve global asymptotic stability, platoon leader must operate at constant speed; otherwise the desired inter-vehicle distance needs to be updated continuously in real-time and spacing error between two consecutive HDVs will not converge.

4.1 Modeling of Steady-State Mixed Traffic Flow

This section focuses on modeling of mixed traffic flow with passenger cars and HDV platoons. First of all, there are some notations presented in Table 1 before the detailed formulation of speed-density relation.

It is assumed that the mixed traffic flow consists of \( P \) (\( P \geq 0 \)) percent HDVs and \( 1 - P \) (\( 1 - P \geq 0 \)) percent passenger cars. \( L_{\text{car}} \) and \( L_{\text{HDV}} \) denote the extended vehicle length (actual vehicle length plus 1m standstill safe distance, see Figure 4.1b) of passenger and HDV respectively, \( \tau \) denotes the average time gap for passenger cars, single HDVs and HDV platoon leaders. In the scenarios of HDV platooning, all HDV platoon followers operate in uniform spacing polices. In order to incorporate the vehicle interaction in macroscopic mixed traffic flow model, the speed-density
relation is derived from the General Motor’s (GM5) car-following model (Gazis et al., 1961):

$$\ddot{x}(t + \tau) = \alpha \left[ \frac{[\dot{x}(t + \tau)]^n}{[x_{i-1}(t) - x_i(t) - L_{i-1}]} \right]\left[ \dot{x}_{i-1}(t) - \dot{x}_i(t) \right]$$  \hspace{1cm} (4.3)
4.1. Modeling of Steady-State Mixed Traffic Flow

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$</td>
<td>traffic Density</td>
</tr>
<tr>
<td>$k_{\text{free}}$</td>
<td>free flow density, the traffic is free flow if $k &lt; k_{\text{free}}$</td>
</tr>
<tr>
<td>$k_{\text{congest}}$</td>
<td>congested flow density, the traffic is congested if $k \geq k_{\text{congest}}$</td>
</tr>
<tr>
<td>$k_{\text{max}}$</td>
<td>maximum traffic density</td>
</tr>
<tr>
<td>$v$</td>
<td>aggregate highway velocity (space mean speed)</td>
</tr>
<tr>
<td>$v_{\text{free}}$</td>
<td>space mean speed in free flow</td>
</tr>
<tr>
<td>$v_{\text{des,car}}$</td>
<td>desired free-driving speed of passenger car</td>
</tr>
<tr>
<td>$v_{\text{des,HDV}}$</td>
<td>desired free-driving speed of HDV</td>
</tr>
<tr>
<td>$Q$</td>
<td>traffic flow rate</td>
</tr>
<tr>
<td>$P$</td>
<td>percentage of HDVs</td>
</tr>
<tr>
<td>$L_{\text{HDV}}$</td>
<td>extended vehicle length of HDV, see Figure 4.1b</td>
</tr>
<tr>
<td>$L_{\text{car}}$</td>
<td>extended vehicle length of car, see Figure 4.1b</td>
</tr>
<tr>
<td>$r_d$</td>
<td>constant vehicle spacing policy</td>
</tr>
<tr>
<td>$t_d$</td>
<td>constant time gap policy</td>
</tr>
<tr>
<td>$\tau$</td>
<td>average time gap for passenger car and platoon leader</td>
</tr>
</tbody>
</table>

where $x_i$, $\dot{x}_i$, $\ddot{x}_i$ and $\tau_i$ denote the position, speed, acceleration and driver reaction time of vehicle $i$ respectively. In this study, the speed-density relation is divided into three regimes: free-flow regime, restrained-flow regime and congested-flow regime. The speed-density relation of each regime is derived from GM5 model (4.3).

### 4.1.1 Speed-Density Relation in Free-Flow Regime

Since the desired free-driving speeds of passenger cars and HDVs are $v_{\text{des,car}}$ and $v_{\text{des,HDV}}$ respectively, to simplify the modeling of speed-density relation, this study hypothesizes that passenger car and HDVs drive at respective desired speeds in free flow. Thus the parameters $\alpha = 0$ is chosen in (4.3) for the free-flow regime and the space mean speed in free flow is given by:

$$v_{\text{free}} = \frac{k}{k(1-P) + \frac{kP}{v_{\text{des,HDV}}}} = \frac{v_{\text{des,car}} v_{\text{des,HDV}}}{v_{\text{des,car}} P + v_{\text{des,HDV}}(1 - P)}$$  \hspace{1cm} (4.4)

The space mean speed is $v = v_{\text{free}}$ if the traffic density $k \leq k_{\text{free}}$, $k_{\text{free}}$ is determined in later subsections.
4.1.2 Speed-Density Relation in Congested-Flow Regime

When the traffic flow is congested, all vehicles tend to have the same speed in steady state, in which there is no lane changing or overtaking. This can be interpreted as that drivers are more sensitive to relative speed and try to maintain the same speed as the preceding vehicle, therefore \( m = 0 \) and \( l = 0 \) are chosen for the congested-flow regime, this gives:

\[
\ddot{x}_i(t + \tau_i) = \alpha \left[ \dot{x}_{i-1}(t) - \dot{x}_i(t) \right]
\] (4.5)

According to Deng and Burghout (2015), the corresponding speed-density relation is:

\[
k (1 - P)(L_{\text{car}} + v\tau) + kP(L_{\text{HDV}} + v\tau) = 1 \quad (4.6)
\]

