DOCTORAL THESIS IN ELECTRICAL ENGINEERING
STOCKHOLM, SWEDEN 2016

Fuel-Efficient Heavy-Duty Vehicle Platoon Formation

KUO-YUN LIANG

KTH ROYAL INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING

KTH Electrical Engineering

Fuel-Efficient Heavy-Duty Vehicle Platoon Formation

KUO-YUN LIANG

Doctoral Thesis
Stockholm, Sweden 2016

KTH School of Electrical Engineering
TRITA-EE 2016:068 Department of Automatic Control
ISSN 1653-5146 SE-100 44 Stockholm
ISBN 978-91-7729-004-9 SWEDEN

Akademisk avhandling som med tillstånd av Kungliga Tekniska högskolan framlägges till offentlig granskning för avläggande av teknologie doktorsexamen i elektro- och systemteknik fredagen den 10 juni 2016 klockan 14:00 i sal Q2, Kungliga Tekniska högskolan, Osquldas väg 10, Stockholm.

Tryck: Universitetsservice US AB

Abstract

There is a need for intelligent freight transport solutions as the demand for road freight transport is continuously increasing while carbon footprint needs to be significantly reduced. Heavy-duty vehicle (HDV) platooning is one potential solution to partially mitigate the environmental impacts as well as to reduce fuel consumption, improve traffic safety, and increase traffic throughput on congested highways. However, as each goods transport has different origin, destination, and time restriction, it is not evident how the HDVs, carrying the goods, can fully utilize the platooning benefits during individual transport missions. Thus, there is a need to systematically coordinate scattered vehicles on the road to form platoons in order to maximize the benefits of platooning.

This thesis addresses the problem of merging scattered HDVs to form platoons in traffic. The focus is to investigate fuel-efficient coordination strategies where all the HDVs, driving on the road, act to form platoons. When a follower HDV drives faster to catch up with another HDV, it consumes more fuel during the catch up but that additional cost is regained if the vehicles platoon long enough. When a lead HDV slows down to aid the platoon formation, it loses transport time that needs to be compensated by either driving faster once the platoon is formed or when driving alone after the platoon has split. Additionally, surrounding traffic affects the platoon formation in form of delayed merging.

The first contribution of the thesis is the investigation of how and when a pair of HDVs should form platoons given their positions, speeds, and destinations. We formulate the problem as an optimization problem and we derive a break-even ratio that describes how far a vehicle should check for possible vehicles to platoon with. The second contribution is to consider traffic during the merging maneuver when forming a platoon. Traffic may disturb and delay when the two HDVs will form a platoon and such delay leads to less fuel saved than initially planned. Based on shockwave and moving bottleneck theories, we derive a merge distance predictor that calculates where the HDVs will merge depending on the traffic condition. We first validate this in a microscopic traffic simulation tool. Then, we also conduct an experimental study during one month on a public highway between Stockholm and Södertälje to evaluate the merging maneuver with different traffic densities. Lastly, we use vehicle probe data obtained from a fleet management system to investigate the potential fuel savings from coordination in a larger road network. The number of vehicles platooning can be increased significantly through coordination compared to today.

The main result of this thesis indicates that merging HDVs to form platoons leads to great fuel savings and that there are significant potentials to do so in reality. Traffic needs to be considered in order to guarantee that the HDVs save fuel and deliver the goods in time. Furthermore, the earlier the transport assignment is planned ahead of time, the more opportunities there are to collaborate with other fleet owners to reduce the fuel consumption.

Sammanfattning

Det finns behov av intelligenta godstransportlösningar då efterfrågan av godstransporter ständig ökar samtidigt som koldioxidutsläppen måste minskas. Fordonståg (även kallat kolonnkörning eller på engelska *platooning*) är en möjlig lösning för att delvis minska på miljöpåverkan, samtidigt som det minskar på bränsleförbrukningen, ökar trafiksäkerheten och förbättrar trafikflödet. Då många godstransporter har olika start- och slutdestinationer och tidsfrister, är det inte självklart hur man ska bilda fordonståg och utnyttja konceptet fullt ut. Det behövs en systematisk metod att koordinera utspridda fordon för att forma fordonståg för att kunna utnyttja det till fullo.

I denna avhandling studeras problemet att koordinera utspridda lastbilar för att bilda fordonståg i trafiken. Fokuset på avhandlingen är att undersöka bränsleeffektiva koordineringsstrategier där alla lastbilar medverkar och hjälper till att forma fordonståg när de redan kör på vägen. En lastbil som kör snabbare för att köra ikapp förbrukar mer bränsle, men den förlusten kan återfås om man kör i fordonståg tillräckligt länge. En lastbil har också möjligheten att sakta ner för att låta de bakre lastbilarna köra ikapp, men då förlorar den transporttid vilket måste kompenseras genom att köra gemensamt snabbare när fordonståget bildas eller efter att fordonståget splittras då lastbilen kör ensam. Dessutom finns det andra trafikanter som kan påverka koordineringen i form av förseningar.

Det första bidraget av avhandlingen är en undersökning om hur och när två lastbilar ska forma fordonståg med avseende på deras positioner, hastigheter och destinationer. Problemet är formulerat som ett optimeringsproblem och vi introducerar en brytpunkt som beskriver inom vilket avstånd ett fordon ska se för att hitta möjliga kandidater att köra i fordonståg med. Det andra bidraget är att undersöka hur trafiken påverkar koordineringen av lastbilarna. Trafiken kan störa och även försena de två lastbilar som försöker bilda ett fordonståg, vilket innebär en minde bränslebesparing än planerat. Vi tar fram en modell för att prediktera när fordonståg kommer att bildas där metoden bygger på fundamentaldiagram och chockvågsteorier. Vi validerar modellen med hjälp av en mikroskopisk trafiksimuleringsmodell. Vi utför även experiment under en månadsperiod på motorvägen mellan Stockholm och Södertälje för att utvärdera sammanslagningen under olika trafikförhållanden. Till sist använder vi positionsdata från ett fleet managementsystem för att undersöka den potentiella bränslebesparingen genom koordinering i ett störrre vägnätverk. Antalet lastbilar som kör i fordonståg kan öka drastiskt genom koordinering jämfört med nuläget.

Slutsatsen av avhandlingen är att koordinering av lastbilar för att bilda fordonståg leder till stora bränslebesparingar och att det finns möjligheter att genomföra det i praktiken. Det viktiga är att betrakta trafiken för att garantera att lastbilarna sparar bränsle samt att godsen levereras i tid. Dessutom, ju tidigare man planerar sina transporter, desto mera möjligheter finns det att samarbeta med andra åkerier för att minska på bränsleförbrukningen.

To my family

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 main advisor Karl Henrik Johansson at KTH for your excellent guidance, enthusiasm, and energy. Many thanks to my co-advisor Jonas Mårtensson at KTH for your insights, support, and great dedication. Then, I would like to thank Tony Sandberg at Scania for giving me the opportunity to pursue a Ph.D. A heartfelt thanks goes to my supervisor Henrik Pettersson at Scania for his enthusiasm, unbelievable effort, and endless support from the very beginning to the very end and at all times throughout this work. I would like to thank Magnus Adolfson at Scania for your dedication and support. I would like to thank my manager Lars Hjorth for your enthusiastic support. I would like to show my deepest gratitude to Assad Alam at Scania for being a great inspiration to pursue my Ph.D., for the great mentoring and fruitful discussions we had during your Ph.D., and the continuously great support after your Ph.D.

Many thanks go to Jeffrey Larson, Qichen Deng, and Farhad Farokhi for our successful collaborations. I am grateful to Bart Besselink, Håkan Terelius, Patricio E. Valenzuela, Pedro Lima, Pedro Peirera, and Qichen Deng for proofreading parts of the manuscript. Thanks to all former and current members of my steering committee, Tony Sandberg, Pär Wallin, Jan Danielsson, Magnus Adolfson, Henrik Pettersson, Karl H. Johansson, and Jonas Mårtensson, for the valuable inputs and keeping this project on the right direction. Big thanks to Junchen Jin, Mats Olsson, Ismail Izgi, Christoffer Norén, Sami Freiwat, Per Sahlholm, Mengxi Wu, Magnus Selldén, Jonny Andersson, Stanislav Vovk, Johan Brodin, Mattias Nilsson, Johan Skynäs, Ellinore Andersson, and Andreas Högger for helping me out with my platoon formation experiments.

I am very grateful to all my present and former colleagues in the REP department at Scania for providing such an inspiring and positive work environment. Make sure Scania becomes the leader within automated transport solutions! Thanks for all the Master's students I have supervised for your refreshing ideas and discussions. I would also thank Magnus Hahn for establishing the Ph.D. student network at Scania.

The participants of the transportation discussion group at KTH deserve great thanks for the valuable insights and discussions. Many gratitudes to all my office mates and colleagues at the department of automatic control at KTH for the inspiring work environment. Special thanks to the administrators Anneli, Gerd, Hanna, Karin, Kristina, and Silvia for all the assistance with any issue I have had.

The research presented in this thesis has been financed by Vinnova (FFI) and by Scania CV AB. The financial support is appreciated.

Last but not least, I would like to specially thank my parents for your patience, love, support, and believing in me throughout my life. Without you, I would not have come this far.

Kuo-Yun Liang
Stockholm, May 2016.

Contents

Chapter 1

Introduction

"There are only two mistakes one can make along the road to truth; not going all the way, and not starting."
BUDDHA

The demand for freight transport is increasing as the world economy grows. Most noticeable increase in the transport sector is the road freight transport, which has increased with over 33 % between 1995 and 2013 (European Commission, 2015). The increased transport activity leads to increased fuel consumption and more greenhouse gas emissions. To tackle this, research and development in intelligent transportation systems (ITS) has grown rapidly. One important innovation within the field is an integrated goods transport system based on heavy-duty vehicle (HDV) platooning, see Figure 1.1. A system that integrates central office, fleets of HDVs, infrastructures, and other transport modes to provide and obtain information to transport goods seamlessly and fuel efficiently. The concept of HDV platooning is to form a convoy of HDVs driving close behind each other in order to reduce fuel consumption for the follower vehicles. This concept opens up many challenges that need to be tackled. For example, it is required to develop control algorithms that utilize the benefit of platooning as much as possible and without endangering the safety of the vehicles. Protocols and standardizations must be set to avoid miscommunications and conflicts between systems of different manufacturers. A better understanding on how other road users and surrounding traffic affect and get affected by HDV platooning, through studies, is necessary. New legislations to adopt platooning need to be considered. Coordination strategies to form platoons need to be developed to increase the incentives during low market penetration rate.

In this thesis, we look into detail of how HDVs can coordinate and form platoons when the vehicles are already driving on the roads in order to reap the benefit of platooning. This requires intelligent strategies where HDVs need to adjust their speeds to form platoons. This also includes interaction with other road users and surrounding traffic before executing a platoon formation.

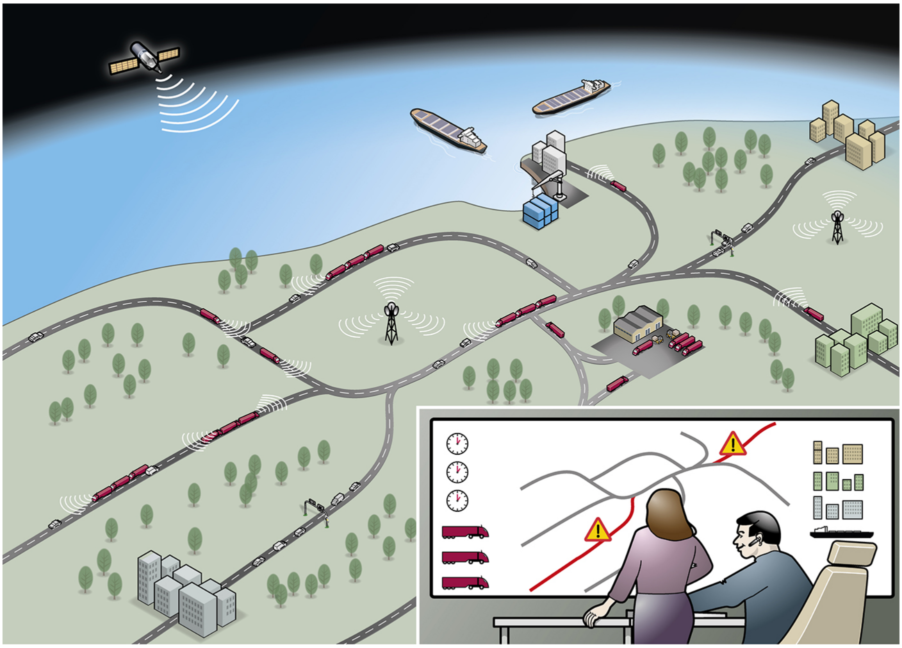


Figure 1.1: An illustration of a future integrated goods transport system. A central office, such as a fleet management system, assigns each vehicle with a transport mission. Each transport mission is scheduled to pick up and deliver goods with minimum waiting time to utilize each vehicle to the fullest. Additionally, the central office systematically coordinates the routes of each vehicle to platoon as much as possible in order to maximize the fuel benefits of platooning. The infrastructures aid both the vehicles and central office in real time by providing information regarding road incidents, road constructions, road tolls, among others in order to minimize disturbances and transport costs. Furthermore, each vehicle acts as an information probe to enhance the information flow.

1.1 The need for fuel-efficient freight transports

Freight transport is highly correlated with the world economy. A clear example is the financial and economic crisis in 2009, which led to a lowered transport activity in 2010 compared to 2005 (Eurostat, 2015). As the world economy is expected to grow, so will the demand for freight transport. European Commission (2013) did a trend analysis to year 2050, with 2013 as a reference scenario and predicted a total growth of 57 % between 2010 and 2050. As a reference, over 2.4 trillion[1] tonne[2]-kilometer of inland freight was transported in 2013, of which 71.9 % was road transport (European Commission, 2015). To support this large amount of transported goods on road,

[1] 1 trillion = 10^{12}
[2] 1 tonne [t] = 1000 kg

more than 1.7 million HDVs were used in the EU-15 countries in 2013 (ACEA, 2014). An increased demand in transport sector leads to higher greenhouse gas and CO_2 emissions from fossil fuel combustion. In the EU-28 countries, the transport sector constituted to more than 25 % of the total greenhouse gas and CO_2 emissions in 2012. Within the transport sector, the road freight transport is dominant with more than 70 % of the emissions (European Commission, 2015). Similar numbers are presented for the emissions worldwide by the International Transport Forum (ITF, 2008). With predictions of rising demands for freight transport, the European Commission sets goals towards a more competitive and resource-efficient transport system. The key goal is to cut the transport emissions by 60 % by 2050 in order to reduce the environmental impacts to avert climate change and maintain a sustainable environment (European Commission, 2011). Therefore, the need of reducing the environmental impacts of transport are inevitable.