Equation (4.6) is the speed-density relation of congested-flow regime in the scenario of no HDV platooning. For the scenarios of HDV platooning, HDVs might operate in one or several platoons. Therefore, (4.6) can be easily modified to:

\[
k (1 - P)(L_{\text{car}} + v\tau) + kP[L_{\text{HDV}} + r_{\text{des}}(v)] + n[v\tau - r_{\text{des}}(v)] = 1 \quad (4.7)
\]

which is the speed-density relation in congested-flow regime for the cases of HDV platooning. Here \( v \) denotes space mean speed and \( r_{\text{des}} = v\tau \) for no HDV platooning scenario or \( P = 0 \) (no HDVs on highway), \( 1 \leq n \leq kP \) represents the number of HDV platoons. This speed-density relation provides strong approximation of real traffic while maintaining simplicity. Note that the spacing policies of HDV platoon are incorporated in speed-density relation (4.7) as vehicle gaps, thus \( v \) can be formulated as a function of traffic density and spacing policy of HDV platoon. Define the upper-bound of congested-flow speed:

\[
v_{\text{congest}} = \begin{cases} 
v_{\text{des,car}} & \text{if } P = 0 \\
\min\{v_{\text{des,car}}, v_{\text{des,HDV}}\} & \text{if } P > 0 
\end{cases}
\] (4.8)

In steady-state, all vehicles have the same speed \( v_{\text{congest}} \), plugging \( v = v_{\text{congest}} \) in (4.7) leads to the density threshold for congested traffic flow:

\[
k_{\text{congest}} = \frac{1 + n [r_{\text{des}}(v_{\text{congest}}) - v_{\text{congest}}\tau]}{(1 - P)(L_{\text{car}} + v_{\text{congest}}\tau) + P[L_{\text{HDV}} + r_{\text{des}}(v_{\text{congest}})]} \quad (4.9)
\]

Furthermore, the maximum traffic density can be derived from \( v \geq 0 \), plugging \( v = 0 \) in (4.7) yields:

\[
k_{\text{max}} = \frac{1 + nr_{\text{des}}(0)}{(1 - P)L_{\text{car}} + [L_{\text{HDV}} + r_{\text{des}}(0)]} \quad (4.10)
\]
### 4.1.3 Speed-Density Relation in Restrained-Flow Regime

Define the regime $[k_{free}, k_{congest}]$ as restrained-flow regime, in which passenger cars are not able to maintain desired speed due to vehicle interaction, while HDVs can still operate at their desired speed. Since $v_{car}^{des} > v_{HDV}^{des}$, passenger cars decelerate to keep a safe distance to the vehicles ahead or change lane, e.g., a passenger car approaching an HDV or overtaking an HDV. For simplicity of modeling, this study assumes that the lane changing maneuver takes place instantaneously, ignoring the detailed movements. The car-following after lane changing is still taken into account. In the restrained-flow regime, vehicles are more aware of the safety and vehicle gap in vehicle interaction, therefore $m = 0$ and $l = 2$ are chosen for GM5 model:

$$\ddot{x}_i(t + \tau) = \alpha \frac{\dot{x}_{i-1}(t) - \dot{x}_i(t)}{[x_{i-1}(t) - x_i(t) - L_{i-1}]^2}$$  \hspace{1cm} (4.11)

According to Deng and Burghout (2015), the speed-density relation of restrained-flow regime is:

$$v = \frac{k}{v_{car}} + \frac{k P}{v_{HDV}} = \frac{v_{HDV}^{des} v_{car}}{v_{car}^{des} (1 - P) + P}$$  \hspace{1cm} (4.12)

where

$$v_{car} = \frac{-\alpha k (1 - P)}{1 - n \left[ v_{HDV}^{des} \tau - r_{des} \left( v_{HDV}^{des} \right) \right] - k (1 - P) L_{car} - k P \left[ L_{HDV} - r_{des} \left( v_{HDV}^{des} \right) \right]}$$  \hspace{1cm} (4.13)

$$\alpha = -\frac{(k_{congest} v_{HDV}^{des} \tau)^2}{1 - n \left[ v_{HDV}^{des} \tau - r_{des} \left( v_{HDV}^{des} \right) \right]} \theta_v (k_{congest})$$  \hspace{1cm} (4.14)

$$\beta = v_{HDV}^{des} - \frac{(k_{congest} \tau)^2 v_{HDV}^{des}}{1 - n \left[ v_{HDV}^{des} \tau - r_{des} \left( v_{HDV}^{des} \right) \right]} \theta_v (k_{congest})$$

$$\theta_v = \frac{(1 - P) (L_{car} + v \tau) + P \left[ L_{HDV} + r_{des} (v) \right]}{k \tau (1 - P) + k P \left( \frac{dr_{des} (v)}{dt} \right) + n \left[ \tau - \frac{dr_{des} (v)}{dt} \right]}$$  \hspace{1cm} (4.16)