The transport sector is facing a great challenge in order to reach the goal of cutting the transport emissions by 60 % by 2050 with a predicted growth of transport activity of 57 % (European Commission, 2013). One of the proposed solutions is to shift half of long distance, over 300 km, freight transports from road to rail and waterborne transports. However, this is not sufficient to reach the key goal as some of the emission problems will just be pushed over to another sector. Statistics show that despite the amount of road transported goods in tonne-kilometer have increased by 1.6 % in 2013 compared to previous year, the number of HDVs used has decreased with 1.9 % (0.3 % decrease for all type of trucks in total) the same year (ACEA, 2014; European Commission, 2015). This indicates a smarter logistics and transport planning, such as less empty driving trucks. This is a small, yet necessary, step towards a sustainable environment.

To achieve the immense emission cuts in the road freight transports, both HDV manufacturers and fleet owners are facing difficult challenges. Not only do they need to comply to legislations and policies, but they also need to make transports more fuel efficient. Figure 1.2 shows the main costs for a fleet owner (Scania CV AB, 2014). Over a third of a fleet owner's costs corresponds to fuel expended to drive HDVs. Driver salaries are represented by the second third of the costs. The last third is divided into smaller costs such as buying the vehicles, repair and maintenance, replacing worn out tires, and administration costs. In general, a fleet owner owns several HDVs that travel over 200 000 km yearly. With an average fuel consumption of 0.3 liter/km and the current diesel fuel price in Sweden, the fuel cost for a single HDV amounts of about € 75 thousand per year. Hence, the fleet owners are extremely sensitive to fuel price and reducing even a small per cent of fuel has a substantial impact.

Vehicle manufacturers have put enormous research efforts to improve combustion engines to the extent that it is difficult to noticeably improve them further. Alternative approaches on reducing greenhouse gas emissions have been focused on electric cars, hybrid vehicles, alternative renewable fuels such as solar cells. Most of these approaches require a reconstruction of the powertrain, which is costly. However, the development of information and communication technology (ICT) has grown

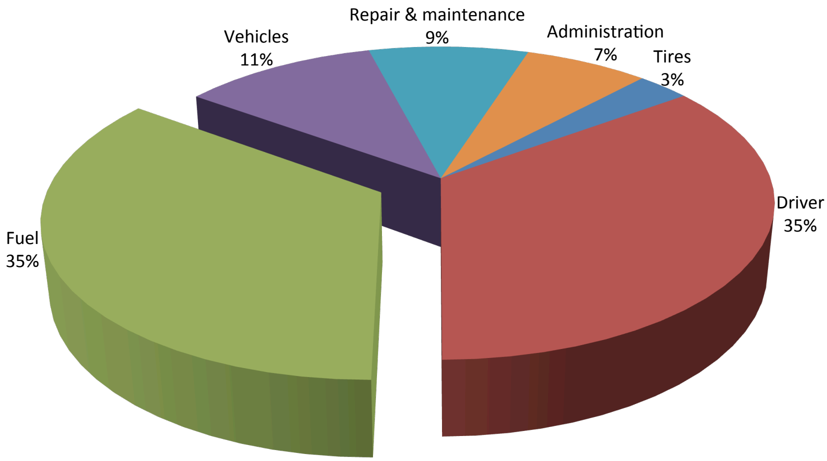


Figure 1.2: Costs for European fleet owners (Scania CV AB, 2014), where the fuel ratio corresponds to more than a third of a fleet owner's costs. The fuel cost ratio is similar for life-cycle costs of European HDVs over a 4 year period (Schittler, 2003).

rapidly, giving excellent opportunity to tackle the emission challenges through novel integrated ITS solutions. By enabling a vehicle to act as an information probe, new possibilities are created. An early example is the use of fleet management system (FMS). The FMS enables a fleet operator to analyze and monitor the operation and condition of each owned vehicle, for instance the amount of coasting, idling, braking, fuel consumption, speed, and position of the vehicle. This allows the fleet owner to cut costs through driver feedback, driver training, driver reward systems, or transport reroutings that leads to lower fuel consumption.

HDV platooning serves as a possible solution to reduce fuel consumption and exhaust gas emissions, see Figure 1.3. Platooning is to form a string of HDVs driving close behind each other. This introduces a slipstream effect for the follower vehicle, caused by an aerodynamic drag reduction that occurs behind a traveling vehicle, and reduces the overall resistive force acting on a vehicle, see Figure 1.4. Thus, the fuel consumption is reduced for the follower vehicle. The platooning concept is not new. The idea of utilizing reduced air drag has been observed in other fields such as professional bicycling, speed skaters, and high speed car racing. Professional truck drivers are also aware of this effect. However, it is not allowed to tailgate another vehicle due to safety reasons, reducing the possibilities to mitigate the exhaust emissions. A general rule of thumb is to have three seconds gap to the vehicle in front to maintain a safe distance, mainly because the need for the driver to react in case of an accident ahead. However, with the advancement in technology, it is becoming possible to drive very close behind another vehicle without endangering the safety. Additionally, by packing vehicles close to each other, the total road capacity is increased.

Figure 1.3: Four HDVs platooning with close intermediate distance. The air drag is reduced for the follower vehicles, which reduces the fuel consumption. Through wireless communication, the vehicles are able to act as a unit by sending information, such as speed, position, upcoming intentions to each other. (Photo courtesy of Scania CV AB)

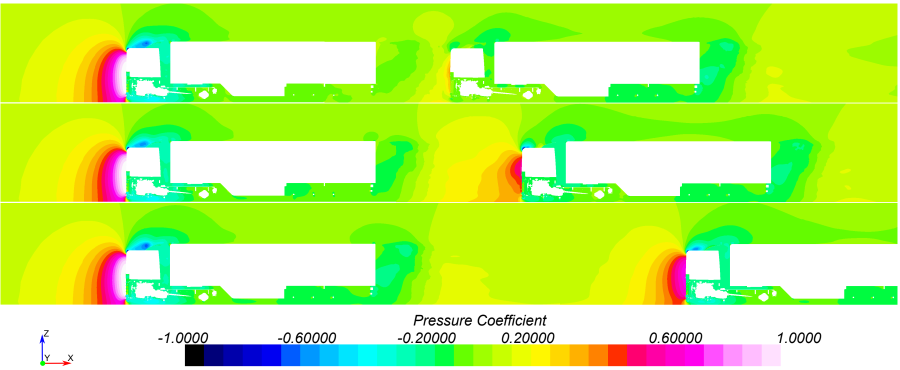


Figure 1.4: An illustration of air pressure that two HDVs experience in a platoon with different intermediate distances. The follower vehicle experiences less pressure as it gets closer to the lead vehicle, resulting in lowered fuel consumption. (Image courtesy of Norrby (2014).)

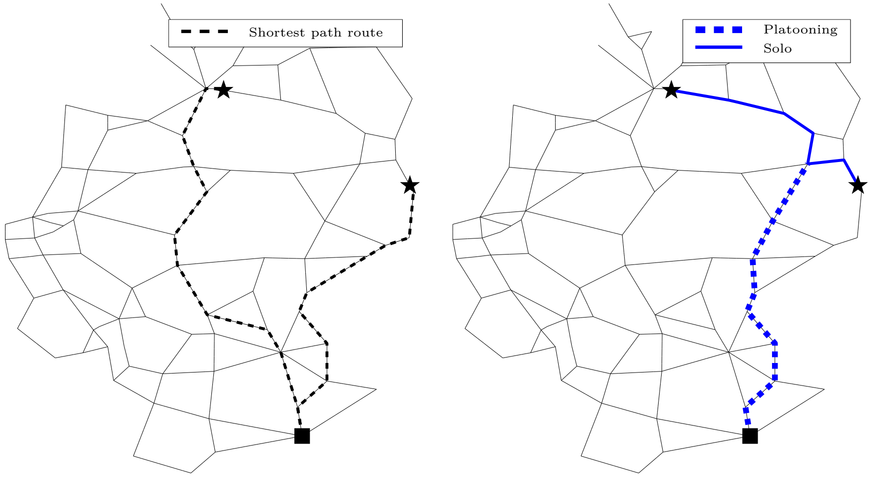
The aerodynamic drag is generally stronger at higher speeds making it an excellent opportunity to platoon on highways. For an HDV on a typical Swedish road, the aerodynamic drag constitutes 23 % of the total force acting on an HDV at highway speed (Sandberg, 2001). Thus, reducing the aerodynamic drag a few per cent by platooning has a noticeable impact on the fuel savings. The Swedish National Road and Transport Research Institute (VTI) reported that more than 70 % of total traveled distance for HDVs, registered in Sweden, are on highways or on roads with speed limits of 90 km/h and above (VTI, 2008). Hence, HDV platooning has great opportunities and potentials to address the issue of safety, traffic congestion, fuel consumption, and exhaust emissions. Experimental studies show that the fuel consumption can be reduced by 15 % (Davila, 2013).

Fleet owners own several HDVs and therefore it is a great opportunity to form platoons within their own fleet to reduce the fuel consumptions. However, a fleet owner has many different transport assignments making it difficult to platoon for any longer stretches. Each assignment might have different pickup location, destination, route, and timing. It may also not be profitable for a fleet owner to only take transport assignments of same type to justify platooning. Thus, by combining the concept of platooning and FMS brings excellent opportunity to develop an integrated goods transport system. The system considers collaborations between other fleets to sync and reroute assignments to utilize platooning in order to address the issue of traffic congestion, fuel consumption, and emissions.

1.2 Control challenges for fuel-efficient HDV platooning

There are many challenges when it comes to realizing HDV platooning and making freight transports more fuel efficient through platooning. We discuss a few challenges regarding control from different aspects. One challenge is to develop vehicle control algorithms that govern the vehicle speed in order to utilize the reduced air drag as much as possible in a platoon. The control algorithm needs to be able to handle and attenuate disturbances such that they do not propagate throughout the platoon, this is also known as string stability. The role of the control algorithm is to (virtually) couple the vehicles in the platoon such that the vehicles move as a unit, despite heterogeneity. As the control algorithm should control the vehicles to drive as close as possible to maximize the fuel savings, the safety of the vehicles need to be addressed. The closer the inter-vehicular distance is between the vehicles, the more aggressive the control has to be in order to ensure safety, i.e., more acceleration and braking, which may not be fuel efficient. As the follower vehicles experience reduced air drag, this may affect the braking capability of the vehicles negatively, as it will require more braking power in a platoon than if the vehicles were driving alone. For two identical HDVs, the relative distance can go down to as low as 2 m and still avoid collision when both vehicles brake harshly (Alam et al., 2014). Preview information of the road topography can further enhance the performance of the control algorithm, both in terms of fuel efficiency and safety (Alam et al., 2013; Turri et al., 2015).

Another control challenge is routing for HDV platooning. Today, there exists sophisticated navigation systems computing the path from one location to another



(a) **(b)**

Figure 1.5: Two HDVs' shortest paths compared to the fuel-efficient path when platooning is considered. The square indicates the starting location and stars the destination.

based on digital maps. A digital map is represented as a network with nodes and edges, where each edge is represented by a cost. The most commonly used algorithm for navigation purpose is based on the shortest path algorithm, also known as Dijkstra's algorithm, which finds the lowest total cost from one node to another. There are different kinds of routing depending on what the edge costs represent, for example the shortest distance path, where the edge cost is the distance or the shortest time path (if the speed limits of the road is known), where the edge cost is the time it takes to travel the edge based on distance and speed. Routings can also be based on the most fuel efficient path, known as eco-routing (Dhaou, 2011), where the edge cost is based on a vehicle model and road information to estimate the fuel cost to travel between the nodes. These are mainly based on static information stored in the digital map. However, more advanced routings can also consider dynamic information such as traffic to enhance the shortest time path route. HDV platooning can improve the fuel-efficient path routing. Figure 1.5 illustrates an example where the most fuel-efficient path when considered platooning is not the fuel-efficient path for the individual vehicles (Larson et al., 2015). Routing with HDV platooning is a great challenge as the vehicles are moving at all times in the network and where the traffic needs to be taken into account. Therefore some coordination between vehicles need to be considered.

A third great control challenge for HDV platooning is transport planning. In order to maximize the fuel savings through platooning, HDVs from different fleet companies need to cooperate as there is only a limited fuel saving potential within their own fleet. Additionally, each HDV has different transport assignment, as they deliver goods from different locations to different destinations and have different timings, making it not evident how platooning should be executed. Therefore, transport planning with platooning includes coordination, routing, and schedule planning to match with other HDVs from other fleet companies. An example is to coordinate HDVs to match merging points and times, hence each vehicle individually adjust their speeds to match the constraint (van de Hoef et al., 2015*b*). As there is a cost associated with cooperation with other fleet companies, in form of time, fuel loss (as the lead HDV in the platoon might not save any fuel), or subscription fee for the service, the fleet owners need incentives for collaboration. Different strategies and cooperation patterns might benefit one type of fleet company more than another, for instance, large fleets compared to small fleets, or hourly transport assignments compared to weekly assignments (Farokhi et al., 2015).

1.3 Problem formulation

Consider a platooning scenario of a single HDV and a platoon of three HDVs as illustrated in Figure 1.6. The routes of the vehicles are partially overlapping and their timing constraints would allow them to be coordinated so that a larger platoon can be formed. A more general case involves two platoons forming a larger platoon (where a single vehicle is also considered as a platoon). The assumption is that the platoons are already driving on the highway with some initial distance between them. The remaining part of the vehicles' journeys until the vehicles reach their final destinations can be split into three phases. The first is the merging phase where the vehicles change their velocities in order for the rear platoon to catch up with the front platoon. Changing the velocity is associated with a cost. The rear platoon can speed up, which increases the resistive force and leads to a higher fuel consumption, or the front platoon can slow down, which either leads to a delayed transport delivery or that the time loss has to be compensated later by an increased velocity. The second phase is where the platooning occurs. The trailing vehicles experience a reduced air drag, which reduces the fuel consumption significantly. Also, the first vehicle may experience some air drag reduction. If the vehicles have different destinations or deadlines, they need to split up at some point, after which they drive solo again. In this third phase, the vehicles could make up for previously lost time, if necessary.

To motivate a platoon merge, the expected reward from platooning must be sufficiently larger than the expected cost of coordination. The likelihood of successful merge could also be evaluated and considered in the decision, since there is an initial cost that is only payed back if the merging is actually successful. As the HDVs are not the sole vehicles driving on the road, other road users have to be considered before executing a platoon merge, as surrounding traffic may effect when the HDVs will merge. In light traffic conditions, it is reasonable to assume that the HDVs, who

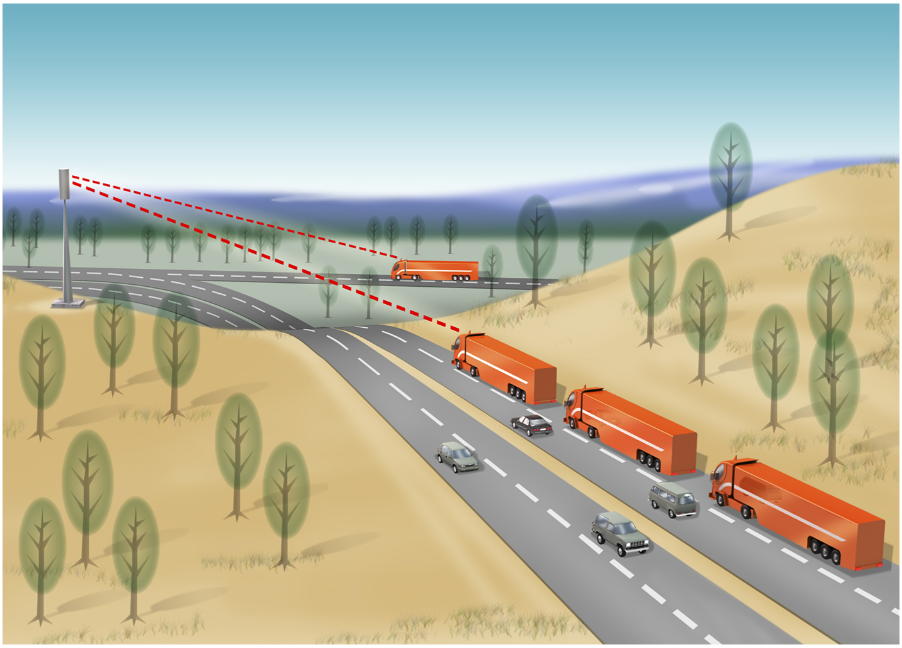


Figure 1.6: A platooning opportunity where a single HDV has the possibility to merge with three-vehicle platoon after a road intersection. If the additional cost associated by changing the velocity of the single vehicle in order to merge the platoon is significantly less than the expected reward from platooning, then the platoon merge is carried out. The operation is supported by vehicle-to-infrastructure communication.

normally drive slower than the average traffic flow, can vary their speed freely and that the merging point can be accurately predicted. In heavy traffic, on the other hand, the average traffic speed is reduced and the HDVs travel at the same speed as the rest of the traffic, leaving no room for closing the gap and forming a platoon. In medium traffic, it is still possible to adapt the speed of the HDVs, but there is significant interference with other vehicles, which could affect the time it takes to merge. In particular, the front HDV is likely to cause a small congestion zone with vehicles that drive slower than the average traffic flow. These vehicles may delay the merging point so that the reward of platooning is decreased and maybe merging is no longer beneficial at all.

The problem that we solve in this thesis is to decide when it is fuel efficient for a pair of HDVs, traveling on a highway, to form a platoon without delaying their transports and considering possible interferences from surrounding traffic. The fuel cost of merging HDVs combined with the fuel cost of platooning should be sufficiently lower than the fuel cost of each HDV driving separately in order to consider forming a platoon. We first model the forces produced by the powertrain and the environmental forces acting on an HDV in motion. In a platoon, the external air drag force is reduced for the trailing vehicles, which leads to less force required to propel the vehicles forward. Then, we address the problem by setting it up as an optimization problem, where we minimize the fuel cost based on the vehicles' speeds without considering any effects from surrounding traffic. Furthermore, we analyze how traffic may affect the platoon formation in terms of delays. The traffic can be modeled on a macroscopic level as traffic flows, assuming that traffic behaves as flow streams. The model describes the relation between traffic density, traffic flow, and traffic speed. The HDVs are described as individual entities moving in the flow. We compare the results with a microscopic traffic simulation and with real experiments conducted between Stockholm and Södertälje.

1.4 Thesis outline and contributions

In this section, we outline the contents of the thesis and the contributions.

Chapter 2: Background

This chapter briefly describes ITS and key technologies that enable ITS. Furthermore, we describe one of the applications of ITS, namely advanced traffic management systems that monitor traffic and provide drivers with realtime traffic information. Lastly, we discuss related work regarding vehicle platooning and platoon formation.

Chapter 3: Modeling

In this chapter, we describe the vehicle and fuel models that our decisions for platoon formation are based on. We also present a traffic model enabling a simple estimation of where the HDVs will merge depending on the traffic condition. Lastly, we describe a system architecture from the transport mission down to the platoon control level in order to overview how they are connected. This chapter is partly based on Section III of the publication

B. Besselink, V. Turri, S. van de Hoef, K.-Y. Liang, A. Alam, J. Mårtensson, and K. H. Johansson. Cyber-physical control of road freight transport. *Proceedings of the IEEE*, 104(5) (2016).

Chapter 4: Fuel-efficient cooperative platoon formation

In this chapter, we first analyze how environmental factors affect a coordination decision. Based on the results, we formulate an optimization problem on how to fuel efficiently form a platoon of two HDVs and without delaying their transports. We expand the idea further to cooperatively form platoons with several HDVs, where their routes partially overlap. Lastly, we evaluate the results through a validated simulation model from Scania that produces reliable results and replicates real-life behavior of an HDV. This chapter is based on the publications

K.-Y. Liang, J. Mårtensson, and K. H. Johansson. Heavy-duty vehicle platoon formation for fuel efficiency. *IEEE Transactions on Intelligent Transportation Systems*, 17(4) (2016*b*),

K.-Y. Liang, J. Mårtensson, and K. H. Johansson. When is it fuel efficient for a heavy duty vehicle to catch up with a platoon? In *7th IFAC Symposium on Advances in Automotive*. Tokyo, Japan (2013).

Chapter 5: The influence of traffic on platoon formation

In this chapter, we study how surrounding traffic might influence two HDVs trying to form a platoon. Using a macroscopic traffic model, we describe shockwaves and moving bottlenecks. An HDV often drives slower than the surrounding traffic, thus it acts as a bottleneck that throttles the traffic throughput as it moves along the highway. Based on this, we estimate when two HDVs will merge depending on the initial gap between the HDVs, the desired speeds, and the current traffic condition. Lastly, we simulate two HDVs trying to form a platoon in different traffic conditions on the traffic simulation tool VISSIM. This chapter is based on the publication

K.-Y. Liang, Q. Deng, J. Mårtensson, X. Ma, and K. H. Johansson. The influence of traffic on heavy-duty vehicle platoon formation. In *IEEE Intelligent Vehicles Symposium*. Seoul, South Korea (2015).

Chapter 6: Experimental evaluation of traffic influence

In this chapter, we present an experimental evaluation of traffic influence on two HDVs merging in practice. With the help of Stockholm's motorway control system (MCS), we obtain traffic data to analyze the traffic conditions during our experiment. The experiment are conducted during rush hours for the whole month of November 2015 to capture different traffic conditions as well for different speeds for the HDVs. We evaluate when the HDVs merged and how often we had passenger cars in between the HDVs that persistently kept driving behind the lead vehicle. This chapter is based on the publications

K.-Y. Liang, S. van de Hoef, H. Terelius, V. Turri, B. Besselink, J. Mårtensson, and K. H. Johansson. Networked control challenges in collaborative road freight transport. *European Journal of Control* (2016*c*). To appear,

K.-Y. Liang, J. Mårtensson, and K. H. Johansson. Experimental evaluation of platoon formation on E4/E20 highway (2016*a*). In preparation.

Chapter 7: Fuel-potential savings evaluated through sparse probe data

In this chapter, we analyze sparse vehicle probe data that we obtained from Scania's FMS. We use simple map-matching and path-inference algorithms to infer the path the vehicles have taken, in order to investigate how many vehicles are platooning and their fuel savings. Furthermore, we introduce a few simple coordination schemes that increase both the fuel savings and the number of platoons several times. This chapter is based on the publication

K.-Y. Liang, J. Mårtensson, and K. H. Johansson. Fuel-saving potentials of platooning evaluated through sparse heavy-duty vehicle position data. In *IEEE Intelligent Vehicles Symposium*. Dearborn, Michigan, USA (2014).

Chapter 8: Conclusion and future outlook

A summary of this thesis and possible future research directions are presented in this chapter.

Other publications

The following publications are not covered in this thesis but they inspired some of the contents and are highly relevant for HDV platooning and platoon formation.

K.-Y. Liang, A. Alam, and A. Gattami. The impact of heterogeneity and order in heavy duty vehicle platooning networks. In *IEEE Vehicular Networking Conference*. Amsterdam, The Netherlands (2011),

J. Mårtensson, A. Alam, S. Behere, A. Khan, J. Kjellberg, K.-Y. Liang, H. Pettersson, and D. Sundman. The development of a cooperative heavy-duty vehicle for the GCDC 2011: Team Scoop. *IEEE Transactions on Intelligent Transportation Systems*, 13(3) (2012),

J. Larson, C. Kammer, K.-Y. Liang, and K. H. Johansson. Coordinated route optimization for heavy-duty vehicle platoons. In *Proceedings of the 16th International IEEE Annual Conference on Intelligent Transportation Systems*. Hague, The Netherlands (2013),

J. Larson, K.-Y. Liang, and K. H. Johansson. A distributed framework for coordinated heavy-duty vehicle platooning. *IEEE Transactions on Intelligent Transportation Systems*, 16(1) (2015),

F. Farokhi, K.-Y. Liang, and K. H. Johansson. Cooperation patterns between fleet owners for transport assignments. In *IEEE Conference on Control Applications*. Sydney, Australia (2015).

Contributions by the Author

The order of the authors' names reflect the workload, where the first author had the main contribution. An exception is the publication Mårtensson et al. (2012), where the first author was the corresponding author and all other authors were in alphabetical order and the contribution were divided into the authors' respective fields. In all other publications, the thesis author participated actively in the discussions and derivations of the theories and results, as well as in the paper writing.

Patents

Along with academic publications, several Swedish and international patent applications have been filed during the course of this work.

A. Alam, A. Gattami, and K.-Y. Liang. *Metod i samband med fordonståg, och ett fordon som använder metoden*. Swedish patent grant number SE 537185 (filed 2011),

A. Alam and K.-Y. Liang. *Anordning och förfarande för utvärdering av framfart inbegripande fordonstågsformering*. Discontinued, Swedish patent application number SE 1251407-1 (filed 2012),

A. Alam, K.-Y. Liang, and H. Pettersson. *Metod och system för hantering av hinder för fordonståg*. Swedish patent grant number SE 537603 (filed 2013*g*),

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Metod och system för gemensam körstrategi för fordonståg*. Swedish patent grant number SE 537482 (filed 2013*c*),

A. Alam and K.-Y. Liang. *Device and method for the evaluation of progress comprising the formation of platoons*. International application number PCT/SE13/051382 (filed 2013*b*),

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Metod och system för organisering av fordonståg*. Swedish patent grant number SE 537598 (filed 2013*f*),

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Ett system och en metod för korrigering av kartdata och positionsdata för fordonståg*. Swedish patent grant number SE 537469 (filed 2013*b*),

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Metod och system för gemensam körstrategi för fordonståg*. Swedish patent grant number SE 537618 (filed 2013*e*),

A. Alam, K.-Y. Liang, and H. Pettersson. *System och metod för att reglera fordonståg med en gemensam positionsbaserad körstrategi*. Swedish patent grant number SE 537985 (filed 2013*k*),

A. Alam, K.-Y. Liang, and H. Pettersson. *System och metod för att reglera ett fordonståg med två olika körstrategier*. Swedish patent grant number SE 537466 (filed 2013*j*),

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Metod och system för gemensam körstrategi för fordonståg*. Swedish patent grant number

SE 537578 (filed 2013*d*),

A. Alam and K.-Y. Liang. *Device and method for the evaluation of progress comprising the formation of platoons*. European application number 13862945.6 (filed 2013*a*),

A. Alam and K.-Y. Liang. *Metod, anordning och system innefattande anordningen för att stödja skapandet av fordonståg*. Swedish patent application number SE1450433-6 (filed 2014*b*),

A. Alam and K.-Y. Liang. *Method, device and system for supporting the formation of platooning*. International patent application number PCT/SE15/050419 (filed 2014*a*),

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Method and system for handling of obstacle for vehicle platoon*. International patent application number PCT/SE2014/051111 (filed 2014*e*),

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Method and system for common driving strategy for vehicle platoon*. International patent application number PCT/SE2014/051112 (filed 2014*d*),

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *A system and a method for correction of map data and position data for a vehicle platoon*. European patent application number 14848197.1 (filed 2014*a*),

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *A system and a method for correction of map data and position data for a vehicle platoon*. International patent application number PCT/SE2014/051114 (filed 2014*b*),

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Method and system for common driving strategy for vehicle platooning*. International patent application number PCT/SE2014/051117 (filed 2014*c*),

A. Alam, K.-Y. Liang, and H. Pettersson. *System and method relating to vehicle platooning*. International patent application number PCT/SE2014/051119 (filed 2014*h*),

A. Alam, K.-Y. Liang, and H. Pettersson. *System and method relating to vehicle platooning*. European patent application number 14847454.7 (filed 2014*g*),

A. Alam, K.-Y. Liang, and H. Pettersson. *System and method for regulating a vehicle platoon with two different strategies*. European patent application number PCT/SE2014/051122 (filed 2013*h*),

A. Alam, K.-Y. Liang, and H. Pettersson. *System and method for regulating a vehicle platoon with two different strategies*. International patent application number 14849834.8 (filed 2013*i*),

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Apparatus and method for regulating a vehicle comprised in a vehicle train.* International patent application number PCT/SE2014/051120 (filed 2013*a*),

A. Alam, K.-Y. Liang, and H. Pettersson. *Styrenhet och metod för att reglera hastigheten på ett fordon i ett avståndsreglerat.* Swedish patent grant number SE 537992 (filed 2014*f*),

A. Alam, K.-Y. Liang, and H. Pettersson. *Steuereinheit und Verfahren zum Regeln der Geschwindigkeit eines Fahrzeugs in einer abstandsgeregelten Fahrzeugkolonne bei einer Bergfahrt.* German patent application number DE 102015010559.0 (filed 2015).