Finally the free-flow density $k_{free}$ can be computed by letting $v_{car} (k_{free}) = v_{car}^{des}$:

$$k_{free} = \frac{(\beta - v_{car}^{des}) \left( 1 - n \left[ v_{HDV}^{des} \tau - r_{des} \left( v_{HDV}^{des} \right) \right] \right) \alpha (1 - P) + (\beta - v_{car}^{des}) \left( (1 - P) L_{car} + P \left[ L_{HDV} + r_{des} (v_{HDV}^{des}) \right] \right)}{(\beta - v_{car}^{des}) \left( (1 - P) L_{car} + P \left[ L_{HDV} + r_{des} (v_{HDV}^{des}) \right] \right)}$$  \hspace{1cm} (4.17)
Table 4.2: vehicle parameters and spacing policy constants.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{car}}$</td>
<td>5 m</td>
<td>—</td>
</tr>
<tr>
<td>$L_{\text{HDV}}$</td>
<td>25 m</td>
<td>—</td>
</tr>
<tr>
<td>$t_d$</td>
<td>0.5 s</td>
<td>Ploeg et al. (2011a)</td>
</tr>
<tr>
<td>$r_d$</td>
<td>3 m</td>
<td>Browand et al. (2004)</td>
</tr>
<tr>
<td>$\tau$</td>
<td>2 s</td>
<td>Nilsson (2001)</td>
</tr>
<tr>
<td>$v_{\text{des,car}}$</td>
<td>110 km/h</td>
<td>Aronsson (2006)</td>
</tr>
<tr>
<td>$v_{\text{des,HDV}}$</td>
<td>90 km/h</td>
<td>Aronsson (2006)</td>
</tr>
</tbody>
</table>

4.1.4 Overall Speed-Density Relation for Mixed Traffic Flow

Based on (4.4)-(4.17), a three-regime model is proposed to describe the speed-density relation of mixed traffic flow:

$$v(k, P, r_{\text{des}}(v)) = \begin{cases} 
    v_{\text{free}} & 0 \leq k \leq k_{\text{free}} \\
    \frac{v_{\text{des,car}}}{v_{\text{HDV}}(1-P)v_{\text{car}}} P & k_{\text{free}} < k \leq k_{\text{congest}} \\
    \frac{1 + nr_{\text{des}}(v) - k(1-P)L_{\text{car}} - kP[L_{\text{HDV}} + r_{\text{des}}(v)]}{k(1-P)\tau + n\tau} & k_{\text{congest}} < k \leq k_{\text{max}} 
\end{cases} \tag{4.18}$$

However, (4.18) is only valid for $0 < P < 1$, for the trivial scenarios, $P = 0$ and $P = 1$, Equation (4.4) and (4.8) imply:

$$v_{\text{congest}} = v_{\text{free}} = v_{\text{car}}^P = 0$$ \tag{4.19}$$

$$v_{\text{congest}} = v_{\text{free}} = v_{\text{HDV}}^P = v_{\text{des,HDV}}$$ \tag{4.20}$$

The proposed model (4.18) is reduced to a two-regime model for $P = 0$ and $P = 1$. Hence, for the scenario $P = 0$, namely, there is no HDV on the highway, substitution of $r_{\text{des}}(v) = v\tau$ (no HDV platoon spacing policy is applied) in (4.7) gives:

$$v(k) = \begin{cases} 
    v_{\text{des,car}} & 0 \leq k \leq k_{\text{free}} \\
    \frac{1 - kL_{\text{car}}}{k\tau} & k_{\text{free}} < k \leq k_{\text{max}} 
\end{cases} \tag{4.21}$$

In another extreme, for the scenario $P = 0$, namely, there is no car on the highway:

$$v(k) = \begin{cases} 
    v_{\text{des,HDV}} & 0 \leq k \leq k_{\text{free}} \\
    \frac{1 + nr_{\text{des}}(v) - k[L_{\text{HDV}} + r_{\text{des}}(v)]}{n\tau} & k_{\text{free}} < k \leq k_{\text{max}} 
\end{cases} \tag{4.22}$$

The detailed parameters for the scenario of no HDV platooning, HDV platooning with CVS policy and HDV platooning with CTG policy are presented in Table 4.2. An illustration of three-regime speed-density relation for mixed traffic flow can be seen in Figure 4.2.
4.2 Numerical Results

In this section, the traffic throughput under different spacing policies of HDV platoon is analyzed. In order to investigate to what extent a spacing policy of HDV platoon affects traffic flow, this study further assumes that all HDVs are operating in one platoon with the same spacing policies, that is, \( n = 1 \), since the benefits of HDV platooning to traffic throughput and capacity would be maximized.

Figure 4.3a - 4.3d show the improvement of HDV platooning on highway capacity (maximum traffic flow rate). Platooning HDVs with CVS policy \( r_d = 3m \) leads to maximum increase on highway capacity. For example, the absolute increases under CVS policy are 3.7%, 8.4%, 13.4% and 18.6% for HDV percentage 10%, 15%, 20% and 25% respectively; and under CTG policy \( t_d = 0.5s \), the absolute increases...
are 2.9%, 6.5%, 10.2% and 14.1%. It is also interesting to see that both no HDV platooning case and HDV platooning with CTG policy have better performance than CVS policy in heavily congested traffic flow. This can be explained by

\[ vt_d \leq r_d \Rightarrow v \leq \frac{r_d}{t_d} = 6 m/s \]  

\[ v\tau \leq r_d \Rightarrow v \leq \frac{r_d}{\tau} = 1.5 m/s \]  

In heavily congested traffic flow, the inter-vehicle distances in HDV platoon decrease to very small when CTG policy is applied or no policy is applied due to low vehicle speed, while CVS policy still keeps fixed inter-vehicle distances. CTG policy has
4.3 Mixed Spacing Policy

According to the analysis in the previous subsection, each spacing policy has its unique advantage. CVS policy $r_d = 3m$ yields the most significant improvement on highway capacity; CTG policy $t_d = 0.5s$ has better performance than CVS policy in heavily congested traffic flow. It is generally difficult to have a single spacing policy that has the advantages from both CVS and CTG policies while evolving smoothly along vehicle speed and maintaining string stability. Therefore it is intuitive to propose a mixed HDV platoon spacing policy in order to combine the benefits from both CVS and CTG policies. A mixed CVS-CTG policy has the form:

$$r_{des} = \delta_k r_d + (1 - \delta_k) v t_d$$

(4.25)

where $\delta_k$ is a traffic density related parameters and given by:

$$\delta_k = \begin{cases} 
1 & \text{if } k \leq k_r \\
0 & \text{if } k > k_r 
\end{cases}$$