Chapter 2

Background

“To know, is to know that you know nothing.
That is the meaning of true knowledge.”
SOCRATES

In this chapter, we provide an overview over intelligent transportation systems (ITS) and the technology that so far has supported the advancement of ITS. We then narrow it down to focus on advanced traffic management systems. We describe several systems and technologies that enabled the deployment of the motorway control system (MCS) in Stockholm, which monitors the traffic, changes variable message signs and speed limits according to the current traffic situation, in order to maximize the safety and throughput of the highway. Lastly, we present an overview of the related work on vehicle platooning and platoon formation. The literature over this field is quite extensive and we, by no means, cover everything, but rather give an overview over the conducted work.

The outline of this chapter is as follows. In Section 2.1, we briefly describe ITS. In Section 2.2, we give an overview of key technologies enabling ITS. In Section 2.3, we discuss the technology of advanced traffic management system combined with some related work. In Section 2.4, we focus on related work regarding vehicle platooning, where, in all the conducted work, the number of vehicles is assumed fixed. In Section 2.5, we shift our focus to platoon formation, where the vehicles are not necessarily in a platoon but, through some means, have the possibility to form platoons. Lastly, a summary in Section 2.6 concludes this chapter.

2.1 Intelligent transportation systems

The transportation system is of central importance for any modern economy and a core element of everyday life. It can be perceived as a large and complex mobile network. By introducing information and communication technology (ICT) to the network, decisions are allowed to be made based on accurate information and enables

Figure 2.1: An illustration of ITS. ITS includes telematics and all types of communications in vehicles, between vehicles, and between vehicles and infrastructure. Note that ITS is not restricted to road transport as it also includes the use of ICT for rail, water, and air transport, including navigation systems. (Illustration courtesy of ETSI (2016).)

transportation of goods and people with higher efficiency, thus inducing intelligence to the transportation system. ITS, illustrated in Figure 2.1, is a broad area that includes all types of navigation systems and communications in transport on road, rail, water, air, and with infrastructure. In general, ITS may be described as an application and integration of advanced technologies of information, communication, computer, control, sensing, and detecting in road transportation systems in order to improve and enhance safety, environmental benefits, traffic congestions, and traveler conveniences through transmission of real-time information. Although ITS may refer to all transport modes, EU directive refers to ITS as ICT application to only road transport, including infrastructure, vehicles, users, and traffic management, as well as for interfaces with other modes of transport (European Union, 2010).

ITS has many applications and can be divided into five main categories (Ezell, 2010), namely

- Advanced public transportation systems – include systems for transport carriers, for example trains, buses, and boats, to report real-time information, such as position, arrival, and departure information, to the passengers.

- Advanced traffic management systems – include ITS applications that focus on traffic control devices, such as traffic signals, ramp meters, and dynamic message signs to monitor traffic and provide drivers realtime messaging about traffic or highway status.
- Advanced traveler information systems – provide travelers with real-time information, such as navigation routes, traffic congestions, delays, accidents, weather conditions, road repair work, and vacant parking spaces.
- ITS-enabled transportation pricing systems – include systems such as electronic toll collection, congestion pricing, and variable parking fees.
- Fully integrated ITS – includes integration and communication between different actors in the transportation system, where vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication serve as a basis to provide services, such as intersection collision avoidance and intelligent speed adaptation.

There are numerous agencies worldwide dedicated to advance research, development, and deployment of ITS. These include ERTICO in Europe, ITS America, ITS China, ITS Japan, ITS Australia among others.

2.2 Key technologies for ITS

The development of ITS is continuously progressing in order to meet the goal of cutting the emission in the transport sector by 60 % by 2050, set by the European Commission (European Commission, 2011). The development growth of ICT, together with faster and cheaper computer technology, has made it possible to process the growing amount of available information. Technology that was initially developed for entirely different purposes is now finding its use in ITS applications. The understanding of the potential benefits with ITS is growing rapidly. To support this, there are numerous underlying key technologies that make ITS possible. In this section, we describe some of the key components for ITS, namely wireless communication, global positioning system (GPS), probe data, sensors, and cloud computing.

2.2.1 Wireless communication

There are several kinds of wireless communication technologies proposed for ITS. We focus on two types of communication that look the most promising for advanced ITS applications, namely vehicle-to-vehicle and infrastructure (V2X) communication based on wireless local area network (WLAN) and cellular communication. V2X communication allows vehicles to “talk” to each other or with road side units in order to improve traffic safety and avoid possible collisions. Two message types have been defined, in Europe, for this purpose, namely cooperative awareness message

(CAM) and decentralized environment notification message (DENM). CAM is a time-triggered broadcasted message that informs other road users or road side units of the status of the sending unit such as location and velocity (ETSI, 2014*a*). DENM is an event-driven message that informs nearby units of a special event such as an accident (ETSI, 2014*b*). In Europe, the wireless vehicular communication operates in the 5.875–5.925 GHz frequency band and is named ETSI ITS-G5, which is based on the IEEE 802.11p protocol (an amendment to the Wifi standard IEEE 802.11) (ETSI, 2009). 30 MHz of the available 50 MHz frequency band is dedicated to road traffic safety and the other 20 MHz is dedicated to traffic efficiency. Examples of such applications are intersection collision avoidance and vehicle platooning.

Cellular communication is another form of wireless communication where the communication link has to go through a base station. The advantages of cellular network include wide availability in towns and along major roads, thus requiring less infrastructural expansion. However, additional network capacity may be required if ITS applications are fitted with this technology, and network operators might need to cover these costs. Additionally, as for the current 3G and 4G cellular network, they may not be suitable for safety-critical ITS applications due to high latency (ETSI, 2012). The next generation cellular network technology, 5G, considers ITS applications with low end-to-end latency, high reliability, and manage large unit density (5G PPP, 2015). 5G also considers device-to-device communication, making it a highly potential communication technology for ITS applications.

2.2.2 Global positioning system and probe data

A GPS device receives signals from several different satellites to calculate the absolute position of the device. The GPS device requires line of sight to the satellites and it must establish connection with at least four satellites (three for positioning and the fourth for time synchronization) in order to determine the location. The accuracy of the GPS is within ten meters, but it can go down to centimeter precision with the aid of real-time kinematic base stations or differential GPS (Kaplan and Hegarthy, 2006). Installing a GPS device on a vehicle combined with digital map data, regional environmental awareness is provided to the vehicle or the driver. This can, for example, enhance the fuel performance of the vehicle through road topography information or aid the driver by rerouting to avoid traffic congestions. The price of GPS devices has dropped to the point where each electronic device has one. This has opened up many new ITS applications such as traffic congestion maps or road grade estimation (Sahlholm, 2011).

Technologies for ITS applications do not only enhance the surrounding awareness of a vehicle or road user, they may also be used for managemental, operational, and infrastructural purposes. By allowing vehicles, cellphones, navigators, and devices to act as probes and send data to a backend office or operator, one can improve ITS applications. The collected data are composed of the location and speed of the probe, usually from a GPS device, and they can be composed of additional information depending on the application. The aggregated probe data can, for example, be used to generate an area-wide picture of traffic flow and to identify congested locations. The probe data (also known as floating car data) may be used in navigation systems to estimate travel time or for rerouting purposes to avoid traffic congestions. A fleet owner benefits a lot from probe data using a fleet management system (FMS) to evaluate transport missions and driver performance. Vehicles may also act as probes for each other. This may improve traffic flows by letting the information hop further upstream and letting the vehicles reroute or it may be used for warning purposes through wireless communication.

2.2.3 Sensors

Sensors are essential for ITS applications. Their purpose is to detect events or changes in their environment and then provide a corresponding output. The advancement in sensing technology has made the sensors both cheaper and smaller, which have opened up for several usages. There is a large variety of sensing technologies that can be used for ITS applications. Sensing systems can either be vehicle- or infrastructure-based.

Vehicle sensors are used for perception of the vehicle itself and its surrounding. There are many sensors in a vehicle such as odometer, speed sensor, pedal position sensor, thermometer, gyroscope, among others. However, we focus on some sensors that are commonly used (commercially or in research) for perception with ITS applications, namely doppler radar, camera and lidar. Doppler radar uses the Doppler effect to detect speed and distance of targeted objects. It does it by sending out microwave signals to a desired target and analyze how the target has altered the frequency of the returned signal. The doppler radar is commonly used for the so called adaptive cruise control (ACC). The ACC allows the driver to set a desired speed that the vehicle automatically maintains and, if there is a slower vehicle driving in front, the ACC adapts to the same speed as that vehicle in front. A camera captures images of the scene and through image processing it is possible to detect and identify objects in the image. It is possible to identify different objects such as traffic signs, road markings, pedestrians, car types, among others. With a stereo camera, it is possible to calculate depth of the objects and by analyzing sequential images, the relative speed of objects can be calculated. Lastly, lidar measures distance to a target by illuminating the target with a laser light. The term lidar is a word combination of light and radar. The lidar can be used for mapping of the surrounding and has been highly used for that purpose for research on self-driving vehicles, in particular using a 360° Velodyne LiDAR (Velodyne, 2016; Moosmann and Stiller, 2011).

Infrastructure sensors are mainly used to measure traffic flows, detect traffic regulation violations, or charge congestion taxes. The technologies are very similar to the vehicle sensors. Doppler radar is used to measure traffic flows or detect speed limit violators (can even be used using lidar). Additionally, another commonly used technology to measure traffic flows is inductive loop detection. Inductive loops detect vehicles as they pass the magnetic field of the loop and are often placed in the roadbed. Camera is used to capture the number plate of the traffic regulation violator or to charge congestion taxes. Congestion pricing is a system to charge road users depending on the time of the day in order to reduce traffic congestion during peak hour and even it out throughout the day. Large cities, such as Stockholm, Gothenburg, London, Singapore, and Milan have deployed this system.

2.2.4 Cloud computing

Cloud computing has rapidly found its use in many applications, including ITS. Cloud computing is a networked-based computing that provides processing resources and data to devices on demand, making it a service rather than a product. It allows access to a shared pool of computing resources, such as servers and storages. The access can quickly be granted and released with minimal management effort, allowing many devices to access the pool. The advantages with cloud computing are high computing power, high performance, cheap cost of services, and scalability. This allows, for example, a shift of many high computational (non-crucial) tasks from the vehicles to the cloud, reducing costs as well as save physical space in the vehicle. Service models for cloud computing is divided into three different models. Infrastructure as a service (IaaS) provides end users with physical computing resources, such as computers and virtual machines. Platform as a service (PaaS) offers end users a development environment where they can develop their own software using tools and libraries provided by the cloud. Software as a service (SaaS) enables end users to gain access to an application software, which they can execute it remotely. Bitam and Mellouk (2012) proposed a cloud computing model for ITS applications, which they called ITS-cloud and includes all three service models, all kinds of communications, GPS, and end users (both passengers and vehicles).

2.3 Advanced traffic management systems

Advanced traffic management systems are an umbrella term for many different ITS systems that help to monitor and improve traffic flow, travel time, and safety, using different measures and techniques such as ramp metering, variable speed limit (VSL), variable message signs (VMS) and automatic incident detection (AID). These are widely deployed in many parts of the world. Advanced traffic management systems have been in use in the United States since the 1960's on the New Jersey Turnpike and on the John C. Lodge Freeway in Detroit. A selection of these systems have been deployed on the highways of larger cities in Europe in 1970's. Stockholm, Sweden, deployed their first motorway control system (MCS) on the northern part of the E4 highway in Stockholm in 1996 (Nissan and Bang, 2006).

MCS in Stockholm is an automatic traffic jam warning system. It uses microwave detectors mounted on gantries to measure traffic flow, traffic speed, and detect where traffic jams start and end (Trafik Stockholm, 2016; Nissan, 2010). The information is analyzed and, if needed, communicated back to road users by VSL and VMS along the highway. For example, the system can close a lane completely due to a traffic

(a) (b)

Figure 2.2: Two consecutive gantries of Stockholm's MCS during an accident, where the system warns drivers with a recommended speed of 50 km/h and a lane change followed by a closed lane sign.

accident. The VMS can inform drivers and VSL can indicate closed lanes, arrows to switch lanes, and lower the speed limit as depicted in Figure 2.2. Additionally, the MCS uses AID to detect traffic incidents in order for a traffic operator to promptly take action accordingly.

There are several deployed traffic control management systems in Europe. The Dutch motorway control and signaling system is a system similar to the MCS in Stockholm. It uses inductive loops, instead of microwave detectors, for traffic measurement. Additionally, the system informs drivers, through VMS, about travel times or traffic jam length (Regiolab Delft, 2016). The M25 controlled motorway system (M25 is also known as London orbital motorway) collects data through inductive loops and cameras to govern the speed limits through VSL. It also has an automatic signal setting in response to traffic conditions and AID as well. Additionally, the system captures speed violators using automatic camera technology (Highways Agency, 2004). Grenoble Traffic Lab is a platform for collecting real-time traffic data from wireless magnetic sensors in the southern ring of Grenoble. The data collection is to estimate traffic and to make traffic predictions. Compared to the aforementioned systems, the Grenoble Traffic Lab does not have an infrastructure set up, instead it relies on a web interface or smartphone application to display traffic information, such as travel time, to the drivers (Canudas de Wit et al., 2015).

We briefly describe three commonly used systems, namely ramp metering, VSL, and AID.

2.3.1 Ramp metering

On-ramps can cause congestions on the highway leading to longer travel times. Ramp metering is an easy solution to reduce the congestion on a highway and only affect the vehicles entering the highway and therefore improve both the traffic throughput and safety on the highway (Papageorgiou and Kotsialos, 2000). Ramp metering is a traffic light that governs when vehicles can enter the on-ramp to the highway. It may simply be time based, for example be active during peak hours and turned off during the rest of the day, or it may have a feedback control loop based on real-time measurements, such as current traffic condition (Papageorgiou and Kotsialos, 2000).