(4.26)

Figure 4.4: comparison of HDV platooning with different spacing policies. HDVs compose 20% of total traffic. CVS policy $r_d = 3m$ results in maximum improvement on capacity; CTG policy $t_d = 0.5s$ has better performance than CVS policy when the traffic density is higher than 51.6 vehicles per km per lane; mixed CVS-CTG policy combines the benefits from both CVS and CTG policies.

better performance than CVS policy when $v \leq 6m/s$, and HDV platooning with CVS policy is worse than no HDV platooning when $v \leq 1.5m/s$. 

4.3 Mixed Spacing Policy

According to the analysis in the previous subsection, each spacing policy has its unique advantage. CVS policy $r_d = 3m$ yields the most significant improvement on highway capacity; CTG policy $t_d = 0.5s$ has better performance than CVS policy in heavily congested traffic flow. It is generally difficult to have a single spacing policy that has the advantages from both CVS and CTG policies while evolving smoothly along vehicle speed and maintaining string stability. Therefore it is intuitive to propose a mixed HDV platoon spacing policy in order to combine the benefits from both CVS and CTG policies. A mixed CVS-CTG policy has the form:

$$r_{des} = \delta_k r_d + (1 - \delta_k) v t_d$$

(4.25)

where $\delta_k$ is a traffic density related parameters and given by:

$$\delta_k = \begin{cases} 
1 & \text{if } k \leq k_r \\
0 & \text{if } k > k_r 
\end{cases}$$

(4.26)
The density threshold \( k_r \) is the density threshold for changing spacing policy. For driving safety, the switch between CVS and CTG is only allowed when the platoon is in steady state. Every time instance there is only one HDV platoon spacing active. Moreover, the density threshold \( k_r \) can be calculated by:

\[
v(r_d) = v(\nu_d) \Rightarrow k_r = \frac{t_d - r_d \tau + r_d \tau}{Pr_d + (1 - P)r_d \tau + P L_{HDV} \tau_d + (1 - P)L_{car} \tau_d}
\]

Consequently the speed-density relation under mixed spacing policy is:

\[
v_{\text{mix}}(k) = \begin{cases} 
  v_{\text{free}} & 0 \leq k \leq k^{CVS}_{\text{free}} \\
  v_{\text{HDV}}(1 - P) + v_{\text{HDV}} P & k^{CVS}_{\text{free}} < k \leq k^{CVS}_{\text{congest}} \\
  1 + r_d \tau + k(1 - P)L_{car} + kP(L_{HDV} + r_d) & k^{CVS}_{\text{congest}} < k \leq k_r \\
  1 + k(1 - P)L_{car} + kPL_{HDV} & k_r < k \leq k^{CTG}_{\text{max}} 
\end{cases}
\]

Figure 4.4 compares the performance of no HDV platooning, HDV platooning with CVS policy, CTG policy and mixed CVS-CTG policy on traffic flow rate (HDVs compose 20% of total traffics). In line with previous analysis, the mixed CVS-CTG policy combines the advantages of CVS policy and CTG policy: the HDV platoon adopts CVS policy before the traffic density reaches 51.6 veh/ lane/ km, thus it contributes to the most significant improvement on highway capacity. When the traffic is congested and the density \( k > 51.6 \), the mixed policy switches from CVS to CTG, which does not require fixed desired inter-vehicle distance. Therefore the inter-vehicle distance could be further reduced compared with the scenario of HDV platooning with CVS policy.

### 4.4 Summary

In this chapter, the speed-density relation of mixed traffic flow is presented. First of all, the model formulation of mixed traffic flow takes the percentage of HDVs and the number of HDV platoons into consideration. Secondly, the space mean speed of mixed traffic flow is formulated as a function of HDV percentage, traffic density and HDV platoon spacing policy. Thirldly, the three-regime speed-density relation can be used to analytically estimate the maximum improvement on highway capacity from different spacing policies. This could bring inspiration on development of more advanced spacing policies for HDV platooning.

This study relies on the GM5 car-following model due to its tractability and broad acceptance, alternative car-following model could as well be considered in the formulation of speed-density relation. The parameters presented in Table 4.2 are chosen from the studies carried out by other researchers. However, for practical application of the proposed three-regime speed-density relation, the desired free-driving speed of passenger car \( v_{\text{des car}} \), desired free-driving speed of HDV \( v_{\text{des HDV}} \) and average time gap of passenger vehicle \( \tau \) need to be calibrated and validated.
This chapter is based on the Paper I (Deng, 2015a) and Paper III (Deng, 2015b). Nowadays, the development of ICT has promoted the feasibility of HDV platooning on highway. Extensive industrial research has been carried out on development of robust platoon control system (e.g., ACC or CACC) and coordination strategy. However, there is little study on implementation of different platoon operations and quantification of effects of HDV platoons to traffic flow. In order to better understand the benefits of HDV platooning, an essential step is to quantify critical performance indicators of HDV platoons and passenger vehicles concerning fuel efficiency and detailed traffic flow characteristics.