Hadj-Salem et al. (1990) proposed a ramp-metering control strategy, named ALINEA, which has been shown to be a remarkably simple, highly efficient, and easily implemented ramp-metering application. It is a form of PID (proportional-integral-derivative) control where the metering rate is reduced when the current traffic density exceeds a pre-set value and vice versa. Other methods have been proposed such as model predictive control (MPC) (Bellemans et al., 2006) and iterative learning control (Hou et al., 2007). Amsterdam A10 ring road is one of the many examples with deployed ramp metering, which has shown great improvement with 30 % reduction of travel time for the studied sections (van der Veen and Taale, 2011).

2.3.2 Variable speed limit

VSL is a display system that can change the speed limit of the road. The main purpose of VSL is to increase the safety and to decrease accidents on the road by reducing the speed variances of the drivers through lowered speed limit. For example, it can warn drivers about accidents with successively decreasing speed limits upstream. VSL has also been used on highways to warn drivers to adjust their speeds due to adverse weather conditions, wet road surface, and darkness (Nissan, 2010). According to Papageorgiou et al. (2008), there is no clear evidence of improved traffic flow capacity when VSL is in operation, some locations showed a small increase whereas no increase were observed at other locations. Hegyi et al. (2005) showed that shockwaves can be suppressed during traffic congestion by optimally coordinating several VSL signs using MPC, which leads to reduced total time spent on the highway.

2.3.3 Automatic incident detection

Traffic incident is an unforeseeable and non-recurring event that limits or totally blocks the traffic throughput of the road, causing significant delays and costs. It is therefore important to quickly detect such incident in order for road assistance to quickly help and reduce the impacts of the incident. AID techniques rely on traffic measurements acquired by inductive loop detectors or video detection cameras. Video-based AID is heavily affected by the environmental factors such as shadows, snow, rain, and glare, but can be compensated for to increase the accuracy (Shehata et al., 2008). Different data processing techniques have been proposed including low-pass filtering (Stephanedes and Chassiakos, 1993) and neural networks (Srinivasan et al., 2005).

2.4 Vehicle platooning

Vehicle platooning can be described as a string of vehicles, traveling together behind each other with a set intermediate distance and speed, acting as one unit. The concept of vehicle platooning is not new, in fact, it has existed for several decades. The concept idea was first presented by General Motors at the 1939 New York World's Fair in New York with their visioning film entitled *To New Horizons* (General Motors, 1939). A vision of cars driving autonomously with the help of curved sides to keep the cars in the lane, and with automatic radio control to maintain safe distances between the cars at unreduced speed. The first study of vehicle platooning did not originate from automatic control of vehicles, but rather from traffic dynamic studies. The aim was to find a vehicle-follower model in order to understand and develop traffic flow models. An early work by Pipes (1953) studied the dynamics of a line traffic with N vehicles and a *wave* phenomena was noticed. The paper states that it has been found that when a light turns green, the whole line of vehicles does not move as a unit, but a wave travels down the line of vehicles. This has become, what we know today in vehicle platooning, as string stability and the term was first introduced by Peppard (1974). The word platoon was first introduced by Rothery et al. (1964), however the word only became frequently used in the very late 20th century.

As further research of vehicle-follower models was continued to be studied, more and more research regarding string stability arose. String stability can be described as the ability to attenuate a disturbance in position, speed, or acceleration as it propagates along the string of vehicles. A rigorous definition of string stability is found in Swaroop and Hedrick (1996). String stability is sufficient but not necessary condition for a stable vehicle platoon. A vehicle platoon does not need to have the string stability property, if the propagation error stay uniformly bounded, then the disturbance attenuation is also ensured (Shaw and Hedrick, 2007). Note that string stable does not equal safety, it only guarantees that there is no disturbance propagation along the platoon. String stability has been studied extensively with different approaches and focuses. There are centralized and decentralized control design of vehicle platoons by Levine and Athans (1966) and Khatir and Davison (2004), respectively, study of variable time headway by Yanakiev and Kanellakopoulos (1995), utilizing both front and back vehicle information with radar to achieve string stability by Chien et al. (1999), and string stability in lateral direction through active steering by Kianfar et al. (2013) to name a few.

The research of vehicle platooning and string stability were initially mainly restricted to theoretical studies. It was not until the 1990's when technology started to advance and be mature enough to start implementing and test the concept of vehicle platooning in practice. California PATH was one of the first to experimentally test platooning with two cars driving at highway speed and using wireless communication (Chang et al., 1991). Their main motivation for platooning was to increase the highway throughput, which they estimated to increase by a factor of two or three. The research continued with a demonstration of platooning with four cars in 1994

(Hedrick et al., 1994) and eight cars in 1997 (PATH, 1997). The air drag reduction potentials of a car platoon were stressed, however no measurements were made. Instead, studies on wind tunnel with car models were conducted and indicated an average air drag reductions of 55 % for a four car platoon (Zabat et al., 1995).

Reduced air drag implies less force required for a vehicle to propel forward, which leads to a reduction of fuel consumption. This opened up many opportunities to study the possible fuel consumption reduction when platooning. Studies on fuel reductions in platooning have mainly been on HDVs where the potentials are greater due to the shape of the vehicle. The earliest HDV platoon experimental study in 2000, indicates a fuel consumption reduction of 21 % for the follower HDV driving at 80 km/h with a gap of 10 m (Bonnet and Fritz, 2000). More experimental studies of fuel consumption reduction for HDV platooning were conducted, and are still being conducted, worldwide by other researchers such as Browand et al. (2004); Zhang and Ioannou (2004); Tsugawa (2013); Roeth (2013); Lu and Shladover (2014); Lammert et al. (2014); Alam et al. (2015). All of these studies have shown significant fuel savings despite different types of HDVs. A fuel experimental study with mixed cars and HDVs in platoons has been conducted by Davila (2013). All these experimental studies have also indicated that more fuel savings can be achieved the shorter the intermediate distance between the vehicle is and all this fuel savings are achievable through automatic control of the vehicles. However, the controller also has an influence on the fuel consumption. If a controller constantly needs to accelerate and brake to maintain a fixed gap to the vehicle ahead, it will be fuel inefficient, which might have happened in the case of the KONVOI project. They showed fuel savings on their test site, but no savings during test on public highway due to that the HDVs needed to vary their speeds to adapt to other vehicles and traffic conditions (Shladover, 2012). A platoon control can be further improved and be more fuel efficient using preview information of the road topography ahead (Alam et al., 2013; Turri et al., 2014).

The closer the intermediate distances are between the vehicles in a platoon, the higher the traffic throughput and air drag reduction are. However, a closer gap requires a more aggressive controller to ensure safety and prevent collisions in case of emergency. Guaranteeing safety from collision for HDVs has been studied by Alam et al. (2014) using a game-theoretical approach and computing safety sets. Studies of collision avoidance for cars have been conducted by several researchers such as Alvarez and Horowitz (1997); Seiler et al. (1998).

As HDV platooning is closer of being a reality, little is known of the impact it has on the surrounding traffic and vice versa. Deng and Ma (2015) tried to close the gap by developing a simulation platform based on microscopic traffic simulation software VISSIM that can be used to analyze HDV platoon operations and impacts on traffic flow. This was continued by analyzing how different spacing policies of the HDV platoon affected the traffic flow characteristics, where a mixed spacing policy was proposed in order to maximize the traffic flow for all traffic densities (Deng and Boughout, 2016). The simulation experiment conducted by Gordon and Turochy (2016) studies mixed traffic based on real traffic data to understand how their platooning system affects the highway traffic flow with respect to different time gaps, market penetration rate, and peak hour volume. However, studies of car platooning with different penetration rate of cars with platooning equipment (or cooperative ACC (CACC)) in traffic are plenty, as that is where the first platooning studies (in the form of string stability) originated from. To name a few, we have Shladover et al. (2012) showing improved road capacity with higher penetration rate and van Arem et al. (2006) showed that low penetration rate (<40 %) does not have an effect on the traffic flow throughput while high penetration rate (>60 %) has benefits on traffic stability and throughput.

Many HDV platooning projects with demonstrations have been conducted. PATH showed fuel saving with two HDV platoon with 3–10 m intermediate gap (Browand et al., 2004). CHAUFFEUR I & II were the first platooning project in Europe, where the lead vehicle was driven manually and the follower vehicle automatically with wireless communication (Bonnet and Fritz, 2000). The focus of KONVOI was highway utilization. Their platooning system was designed to split the platoon when a vehicle cuts-in (Lank et al., 2011). SARTRE was the first project with mixed typed of vehicles in a platoon (Robinson et al., 2010). Scoop (Mårtensson et al., 2012) was a collaboration between university and industry to compete as one of the many teams in the Grand Cooperative Driving Challenge (GCDC) 2011 (van Nunen et al., 2012). Energy ITS was conducted in Japan in order to reduce the energy consumption and CO_2 emissions in the transportation sector (Tsugawa, 2013). The European truck platooning challenge was a recent challenge where six HDV brands, DAF trucks, Daimler, Iveco, MAN, Scania, and Volvo, were each assigned to drive in platooning on public roads from several different European cities to Rotterdam in the Netherlands. The aim of the challenge was to bring platooning one step closer to implementation (European Truck Platooning Challenge, 2016). In Figure 2.3, we see Scania driving their way to Rotterdam from Södertälje, Sweden with three HDVs.

2.5 Platoon formation

Most of the conducted work in vehicle platooning have mainly focused on vehicles staying in the platoon throughout the study. However, in practice, vehicles have different origins, destinations, and timings, which mean that one platoon might be formed, merged, and split several times. One vehicle might start in a platoon and end up with another platoon. We define platoon formation as vehicles, that are initially separated, form a platoon through some incentive means where otherwise they would have not done so.

Studies of fuel-efficient HDV platoon formation have been highly neglected up until recently. Thus, there are only a handful of studies regarding platoon formation. One of the earliest paper was conducted by Meisen et al. (2008), where they used data-mining technique to plan and organize platoons. They considered finding common routes and timings of the vehicles, and also considered the reduced fuel consumptions when platooning and possible additional costs (such as waiting time)

Figure 2.3: Three Scania HDVs on their way to Rotterdam from Södertälje in the European truck platooning challenge. (Photo courtesy of European Truck Platooning Challenge (2016).)

when organizing the platoons over a network. This work was part of the KONVOI project.

The California PATH program has also considered platoon formation. Their argument is that some form of coordination is needed to aid the HDVs, especially at low market penetrations of V2V and platooning systems. They catagorize it into three strategies, namely ad hoc, local and global coordination strategies (Shladover et al., 2014; Nowakowski et al., 2015). The first strategy is ad hoc, where the vehicles only couple if they happen to be following each other. The second strategy is local coordination, where the vehicles are already on the highway and within a certain distance of each other and could adjust their speeds to form platoons. Lastly, the third strategy is global coordination, which involves planning before traveling. Vehicles with similar origins and destinations might be clustered together with some adjustments to their departure time and match where and when to meet. Each strategy is discussed in more detail, with some practical issues that may need to be considered and with some suggestion for possible solutions.

The project Driver-Assistive Truck Platooning (DATP) focuses on prototyping, evaluating, and testing DATP, which is a form of CACC (Bishop et al., 2014). Their focus is to go to market as they think that their DATP technology is ready for industrial use. They have also considered how to form platoons, which they call it for DATP linking. They have considered three different scenarios that are being explored. First is HDVs leaving a terminal together, driving from hub to hub together. Second is ad hoc linking, where HDVs find each other on the road, similarly to PATH's ad hoc strategy. The third scenario is ad hoc linking with stop kiosks. The concept is similar to hubs, where there is a good amount of HDVs. The facilities enable the drivers to rest and register upon arrival. At departure, the driver checks for pairing candidate.

The EU project COMPANION aims to develop a cooperative vehicle on-board and off-board system for creation, coordination, and operation of HDV platoons for fuel efficiency (Pillado et al., 2015). Additionally, the project will propose legal solutions for adoption of platooning technologies and demonstrate the COMPANION system on European roads and the capability of the off-board platform system. Most of the theoretical work and research regarding platoon formation in general have been conducted under the COMPANION project. Zhang et al. (2016) consider a basic scheduling problem with platooning as one of the decision variables with HDVs having a (partially) common route. They consider transport costs consisting of three components, including fuel cost, driver cost, and penalty for schedule miss. Van de Hoef et al. (2015*b*) consider a centralized-based coordination of HDVs to form platoons for fuel efficiency based on their shortest path. This may be seen as a planning system deciding the speed each vehicle should drive on the road segments, however the complexity of the algorithm seems to be problematic as the number of vehicles that can platoon grows. The extended work van de Hoef et al. (2015*a*), tackles the complexity issue by choosing the most suitable leader for each platoon cluster. However, the speed profile of the leader becomes fixed, i.e., it cannot adjust its speed, instead the other vehicles in that cluster adapt their speed to merge with the leader and then compensate the time loss/gain after split. Simulations showed that their proposed method can quickly find plans for a large number of vehicles. Closely related to the COMPANION project, the work by Larsson et al. (2015) studies HDVs traveling on a road network where the vehicles have the possibility to stop and wait for another vehicle to platoon with. The work by Farokhi and Johansson (2013) considers a game-theoretical approach of two types of agents (cars and HDVs), where each agent chooses the time interval it wants to travel on the road. The agents trade-off between the time to use the road, the average speed of the flow for that time, and the dynamic congestion tax they are paying to use the road. The HDVs have platooning capabilities and therefore have an incentive to use the road at the same time as other HDVs.

2.6 Summary

A brief introduction of ITS was provided in this chapter. ITS aim to improve and enhance safety, environmental benefits, traffic congestions, and traveler conveniences through ICT application on road transport. There are several key technologies that makes ITS possible, namely V2X communication, cellular communication, GPS, various of sensors, including doppler radar and camera for both vehicular and infrastructural use, and cloud computing. Initially these technologies were developed for entirely different purposes, but have found its use in ITS applications. We then narrowed the scope to focus on advanced traffic management systems where several different systems have been deployed in many different cities around the world to improve traffic. Ramp metering essentially shifts traffic congestion from highways to on-ramps. Variable speed limit and message signs warn drivers in order to increase the safety and decrease accidents on the road. Furthermore, we presented work that have been conducted in vehicle platooning, from the concept idea by General Motor's future vision in 1939 until recent work. Lastly, we mention a handful of work that have been studied regarding fuel-efficient platoon formation.