5.1 Development of Simulation Framework

Traffic simulation is a powerful tool in analysis of transport system. It has been widely applied in vehicle-based ITS and driver behavior studies. In particular, microscopic simulation describes traffic flow at high level of details: it mimics the dynamics of moderate-sized traffic system, where the number of transport units passing through is relatively small and meanwhile there is requirement to represent the behavior of individual vehicle units (May, 1990). The essence of the platoon effects in mixed traffic flow is the interaction between passenger cars and HDV platoons. Since the commercial microscopic traffic simulator VISSIM has already integrated psychophysical car-following model and lane-changing model to determine longitudinal and lateral driving behaviors of passenger vehicles, it can be adopted as main simulation engine for the framework. Besides, specific car-following of HDV platoon followers can also be implemented through VISSIM COM server interface. The COM server shares the internal vehicle states of VISSIM objects during simulation so that users can access and modify vehicle driving behaviors. With assistance of VISSIM COM, the simulation framework extends VISSIM with Input/Output Unit, Vehicle Generator, Vehicle State Updater, HDV Platoon Model and Database, an overview of simulation framework can be seen in Figure 5.1.
Simulation Framework and Experiments

Figure 5.1: architecture of simulation framework: the simulation framework is developed based on traffic simulator VISSIM, user-defined components can be integrated with VISSIM through VISSIM COM server.

5.2 Work Flow of Simulation

Figure 5.2 depicts the work flow of the simulation process. In addition to traffic demand and traffic composition, ACC/CACC parameters and simulation time need to be set in advance. After that, the input unit triggers the simulation process and vehicle generator starts to generate vehicles and load traffic on simulation network. Once the simulation starts, the longitudinal motion of passenger cars, single HDVs and HDV platoon leaders will be determined by VISSIM car-following model. On the other hand, the car-following behavior of HDV platoon followers will be determined by ACC/CACC algorithm. Fuel consumption of passenger cars and single HDVs are estimated without considering air-drag reduction. Fuel saving due to air-drag reduction of HDV platooning will be estimated according to vehicle dynamics and current inter-vehicle distances between HDVs. The state of each vehicle will be continuously saved and updated during simulation. If required simulation runs complete, the simulation results will be exported to database.

5.3 A Constant Spacing Policy for Platoon Disaggregation

An HDV platoon should have the capability of adjusting its inter-vehicle distances. This could be specified by giving the HDV platoon several spacing policies to switch between in different situations. For the case of two possible spacing policies, one can write:

\[ r_{\text{des}} = \delta r_0 + (1 - \delta) r_{\text{large}} \]  

This means that the spacing policy \( r_{\text{des}} \) can be switched between \( r_0 \) and \( r_{\text{large}} \) (\( r_{\text{large}} > r_0 \)) by setting \( \delta \) to either zero or one. \( \delta \) has the default value one, meaning
5.3. A Constant Spacing Policy for Platoon Disaggregation

- Traffic Demand
- Traffic Composition
- ACC/CACC Parameters
- Simulation Time

Vehicle Generation

Passenger Car
Single HDV
HDV Platoon Leader

HDV Platoon
Follower

Simulate Vehicle Dynamic for one Time Step with VISSIM Car-Following Model

Calculate Fuel Consumption

Update Vehicle State
- Speed
- Acceleration
- Position

Is Simulation Time Over?

Yes

Export Simulation Results to Database

No

Simulate Vehicle Dynamic for one Time Step with ACC/CACC Algorithm

Estimate Air-Drag Reduction and Calculate Fuel Consumption

Update Time Step

Figure 5.2: Work flow of simulation process.
that the HDV platoon has the default spacing policy $r_0$. When the HDV platoon approaches an off-ramp area, $\delta$ is set to 0, meaning that the spacing policy is switched from $r_0$ to $r_{\text{large}}$ in order to increase the inter-vehicle distance. Though the desired gap switches instantaneously between $r_0$ and $r_{\text{large}}$, the platoon follower adjusts its speed at a limited pace. After all HDVs have passed the off-ramp area, $\delta$ is reset to one again.

5.4 Parameters of CACC System for HDV Platoon

Although a variety of ACC/CACC algorithms have been proposed for vehicle platooning, how to decide the control parameters in ACC/CACC algorithm is still an open research question. In Paper III (Deng, 2015b), the feasible region of CACC parameters is derived from analysis of asymptotic stability, driving safety and acceleration and braking capabilities of an HDV. The resulting feasible region of CACC parameters is:

$$k_r \leq \min \left\{ \frac{a_{ub}v^2}{r_{\text{max}}}, \frac{a_{\min}}{r_{\text{max}}} \right\}$$

(5.2)

$$k_v \geq 2\sqrt{k_r}$$

(5.3)

where $a_{ub} = \frac{\rho_a A_{\text{a}} c_{D}}{2V} (v_{\text{max}}^2 - v_{\text{ub}}^2)$. The detail of parameters can be seen in Table 5.1. Substitution of those parameters in (5.2) and (5.3) gives the feasible region of CACC parameters:

$$k_v \geq 0.2 \quad \text{and} \quad k_r \leq 0.01$$

(5.4)

Based on the numerical experiments in the paper (Deng, 2015b), $k_v = 0.4$ and $k_r = 0.01$ are selected.

5.5 Simulation Experiments

In this section, the simulation framework is applied on three experimental cases. In the first case, the impacts of HDV platooning on traffic flow are investigated; in the second case, the influence of traffic on HDV platoon formation is studied; in the third case, the proposed constant spacing policy (5.1) is applied on HDV platoon disaggregation at highway off-ramp.