Chapter 3

Modeling

"A mathematical model does not have to be exact; it just have to be close enough to provide better results than can be obtained by common sense."
Herbert A. Simon

Heavy-duty vehicles (HDVs) are complex systems with a large number of interacting dynamics. For example, when the gas pedal is pressed, fuel is injected into the cylinder of the diesel engine and together with highly compressed hot air ignites the fuel, which pushes the piston down, creating torque in the crankshaft. The torque goes through the powertrain before finally going to the wheels, which propels the vehicle forward. In this chapter, we derive a mathematical model that describes the movement of an HDV, which serves as a basis for our platoon formation decision in the next chapter. Additionally, as HDVs are driving together with other road users, the interaction with the surrounding traffic is important to understand. Therefore, we present a macroscopic traffic flow model that describes the average traffic behavior using the relation of density, flow, and speed. The macroscopic traffic flow model is the foundation for shockwave theory as well as our merge estimator presented in Chapter 5. Lastly, we describe a hierarchical transport system architecture that decomposes the large complex system of transporting goods into manageable subsystems.

The outline of this chapter is as follows. In Section 3.1, we describe a general vehicle model based on the environmental forces acting on a vehicle in motion. In Section 3.2, we derive a fuel model from the work required to propel an HDV forward. In Section 3.3, we present the basics of macroscopic traffic flow theory. In Section 3.4, a system architecture of goods transport and platooning is described. Lastly, a summary in Section 3.5 concludes this chapter.

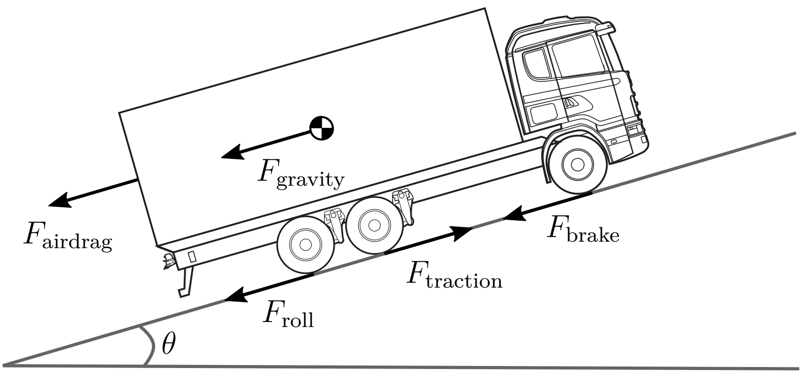


Figure 3.1: Illustration of the forces acting on an HDV along the longitudinal direction.

3.1 Vehicle model

In this section, we present a longitudinal vehicle model that serves as the basis for the control formulation presented in Chapter 4. A more detailed vehicle model can be found in Gillespie (1992). There are many forces acting on an HDV in motion. The force produced by the engine propels the vehicle forward, while the brake force slows down or stops the vehicle. We assume that neither can be applied at the same time, as it is not fuel efficient. Air drag and roll friction act as resistive forces, while the gravity can either yield to a resistive or assisting force depending on the road grade. The main longitudinal forces with sign conventions are depicted in Figure 3.1, with θ denoting the slope of the road. By applying Newton's second law of motion, the dynamics of a vehicle can be expressed as

$$\begin{aligned} \dot{s} &= v, \\ m\dot{v} &= F_{\text{traction}} - F_{\text{brake}} - F_{\text{airdrag}} - F_{\text{roll}} - F_{\text{gravity}}, \end{aligned} \tag{3.1}$$

where s denotes the vehicle's longitudinal position, $v > 0$ the vehicle speed, and m the vehicle mass. When we consider several HDVs, we assume that all the coefficients and constants are the same, except the vehicle mass.

Powertrain

A powertrain consists of many different components including engine, clutch, gearbox, propeller shaft, final drive, drive shafts, and wheels. The engine produces torque through diesel combustion and the torque gets transformed, through all the components of the powertrain, into traction force. These components are not included in the vehicle model because it is not necessary for our control purpose. Therefore, the traction force F_{traction} is treated as a control input. The engine has a limit of how much torque it can produce, which can be modeled as a constraint as

$$0 \le F_{\text{traction}} \le F_{\text{traction}}^{\text{max}}. \tag{3.2}$$

Note the limit $F_{\text{traction}}^{\text{max}}$ depends on the gear ratio, final drive ratio, and the revolution of the engine, however we assume a constant maximum value for simplicity. Additionally, the engine brake is considered as a braking force. In order to use the model for fuel-efficient control purpose, we derive a fuel model that relates the fuel consumption to the traction force in Section 3.2.

Braking force

The braking system of an HDV is composed of several actuators. There are pneumatic brake, retarder, exhaust brake, parking brake among others. Following the same reasoning as for the powertrain, we assume that the braking force is a control input. The braking actuators acting on each axle can generate a maximum torque, which can be modeled as a constraint as

$$0 \le F_{\text{brake}} \le F_{\text{brake}}^{\text{max}}. \tag{3.3}$$

There are two factors that decide the maximum braking force, which is the minimum of either the maximum torque that the braking actuators can generate, or the maximum force that the wheels are able to transfer on the ground. As previously, we assume a constant maximum value for simplicity.

Roll resistance

The roll resistance force occurs due to the frictional force between the road and the wheels. The roll resistance force is modeled as

$$F_{\text{roll}} = c_r m g \cos\theta(s), \tag{3.4}$$

where c_r denotes the roll resistance coefficient and g the gravitational constant. The parameter c_r can be influenced by different factors, such as pressure, temperature, and width of the tires (Sandberg, 2001). Recall that θ denotes the road grade, which depends on where the HDV is driving along the road.

Gravitational force

As an HDV travels along a road, the gravitational force is either a resistive or assistive force depending on the road grade. The gravitational force has a strong influence on the HDV compared to a passenger car due to its large mass. A small ascent can force the HDV to decelerate, even though the HDV is driving at full power. Similarly, a small descent can accelerate an HDV without any fuel injection. The gravitational force is given by

$$F_{\text{gravity}} = m g \sin\theta(s). \tag{3.5}$$

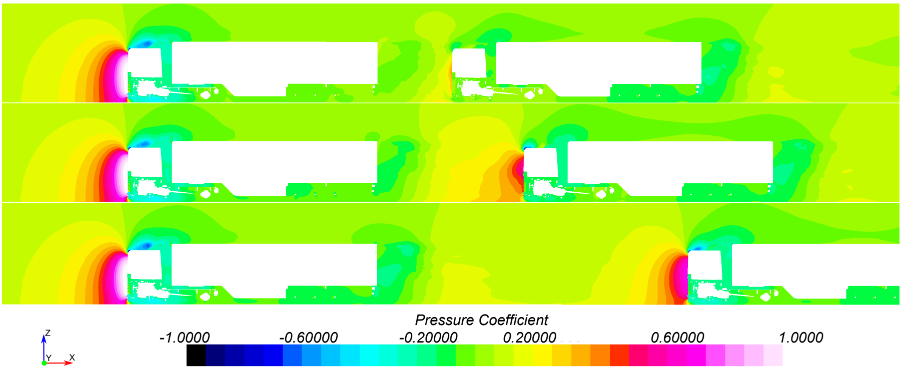


Figure 3.2: A computational fluid dynamic (CFD) simulation illustrating the air pressure two HDVs experience with respect to different intermediate distances. The intermediate distances are 5, 10, and 15 m for top, middle, and bottom figure, respectively. The follower vehicle experiences less pressure as it gets closer to the lead vehicle, resulting in lowered air resistance. (Image courtesy of Norrby (2014).)

Air drag

The aerodynamic drag is a resistive force due to the interaction between the vehicle and the surrounding air. It has generally a strong impact with higher velocity and can account up to 50 % of the total resistive force at full speed. Studies have shown that the air drag resistance can be reduced significantly by aligning HDVs close behind each other in a platoon as illustrated in Figure 3.2. It is mainly the follower vehicle that experiences a significant reduction in air drag resistance due to the lowered pressure at its front. The lead vehicle might also experience an overall reduced air drag if the follower vehicle drives close enough to dissolve the turbulent wake that occurs behind a vehicle, however the reduction is not as significant as for the follower vehicle. The air drag reduction decays as the distance between the vehicles increases.

An overall reduced air drag lowers the fuel consumption for the vehicle. Let $\phi(d_r)$ denote the nonlinear air drag ratio, which is given by a graphical model as shown in Figure 3.3. The air drag force can then be given as

$$F_{\text{airdrag}} = \frac{1}{2} c_D A_a \rho_a v^2 \phi(d_r), \tag{3.6}$$

where c_D denotes the air drag coefficient, A_a the maximum cross-sectional area of the vehicle, and ρ_a the air density. The velocity of the wind also affects the air drag resistance, however it is typically unknown and is therefore not modeled and neglected in this work.

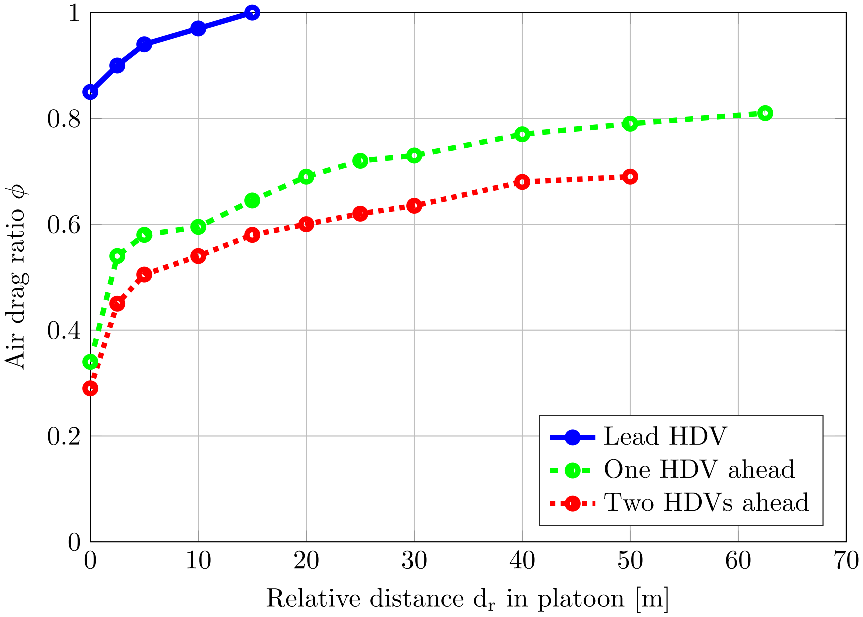


Figure 3.3: Empirical result of air drag coefficient of HDV platooning, adapted from Wolf-Heinrich and Ahmed (1998). A more recent CFD simulation study indicates similar results (Humphreys et al., 2016). The relative distance is the distance to the vehicle ahead, except for the lead HDV case, where it is the distance to the follower vehicle.

3.2 Fuel model

In this section, we derive a simple fuel model based on the work required to move an HDV. Recall the vehicle dynamics in Equation (3.1), where we assume the control inputs F_{traction} and F_{brake} cannot be applied simultaneously. Only F_{traction} contributes to propelling the vehicle forward and consuming fuel, while F_{brake} decelerates and stops the vehicle.

The work required to move an object is generally known as

$$W = \int_0^T F(t)v(t)\,\mathrm{d}t = \int_0^L F(s)\,\mathrm{d}s, \tag{3.7}$$

where W denotes the work, F the force, T the total time of the trip, and L the total length of the trip. Note that we switched from time domain to the spatial domain through the following transformation

$$v(t)\mathrm{d}t = \frac{\mathrm{d}s}{\mathrm{d}t}\mathrm{d}t = \mathrm{d}s, \tag{3.8}$$

where $v(t) > 0$ and is a continuous function. Studying the fuel cost in spatial domain is more convenient than in time domain, since the road topography is position based.

Therefore, knowing the vehicle's position and velocity, we can determine the fuel cost. The force F required to move the vehicle forward is the force produced from the engine, F_{traction}. The work required to move a vehicle can be translated into fuel with an energy conversion factor k_E, which is based on energy density of diesel and engine combustion efficiency. From this, we obtain our fuel cost ψ modeled as

$$\psi = k_E \int_0^L F_{\text{traction}}(v, s, \theta(s), d_r)\, \mathrm{d}s. \tag{3.9}$$

If we assume that the vehicle does not brake (coasting is allowed), then given the vehicle mass, a road grade and velocity profile, the total fuel cost of the trip is computed as,

$$\psi = k_E \int_0^L \left(mv(s)\frac{\mathrm{d}v}{\mathrm{d}s} + \frac{1}{2}c_D A_a \rho_a v^2(s)\phi(d_r) + c_r mg\cos\theta(s) + mg\sin\theta(s) \right) \mathrm{d}s, \tag{3.10}$$

where the acceleration is transformed to spatial domain, by the following equation

$$\dot{v} = \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{\mathrm{d}v}{\mathrm{d}t}\frac{\mathrm{d}s}{\mathrm{d}s} = v\frac{\mathrm{d}v}{\mathrm{d}s}. \tag{3.11}$$

3.3 Traffic flow model

In this section, we describe the basics of traffic flow theory, starting with the relation between microscopic and macroscopic traffic flow variables. Then, we describe fundamental diagrams and a macroscopic traffic flow model based on shockwave theory that serves as the basis for our formulation of merge estimation presented in Chapter 5. For more in-depth details, we kindly refer the interested reader to Immers and Logghe (2002); Hoogendoorn and Knoop (2012).

3.3.1 Microscopic traffic flow variables

In a microscopic approach for traffic modeling, each individual vehicle is considered and examined separately. Each vehicle is described with a vehicle trajectory, which is the position of the vehicle $x(t)$ over time along the road. For simplicity, the lateral component of the trajectory is not considered. Figure 3.4 illustrates seven vehicle trajectories. The slope of the trajectory corresponds to the vehicle speed v, i.e.,

$$\dot{x}_i(t) = v_i(t), \tag{3.12}$$

where i denotes the ith vehicle for $i \in [1, 7]$ for Figure 3.4.