5.5.1 The Impacts of HDV Platooning on Traffic Flow

Firstly, a two-lane highway of 3.5km without any ramp is modeled to analyze the effects of HDV platooning to traffic flow. As depicted in Figure 5.3a, the test highway includes a 0.5km warm-up segment and 3km simulation segment. The purpose of
5.5. Simulation Experiments

Table 5.1: Overview of vehicle parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>40000 kg</td>
<td>Sahlholm (2011)</td>
</tr>
<tr>
<td>$c_D$</td>
<td>0.6</td>
<td>Sahlholm (2011)</td>
</tr>
<tr>
<td>$\rho_a$</td>
<td>1.29 kg/m$^3$</td>
<td>Sahlholm (2011)</td>
</tr>
<tr>
<td>$A_a$</td>
<td>10.26 m$^2$</td>
<td>Sahlholm (2011)</td>
</tr>
<tr>
<td>$v_{\text{max}}$</td>
<td>160 km/h</td>
<td>—</td>
</tr>
<tr>
<td>$a_{\text{min}}$</td>
<td>$-3 m/s^2$</td>
<td>Hoberock (1977)</td>
</tr>
<tr>
<td>$r_0$</td>
<td>10 m</td>
<td>—</td>
</tr>
<tr>
<td>$r_{\text{max}}$</td>
<td>100 m</td>
<td>—</td>
</tr>
<tr>
<td>$v_{\text{ub}}$</td>
<td>90 km/h</td>
<td>Aronsson (2006)</td>
</tr>
<tr>
<td>$v_{\text{lb}}$</td>
<td>50 km/h</td>
<td>—</td>
</tr>
</tbody>
</table>

The warm-up segment is to avoid vehicle loading effects, vehicles can adjust their speeds and vehicle gaps before entering the simulation segment.

The traffic simulation consists of 30 simulation runs. Each simulation run is 45 minutes. The first 15 minutes is for loading traffics on highway with output excluded from the impact analysis. The traffic consists of 10% HDVs and 90% passenger cars (May, 1990). The traffic demand is set to 1600 vehicles per lane per hour. The desired speed of HDV is set to 90 km/h. The simulation experiments are conducted for different desired speed of passenger cars, 110 km/h, 100 km/h and 90 km/h. The desired speed of passenger cars follows a normal distribution with mean 110 km/h, 100 km/h and 90 km/h respectively for each scenario, and has the same standard deviation 8 km/h. The HDV platoons are generated directly and the total number of HDVs is restricted to approximately 10% of total traffic according to traffic composition. The size of HDV platoon is restricted to maximum three vehicles due to limited data for air-drag reduction estimation. Each HDV is equal to 4 passenger cars according passenger car equivalence. The CACC parameters are set to $k_a = 1$, $k_v = 0.58$, $k_r = 0.1$ and $t_d = 0.5$ referring to Arem et al. (2006). CACC updates acceleration of HDV platoon follower every 1 s ($\Delta t = 1$).

The impacts of HDV platoons on traffic flow are investigated in terms of space mean speed and average traffic flow rate. Statistical independences of data from different platoon penetration rates are always checked before analysis. Figure 5.3b shows that platooning HDVs slightly decreases space mean speed with increasing penetration rate of HDV platooning at high traffic demand. This phenomenon can be explained by the fact that HDV platooning saves space on the highway, therefore the highway can accommodate more passenger cars and HDVs, more HDVs on the highway generally result in decreasing of space mean speed due to their lower desired speed than passenger cars. On the other hand, Figure 5.3c shows that the average...
traffic flow rate is significantly increased as the penetration rate of HDV platooning increases. Traffic flow rate is the product of space mean speed and traffic density. Thus the improvement of traffic flow rate can be interpreted as a result of increasing traffic density on the highway but only slight decreasing in the space mean speed.

The fuel saving of HDV platooning has been extensively investigated in many
projects. However, the impact of HDV platoons on fuel efficiency of passenger cars is still unknown. In this study, how HDV platooning affects fuel efficiency of passenger cars is also presented. Figure 5.3d shows that increasing penetration rate of HDV platooning can slightly increase the fuel efficiency of passenger cars, that is, passenger cars can travel for longer distances with the same amount of fuel under high penetration of HDV platooning. This might be explained by the fact that it is easier for a passenger car to overtake a two-/three-HDV platoon than overtaking two/three single HDVs. The acceleration and braking frequencies of passenger cars are reduced. As a consequence, the average number of lane changing of each passenger car is reduced, which can be seen in Figure 5.3e. Therefore, platooning more HDVs can potentially improve both fuel efficiency and traffic safety.

5.5.2 The Influence of Traffic on HDV Platoon Formation

The proposed simulation framework could also be applied on study of HDV platoon formation. Up until now, most of conducted work about HDV platoon assumes that the platoon maintains its structure throughout the trip, no HDV enters or leaves the HDV platoon. In practice, HDVs might start from different origins and have different destinations, meaning that HDV platoons will be frequently formed and disaggregated. However, little literature is available that described whether or how two HDVs form a platoon, let alone the platoon formation considering real time traffic condition. In this subsection, the HDV platoon formation is investigated considering the influence of passenger vehicles. The initial distance between two HDVs is 3 km (see Figure 5.4a), both HDVs have initial speed 80 km/h. These two HDVs form a two-HDV platoon under different traffic densities: light traffic (11 vehicles per lane per km), medium traffic (15 vehicles per lane per km) and heavy traffic (19 vehicles per lane per km). The desired speed of passenger car follows a normal distribution with mean 110 km/h and standard deviation 8 km/h. During the platoon formation, the trailing HDV increases its speed from 80 km/h to 90 km/h. The formation is completed if the distance between two HDVs is less than 30 m and there is no other vehicle between two HDVs. Simulations are carried out under lead HDV speed 70 km/h, 75 km/h and 80 km/h respectively. For each front HDV speed, the simulation is repeated for 30 times.

The ideal platoon formation time (when there is no passenger car on highway) can be calculated from:

$$ t = \frac{d}{v_2 - v_1} \quad (5.5) $$

where $d$ is the initial distance between two HDVs, $v_1$ and $v_2$ denote the speed of front HDV and trailing HDV. As a result, the ideal HDV platoon formation time under front HDV speed 70 km/h, 75 km/h and 80 km/h are 0.15 h, 0.2 h and 0.3 h respectively (since the desired speed of trailing HDV is 90 km/h). Figure 5.4b presents the average platoon formation time under different traffic densities and front HDV speeds. In light traffic, the platoon formation can be executed more or
Simulation Framework and Experiments

Figure 5.4: (a) the simulation scenario for studying influence of HDV platoon formation on traffic, the initial distance between two HDVs is 3km and the simulation segment is 50km, two HDVs merge into a platoon when driving on highway; (b) average platoon formation time of two HDVs under different front HDV speeds and traffic densities; (c) average speed of trailing HDV during platoon formation under different front HDV speeds and traffic densities.

less flawlessly. In medium traffic, the platoon formation is delayed by 58%, 45% and 21%; in heavy traffic, platoon formation time significantly increases by 83%, 72% and 48%. It is observed that deceleration of front HDV to lower speed creates a moving bottleneck and forces the following passenger cars to slow down or change lane. If passenger cars behind the front HDV could not change lane because of large speed difference or not enough vehicle gap on the other lane, those passenger cars will keep driving behind the front HDV and delay the platoon formation. On the contrary, if the front HDV operates in higher speed (e.g. 80km/h), the percentage of delay is greatly reduced in medium and heavy traffic, namely, two HDVs will complete the platoon formation with relatively shorter delay compared with its ideal platoon formation time.

On the other hand, the average speeds of trailing HDV during platoon formation are plotted in Figure 5.4c. Although the trailing HDV has desired speed 90km, when the front HDV decelerates, it affects the speeds of passenger cars behind and therefore affects the speed of trailing HDV. In medium traffic, the average speed of trailing HDV decreases from 90km to 83km/h, 86km/h and 88km under front HDV speeds and traffic densities.
5.5. Simulation Experiments

HDV speed 70 km/h, 75 km/h and 80 km/h; in heavy traffic, the speed of trailing HDV further drops to 81 km/h, 83 km/h and 87 km/h respectively, indicating that deceleration of front HDV to low speed during platoon formation results in late arrival. And late arrival will probably incurs penalty and other additional costs. Hence, there is trade-off between arrival time and platoon formation time in medium and heavy traffic condition.

5.5.3 Disaggregation of HDV Platoon at Highway Off-Ramp

In this experiment, the impacts of HDV platoon disaggregation on traffic flow at highway off-ramp is investigated. As illustrated in Figure 5.5a, a highway section of 6 km with one off-ramp is established for the simulation experiments. The off-ramp is located at 4.3 km on the highway, measured from upstream.

The traffic demand is set to an average value of 1600 vehicles per lane per hour. The desired speed of passenger cars follows a normal distribution with mean 110 km/h and standard deviation 5 km/h. 20% of the passenger cars want to leave the highway through the off-ramp. About 350 s after the simulation starts, a five-HDV platoon with desired speed 80 km/h and default spacing policy \( r_0 = 10 \) m appears on the truck lane at the rightmost. The control parameters of CACC algorithm are set to \( k_v = 0.4 \) and \( k_r = 0.01 \). The traffic simulation is repeated for 50 times. The reference scenario for comparison is that the HDV platoon maintains its structure all the time throughout the experiments.

In the scenario of HDV platoon disaggregation, it takes 150 s to increase the inter-vehicle distance from 10 m to 100 m according to numerical experiments (Deng, 2015b), thus the travel distance of the 1st HDV during platoon disaggregation is given by:

\[
d_{\text{disagg}} = \frac{80}{3.6} \times 150 = 3334 m
\]  

(5.6)

The platoon is expected to complete disaggregation about \( d_{\text{safe}} = 100 m \) before arriving at the off-ramp, therefore the position to start platoon disaggregation is:

\[
4300 - d_{\text{disagg}} - d_{\text{safe}} = 866 m
\]  

(5.7)

This means the five-HDV platoon should start disaggregation 866 m upstream of the off-ramp. At this position, the spacing policy is switched from \( r_0 = 10 m \) to \( r_{\text{large}} = 100 m \). It is worth mentioning that if disaggregation starts too early, the overall fuel efficiency will be decreased. On the contrary, if disaggregation starts too late, it will not be completed before the HDV platoon enters the off-ramp area. After the inter-vehicle distances of platoon are increased to 100 m, the CACC system is turned off and the HDV drivers retake the driving tasks, thus the five-HDV platoon is disaggregated to five individual HDVs.