Space, $s_i(t)$

A vehicle occupies a part of the road and this space $s_i(t)$ consists of the car's physical length and the distance to the vehicle in front. The space $s_i(t)$ is described, from Figure 3.4, as

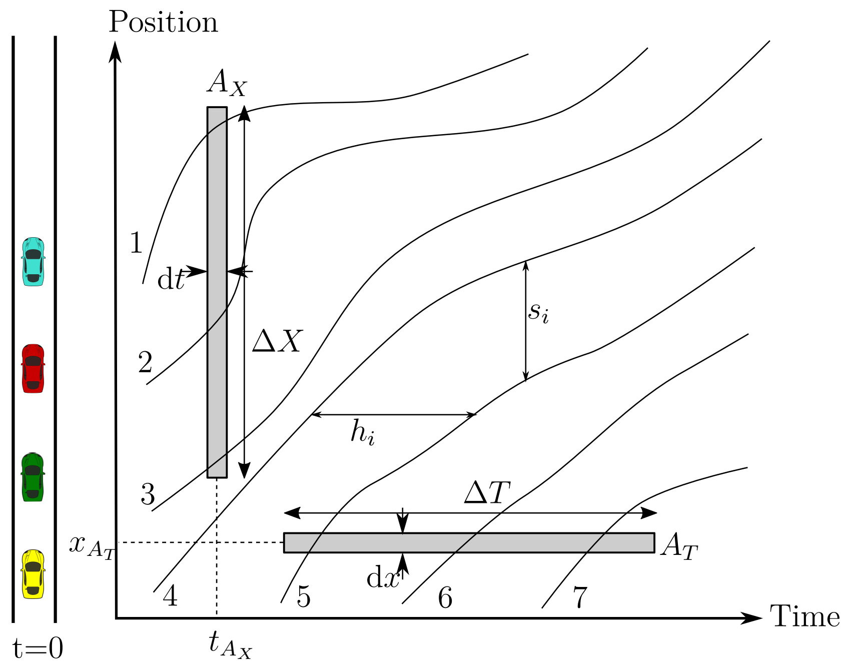


Figure 3.4: Seven vehicles driving on the road represented as vehicle trajectories in time and space. The key microscopic flow characteristics (s_i and h_i) and illustrations of measurement intervals (A_X and A_T) are depicted. The location interval A_X could be captured from an aerial photograph and the time interval A_T could be measured from induction loops.

$$s_i(t) = x_{i-1}(t) - x_i(t), \tag{3.13}$$

which is the distance from the back of vehicle i to the back of vehicle $i-1$ in front.

Headway, $h_i(x)$

Analogously to space, vehicles also use a certain segment of time, which is called headway $h_i(t)$. The headway is described as the time difference between two successive vehicles, which is described mathematically as

$$h_i(x) = t_i(x) - t_{i-1}(x). \tag{3.14}$$

Space and headway are strongly correlated by the equation

$$s_i = v_{i-1}h_i. \tag{3.15}$$

3.3.2 Macroscopic traffic flow variables

At a macroscopic level, we no longer focus on individual vehicles, but rather at flow, density, and mean speed that reflect the average state of the traffic flow. In Figure 3.4, the same as the microscopic traffic figure, we illustrate two measurement intervals, A_X and A_T, where a measurement interval is an area in the time-space plane. A location interval A_X covers a road segment of length ΔX during an infinitesimal time interval dt at time t_{A_X}. We assume that n_X vehicles ($n_X = 3$ in Figure 3.4) move through this interval, where such measurement could be taken from an aerial photograph. A time interval A_T represents an infinitesimal road length dx during a time interval of ΔT at location x_{A_T}. We assume that n_T vehicles ($n_T = 3$ in Figure 3.4) cross this measurement interval, where such measurement could be captured using induction loops. These measurement intervals is used when defining the macroscopic variables.

Density, k

Density k is generally defined as the number of vehicles per distance unit and is measured at a time instance. This corresponds to the location measurement interval A_X, where the density over a road segment is calculated as

$$k_{A_X} = \frac{n_X}{\Delta X} = \frac{n_X}{\sum_{i=1}^{n_X} s_i} = \frac{1}{\bar{s}}. \tag{3.16}$$

The expression shows how density relates to average microscopic behavior as each vehicle occupies space on the road segment, and the observed road segment ΔX is the total space the n_X vehicles occupy. The density may also be calculated in the time measurement interval A_T by generalizing the density definition

$$k_{A_X} = \frac{n_X}{\Delta X} = \frac{n_X \cdot dt}{\Delta X \cdot dt}, \tag{3.17}$$

in other words the total time spent by all vehicles in A_X divided with the area of A_X. By this analogy, we get the density in the time measurement interval A_T as

$$k_{A_T} = \frac{\sum_{i=1}^{n_T} \frac{dx}{v_i}}{\Delta T \cdot dx} = \frac{\sum_{i=1}^{n_T} \frac{1}{v_i}}{\Delta T}. \tag{3.18}$$

Flow, q

Traffic flow q is generally defined as the number of vehicles that passes a certain cross-section per time unit. For a time interval ΔT at any location x_{A_T}, such as the time measurement interval A_T, the flow is calculated as

$$q_{A_T} = \frac{n_T}{\Delta T} = \frac{n_T}{\sum_{i=1}^{n_T} h_i} = \frac{1}{\bar{h}}. \tag{3.19}$$

The expression shows how flow relates to the average headway, thereby relating the macroscopic flow variable to average microscopic behavior. The flow may also be calculated in the location measurement interval A_X through similar analogy given by

$$q_{A_X} = \frac{\sum_{i=1}^{n_X} v_i \cdot dt}{\Delta X \cdot dt} = \frac{\sum_{i=1}^{n_X} v_i}{\Delta X}. \tag{3.20}$$

Mean speed, u

Mean speed u is the last macroscopic variable that completes the fundamental relation of traffic flow theory, namely

$$q = ku. \tag{3.21}$$

Thus, the mean speed is the quotient between flow and density. We calculate the mean speed for both measurement intervals as

$$\begin{aligned} u_{A_X} &= \frac{q_{A_X}}{k_{A_X}} = \frac{\sum_{i=1}^{n_X} v_i}{n_X}, \\ u_{A_T} &= \frac{q_{A_T}}{k_{A_T}} = \frac{n_T}{\sum_{i=1}^{n_T} \frac{1}{v_i}}. \end{aligned} \tag{3.22}$$

Mean speed is computed for a location interval by taking the arithmetic mean of the speeds of all vehicles in this interval. However, the mean speed over a time interval is the harmonic mean of the individual speeds. This mean speed is also known as space-mean speed.

If we take the arithmetic mean of the individual vehicle speeds in a time interval, we get the time-mean speed u_t defined as

$$u_{t,A_T} = \frac{1}{n_T} \sum_{i=1}^{n_T} v_i. \tag{3.23}$$

This time-mean speed u_t differs from the space-mean speed u and therefore it does not comply with the fundamental relation in (3.21). In time-mean speed, the vehicles with higher speeds influence more the mean speed, thus making time-mean speed always larger or equal to the space-mean speed.

3.3.3 Fundamental diagram

A fundamental diagram describes a statistical relation between the macroscopic traffic variables of flow, density, and space-mean speed. It is often based on observations for a specific road. We assume homogeneous and stationary traffic states, i.e., that all vehicles are equal and that the traffic flow do neither change along the road nor over time, and can therefore describe traffic conditions as average behavior. The fundamental relation $q = ku$ is described graphically by three diagrams as illustrated

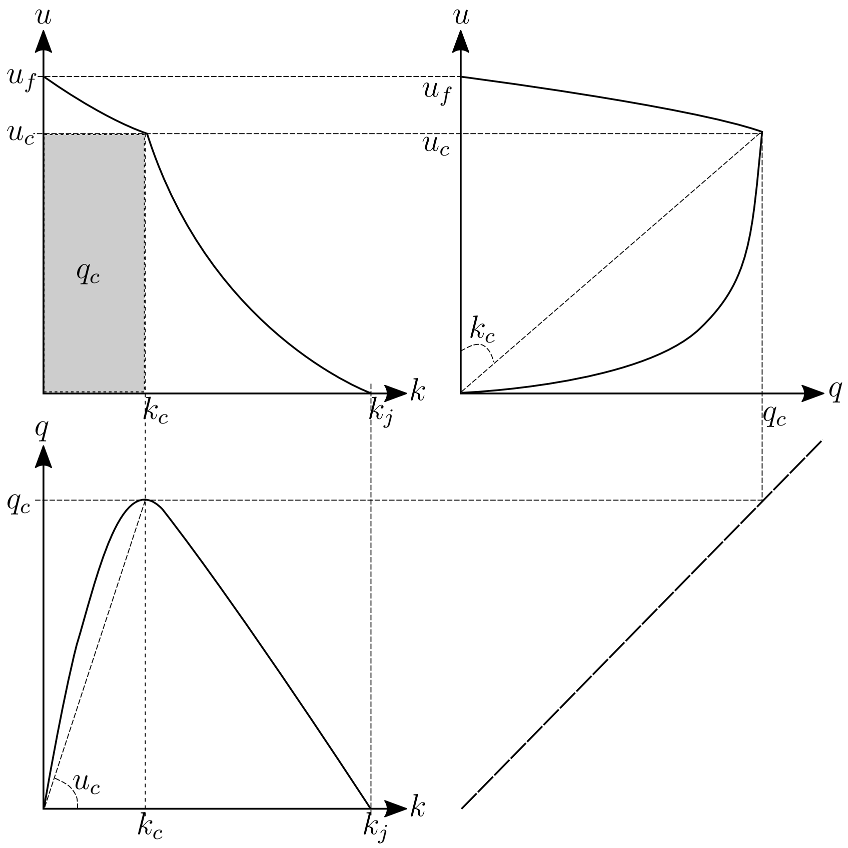


Figure 3.5: An illustration of the three related fundamental diagrams. The subscript f denotes free flow, c capacity, and j traffic jam. Fundamental diagram is based on observations for a specific road.

in Figure 3.5, namely k-u (density-speed), q-u (flow-speed), and k-q (density-flow) diagrams, where the latter is the most commonly used.

Figure 3.5 shows some important points in the fundamental diagram. The first one is the completely free flow traffic, denoted with subscript f, where the vehicles can travel at maximum speed u_f uninterrupted by other vehicles. The second one is the saturated traffic, denoted with subscript j, where the flow and speed are down to zero and vehicles are queuing at maximum density k_j (jam density). Lastly, the capacity traffic, denoted with subscript c, where the capacity of the road is equal to the maximum flow q_c with a corresponding critical speed u_c and critical density k_c. In the figure, we clearly see the difference in traffic behavior below and above the critical density. This is also known as free flow condition ($k < k_c$) and congested condition ($k > k_c$), respectively.

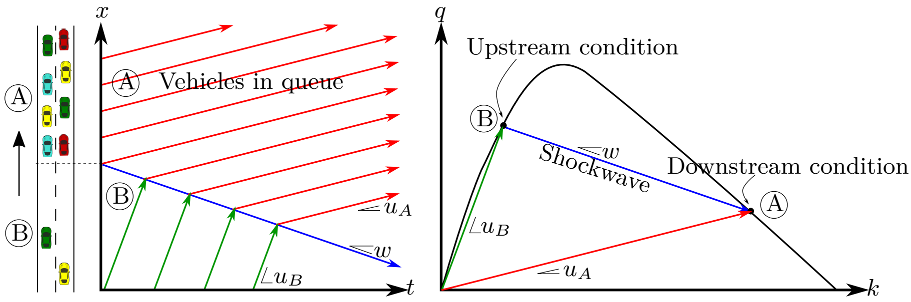


Figure 3.6: Graphical interpretation of shockwave. The left figure illustrates the two different traffic conditions at time $t = 0$. The middle figure illustrates how the shockwave moves in time and space. All the vehicles before the shockwave drive at the speed u_B until they reach the congestion and drive at the speed u_A. The right figure illustrates the fundamental diagram describing the traffic behavior of the road. The shockwave speed created by two different traffic conditions is the slope of the line connecting both traffic conditions.

3.3.4 Shockwave theory

Shockwave is a macroscopic traffic flow model that describes the boundary between two traffic states characterized by different densities, speeds, and flows. Shockwave theory describes the dynamics of shockwaves, i.e., how the boundary between two different traffic states moves in time and space. The theoretical model of shockwaves was first proposed by Lighthill and Whitham (1955) and the idea was complemented by Richards (1956) the following year, completing the so called Lighthill-Whitham-Richards (LWR) model.

Suppose we have two traffic states, A and B as illustrated in Figure 3.6. The flow downstream of A is $q_A = k_A u_A$. Assume that there is a moving observer traveling at the speed w that follows the tail of traffic state A. The observer sees a relative flow of $q_{r,A} = k_A(u_A - w)$. Similarly, if we have a moving observer traveling at the same speed w following the front of traffic state B, it observes a relative flow of $q_{r,B} = k_B(u_B - w)$. Since we do not destroy or create new vehicles, i.e., the conservation of vehicles is applied, these two relative flows are equal, $q_{r,A} = q_{r,B}$. This gives us the speed of the moving observer, thus the speed of the shockwave is given by

$$w = \frac{q_A - q_B}{k_A - k_B}. \tag{3.24}$$

The speed of the shockwave equals the change in flow between the two traffic states divided by the change in density. This gives a nice graphical interpretation illustrated in Figure 3.6. The shockwave speed in time and space is the slope of the line connecting both traffic states in the fundamental diagram.

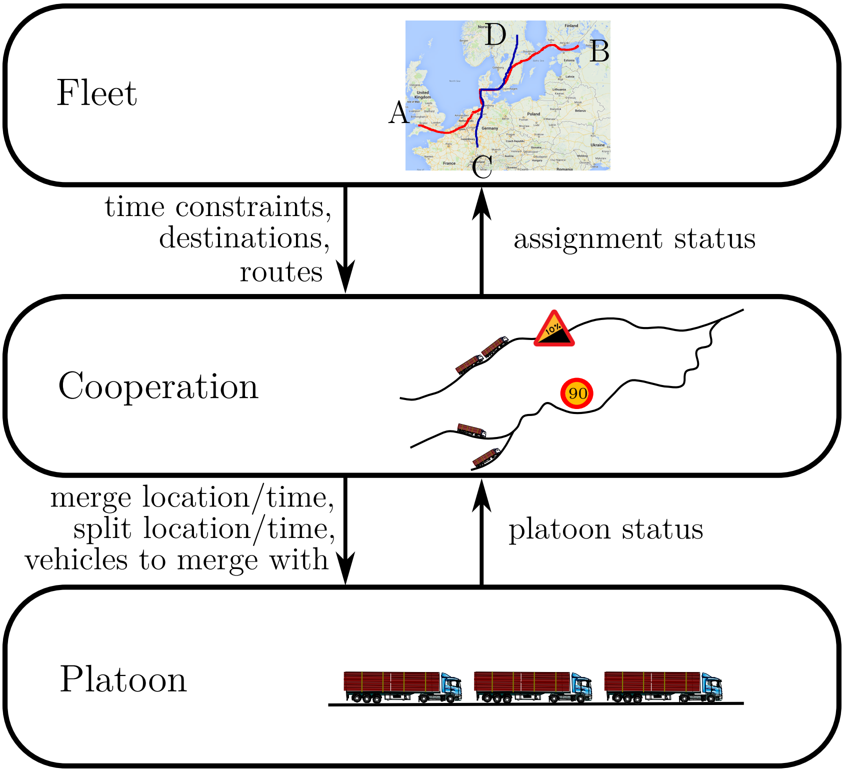


Figure 3.7: A three-layer hierarchical system architecture for goods transport. The scope of the three layers may be seen as a funnel, where the top layer has the largest scope and perspective of where and when the goods should be transported and the bottom layer focuses on the platoon.