The simulation outcomes are presented in Figure 5.5. The average speed shown in the figures is the mean of 50 simulation outcomes. Comparing Figure 5.5b and
Figure 5.5: (a) illustration of HDV platoon disaggregation enabled by proposed CACC at a highway off-ramp; (b) evolution of average speed of Lane 1 in no HDV platoon disaggregation scenario; (c) evolution of average speed of Lane 1 in HDV platoon disaggregation scenario; (d) evolution of average speed of Lane 2 in no HDV platoon disaggregation scenario; (e) evolution of average speed of Lane 2 in HDV platoon disaggregation scenario.
5.5c, there is no obvious improvement of the HDV platoon disaggregation over the no-disaggregation scenario. If the HDV platoon does not disaggregate, the average speed of Lane 1 starts to decrease gradually when the HDV platoon approaches the off-ramp area. This is because some passenger cars on Lane 2 behind the HDV platoon have difficulties to find gaps to change to Lane 1, meaning that they need to slow down and wait until the whole HDV platoon has passed the off-ramp area, and then they change from Lane 2 to Lane 1 at a low speed. At the same time, passenger cars on Lane 1 also need to slow down to let the passenger cars on Lane 2 complete the lane changing maneuver. On the contrary, if the HDV platoon disaggregates before entering the off-ramp area, the average speed of Lane 1 decreases rapidly in the beginning of platoon disaggregation due to the deceleration of platoon members for increasing their vehicle gaps. Meanwhile, passenger cars on Lane 2 going to the off-ramp can find gaps to change to Lane 1, which explains that the average speed recovers earlier than the no-disaggregation scenario. In fact, the disaggregation of HDV platoon facilitates the passenger cars on Lane 2, which can be seen in Figure 5.5d and Figure 5.5e. It significantly improves the traffic flow of Lane 2 in terms of average speed. The increase in average speed of Lane 2 can be up to 8% compared with the no-disaggregation case.

5.6 Summary

The proposed framework is applied on three experimental cases. In the first case, the impacts of HDV platoons on traffic flow are investigated. Simulation outcomes show that platooning HDVs is capable of improving traffic throughput, fuel economy and safety of passenger cars. In the second case, the study of HDV platoon formation is presented. It is observed from simulation results that deceleration of front HDV to low speed could delay the platoon formation to a large extent in medium and heavy traffic. Moreover, there is a trade-off between platoon formation time and HDV arrival time. Merging two HDVs into a platoon in medium and heavy traffic will result in late arrivals of both HDVs and might incur additional costs of penalty. In the third case, a constant spacing policy is applied on platoon disaggregation on a two-lane highway, and the outcomes show potential benefits of HDV platoon disaggregation at highway off-ramp. Compared with no platoon disaggregation scenario, disaggregation of HDV platoon before entering the highway off-ramp is capable of improving space mean speeds in high traffic flow rate.

It is worth mentioning that the simulation experiments are carried out with default car-following and lane-changing parameters of VISSIM. For practical application, those parameters need to be calibrated and validated.
Platooning HDVs on highway is capable of improving fuel efficiency and traffic throughput. While extensive research about HDV platooning focuses on implementation and fuel saving, little knowledge has been found on how HDV platooning affects traffic flow. Since the development of HDV platooning is still at its early stage, it is essential to investigate the possible impacts of HDV platooning on traffic before the corresponding technology becomes feasible and reliable. One way to study the effects of HDV platooning is to model and implement its behaviors in microscopic traffic simulation environment. The work presented in this thesis includes the modeling of HDV platoon and operations, modeling of mixed traffic flow speed-density relation and implementation of HDV platoon disaggregation in microscopic traffic simulation.

In Chapter 3, the properties and operations of an HDV platoon are defined, ACC and CACC system are modeled considering the acceleration capability of HDV and driving comfort. An instantaneous fuel consumption model is also implemented to estimate fuel usage according to vehicle dynamics.

In Chapter 4, a three-regime speed-density relation of mixed traffic flow is presented. The impacts of two HDV platoon spacing policies (constant vehicle spacing policy and constant time gap policy) on traffic flow are investigated. Based on the analysis, a mixed constant vehicle spacing and constant time gap policy is proposed in order to combine the advantages from each spacing policy.

Chapter 5 presents a simulation framework for modeling and analysis of HDV platooning. Furthermore, a constant spacing policy is proposed for HDV platoon disaggregation. The simulation framework is applied on three experimental cases. The first case is about the impacts of HDV platooning on traffic flow, the second case is about HDV platoon formation and the third case is the HDV platoon disaggregation at highway off-ramp.

While the current simulation framework supports the impact analysis of HDV platooning, the framework is still under development for comprehensive evaluation of platooning strategies in different scenarios. For practical application, both the car-following behaviors of passenger vehicles and the macroscopic speed-density relation need to be calibrated and validated, which will be part of the future work.
Another important task of future research is to include the communication delay in the implementation of the CACC algorithm and test its robustness. Furthermore, how HDV platoon formation affects passenger vehicles and vice versa will also be analytically studied.

Moreover, the disaggregation and reformation of HDV platoons not only depend on traffic flow rate but also depend on the distance between two consecutive off-ramps. If two consecutive off-ramps are very near, e.g., less than 5km, the HDV platoon might split into single HDVs at the first off-ramp and those HDVs keep operating individually by the drivers. The HDV platoon disaggregation and reformation will be further investigated considering deployment of road facilities in the future work.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITS</td>
<td>Intelligent Transportation Systems</td>
</tr>
<tr>
<td>HDV</td>
<td>Heavy-Duty Vehicle</td>
</tr>
<tr>
<td>V2V</td>
<td>Vehicle-to-Vehicle</td>
</tr>
<tr>
<td>V2I</td>
<td>Vehicle-to-Infrastructure</td>
</tr>
<tr>
<td>ACC</td>
<td>Adaptive Cruise Control</td>
</tr>
<tr>
<td>CACC</td>
<td>Cooperative Adaptive Cruise Control</td>
</tr>
<tr>
<td>CVS</td>
<td>Constant Vehicle Spacing</td>
</tr>
<tr>
<td>CTG</td>
<td>Constant Time Gap</td>
</tr>
</tbody>
</table>