3.4 System architecture

In this section, we present a transport system architecture. The aim is to decompose the overall complex and large-scale system into manageable subsystems.

3.4.1 Transport system architecture

We present a three-layered system architecture for goods transportation, which is inspired from Alam (2011); Besselink et al. (2016) and is illustrated in Figure 3.7.

The main task, that the transport architecture system handles, is to deliver goods from several locations to different destinations focusing on road freight transport. The three layers are (from top to bottom), fleet layer, cooperation layer, and platoon layer.

Fleet layer

Each fleet owner has transport missions to complete. A transport mission is an assignment to either deliver and/or pick up goods from one location to a different location within a certain time window. Thus, an HDV, starting from an origin location, has several sub-destinations (each with time limits) and a final destination (also with a time limit) to transport and pick up goods from. The fleet owner generally allots the assignments and vehicles to drivers. A delivery could be an order from a company or from an individual person. Therefore, a transport mission may be registered days or months before the assignment, but it may also be added on the fly. Note that the focus of this layer is logistics that may also include rail, sea, and air transports as a mean to transport the goods. However, we only focus on describing the task of road freight transport.

The tasks of the fleet layer are to distribute and assign goods to available HDVs provided by one or several fleets, determine fuel-efficient routes, and coordinate transport assignments. This involves transport planning, routing, and vehicle coordination. The objective of transport planning is to maximize the use of available vehicles and their cargo capacity by grouping similar transport assignments. Goods that need to be delivered to same area can be grouped into one or several HDVs in order to maximize the cargo capacity of each HDV while minimizing the number of HDVs required to deliver the goods. Time constraints and physical constraints, such as total weight and volume, are considered in the objective of minimizing the cost of the transport assignment. The optimization may not only consider costs directly associated with individual fleet owners, but also include other aspects such as traffic congestion and environmental impacts.

The objective of the routing task is to determine the most fuel-efficient path for each HDV delivering goods. It takes physical attributes of the road, such as road topography, speed limits, and road restrictions into account, and also considers historical traffic data. For example, a flat longer road might be more fuel efficient compared to a shorter hilly road, or a detour during rush hour might deliver the goods on time. The driver's driving and resting times are respected in the path planning. Another important aspect for fuel-efficient path planning is to consider coordinating with other HDVs on the same route to benefit from platooning. The challenge of vehicle coordination is the large-scale coordination over a significant geographic area to match HDVs with overlapping sections and timing windows. Thus, the combination tasks of routing and vehicle coordination yield to a path with (sub-)destinations and timing constraints that include forming platoons with other vehicles.

As a large number of vehicles is considered in this coordination and optimization problem, it relies on a centralized implementation that is most likely to be computed in a backend office.

Cooperation layer

The aim of the cooperation layer is to decide whether neighboring vehicles with overlapping route segments should form a platoon. The vehicle coordination in this layer exploits the use of vehicle-to-vehicle and vehicle-to-infrastructure (V2X) communication, which extend only to the relative vicinity of the vehicle and platoon, while the vehicle coordination in the fleet layer spans over a significant large geographical area. The decision-making process considers traffic conditions to evaluate whether a platoon formation may be delayed from traffic influence and if it still yields fuel savings. In addition to the decision-making process, the optimal control of merging maneuvers for platoon formation is handled in this layer and includes tasks such as merging, splitting, and reordering of platoons.

The information provided by the fleet layer are routes, time constraints, and (sub-)destinations that are translated into a reference profile for each vehicle. The reference profile needs to be fulfilled in order to meet up with other vehicles or platoons and deliver the goods in time. The reference profile can be an average velocity profile over the upcoming road segment, which each vehicle or platoon try their best to maintain. An assignment status is sent back to the fleet layer for update and report if the provided constraints can be satisfied. When the constraints cannot be fulfilled, e.g., due to traffic congestions, the fleet layer has the responsibility to provide a new feasible plan.

Platoon layer

The platoon layer aims to compute fuel-optimal velocity profiles for vehicle platoons based on road topography, traffic conditions, and V2X communication without compromising safety of the platoon. For example, by exploiting the knowledge of the road topography ahead when driving on a hilly road, braking can be avoided and additional fuel savings can be obtained. The challenge of this layer is to consider the different constraints of all the vehicles in the platoon when computing the fuel-optimal velocity profiles, as each vehicle has different mass, acceleration capability, braking performance, among others, while maintaining a desired small inter-vehicle spacing policy without increasing the risk of collision. The velocity profiles have to be adjusted to guarantee safety even under presence of disturbances or uncertainties. A platoon status is continuously sent back to the cooperation layer, notifying when platoons have successfully merged or split with the planned vehicle but also to notify delays of the formations. If the requested merge or split cannot be fulfilled, the cooperation layer has the responsibility to provide new feasible plan.

3.4.2 Platoon control system

We consider a platoon control system as illustrated in Figure 3.8, which corresponds to the platoon layer in the transport system architecture in Figure 3.7. The arrows indicate the direction of information flows in the system.

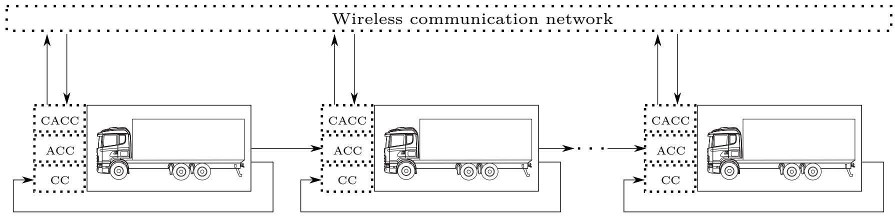


Figure 3.8: Platoon control system for an N vehicle platoon. The control system for vehicle speed control is shown in front of each vehicle and the information flow in the system is indicated by the arrows.

We have cruise control (CC) at the bottom layer, where the main task is to maintain a desired speed set by the driver. Vehicle speed information is obtained through on-board sensors that is fed back to the CC system to compute the necessary change in speed in order to maintain the desired speed. Other advantages with CC is improved fuel efficiency and driver comfort over long distances. In case of system failure, the driver is instructed to take over the control of the vehicle.

The adaptive CC (ACC), in the layer above, extends the feature of CC by maintaining a desired spacing policy set by the driver. It utilizes relative distance and speed information based on the preceding vehicle through measurements from on-board sensors such as radar. It computes the necessary change in speed in order to maintain the desired spacing to the preceding vehicle. Fuel efficiency and driver comfort is further improved as less driver action is required, achieving smoother driving. Additionally, safety is also improved since the ACC system is allowed to actuate the brakes and can react faster than a driver. In case of system failure, the driver is warned and the control actions are degraded to the CC layer.

Lastly, in the top layer, the cooperative ACC (CACC) extends the feature of CC even further by making optimal decentralized decisions based on neighboring vehicles within wireless communication range. The decentralized optimal control includes behavior of surrounding vehicles in a platoon and therefore the control actions are based on self-interest as well as the interest of all the other vehicles. Fuel efficiency, comfort, and safety are improved further. Constraints, such as maximum acceleration and braking capability, can be agreed upon platooning, and actions and intensions of other vehicles are known through the wireless communication network. By ensuring that the preceding vehicle in the platoon does not brake harder than what the follower vehicle can achieve, a short spacing can be maintained. In case of system failure, the driver is warned and the control actions are degraded to the ACC layer.

3.5 Summary

We derived a vehicle model based on the environmental forces acting on a moving HDV. The forces the HDV has to overcome are roll resistance force, gravitational force, and air drag force. Additionally, we derived a fuel model based on the work required to move an object. This serves as our basis for our platoon formation control decisions in the coming chapter. Furthermore, we described the basics of traffic flow theory, starting with the relation of microscopic and macroscopic variables, followed by fundamental diagram and shockwave theory. The microscopic traffic focuses on individual vehicles in traffic and considers the headway and space each vehicle occupies. The macroscopic traffic focuses on the average behavior of the vehicles and studies traffic as flows using flow, density, and speed relation. These variables can be described using three diagrams, the fundamental diagrams, which assumes homogeneous and stationary traffic states. Shockwave is a macroscopic traffic flow model that describes the boundary between two traffic states (with different densities, flows, and speeds) and how it evolves through time and space. Lastly, we presented a three-layered transport system architecture, which decomposes the overall transport control problem into manageable subsystems, namely fleet layer, cooperation layer, and platoon layer. We also presented a platoon control system to provide a better understanding of the main systems involved in control of vehicle platoons in the platoon layer.

Chapter 4

Fuel-efficient cooperative platoon formation

"To raise new questions, new possibilities, to regard old problems from a new angle, requires creative imagination and marks real advance in science."
Albert Einstein

By establishing heavy-duty vehicle (HDV) platoons, the environmental impacts from road freight transport can be reduced as well as the fuel consumption. In order to increase the number of platoons on the road, both departure rescheduling and coordination are required. In this thesis, we focus on one of the aspects, namely the on-the-fly coordination of HDVs to form platoons as the vehicles are driving on the road. This can be done in several ways; either a follower vehicle increases its velocity to catch up with a vehicle ahead or the lead vehicle slows down to form a platoon with the follower vehicle, or a combination of both. In the first case, the follower vehicle consumes more fuel when speeding up until the platoon is formed and time is gained. However, for the second case, the lead vehicle loses time without any vehicle consuming more fuel. This is only possible if the lead vehicle has a sufficient amount of time to spare. An alternative approach to compensate for lost time is to speed up the platoon after it is formed, but the additional fuel consumption affects more vehicles. In this chapter, we look into the possibility for the follower and/or lead HDV to act in order to form a platoon. We also guarantee that the transport is not delayed. The cooperative platoon formation is based on the proposed fuel model in Equation (3.9). We first formulate the problem for two vehicles. Based on the solution, we derive the break-even ratio where the fuel cost of forming a platoon and platoon driving with reduced fuel consumption is equal to the fuel cost of maintaining the original velocity profile and driving independently. This ratio determines a horizon (in space) within which a vehicle can potentially find candidates to platoon with and save fuel. Using this, we extend our platoon formation to N vehicles. Lastly, we compare the fuel saving results using our proposed approach to a more sophisticated simulation model.

The outline of this chapter is as follows. In Section 4.1, we describe an optimal platoon formation for two HDVs. In Section 4.2, we extend the problem to N vehicles. In Section 4.3, we evaluate the results by comparison with a more sophisticated simulation model. Lastly, a summary in Section 4.4 concludes this chapter.

4.1 Optimal formation of two HDVs

It is not evident how a fuel-efficient platoon formation of scattered HDVs on the highway should be executed as each HDV has different destination and time constraint. One vehicle might leave the highway on the next exit and another one might enter right afterwards making it not clear which vehicles should form a platoon. For simplicity, we first analyze how a platoon formation should be executed for two vehicles that are traveling on the same road. We assume that both vehicles have the same destination, which could easily be interpreted as the end of a road segment after which their routes split. We set the freedom for both vehicles to adjust their velocities. If the follower vehicle drives faster, it will consume more fuel during the merging phase but will recover the loss when platooning. Consequently, there is a trade-off in considering when it is beneficial to form a platoon. If the lead vehicle decides to slow down, it will need to compensate for the time loss when platooning in order to ensure that the transport assignment does not get delayed.

4.1.1 Simplification

Before setting up the problem as an optimization problem, we show, based on the proposed fuel model in Equation (3.9) and with a few assumptions, that the air drag is the main deciding factor when making a platoon formation decision. Recall the proposed fuel model as

$$\psi = k_E \int F_{\text{traction}}(v, s, \theta(s), d_r)\, \mathrm{d}s, \tag{4.1}$$

where k_E denotes the energy conversion factor, F_{traction} the produced force by the engine to the wheels, v the vehicle speed, s the longitudinal position of the vehicle, θ the road grade, and d_r the relative distance to the vehicle in front. As we are mainly interested in making a decision on whether the HDVs should form a platoon on longer distances and are not interested in the details of vehicle dynamics and control, we assume that the vehicles do not brake (coasting is allowed). This gives us

$$\psi = k_E \int \left(mv(s)\frac{\mathrm{d}v}{\mathrm{d}s} + k_a v^2(s)\phi(d_r) + k_r \cos\theta(s) + k_g \sin\theta(s) \right) \mathrm{d}s, \tag{4.2}$$

where m denotes the vehicle mass, ϕ the air drag ratio depending on the relative distance, and k_a, k_r, and k_g denote the characteristic coefficients corresponding to air drag, roll resistance, and gravity, respectively. We assume that the coefficients k_E, k_a, k_r, and k_g are identical for all vehicles.

Figure 4.1: A time instant where both vehicles are already on the road. The follower vehicle is located at 0 and the lead vehicle at s_s with a common destination at s_f. If they decide to form a platoon, they will drive at speed v_2 and v_1, respectively, and merge at s_m.

As we are interested in comparing whether an optimal platoon formation is more fuel efficient than the nominal case in which each vehicle maintains the original strategy and drives to its destination independently, we compare the fuel costs of both strategies given that the time constraints are maintained. Thus, we check if

$$J^*_{\text{coordination}} + c_{\text{th}} < J_{\text{nominal}}, \tag{4.3}$$

where $J^*_{\text{coordination}}$ is the optimal total fuel cost for merging and platooning the vehicles, J_{nominal} is the nominal total fuel cost that the vehicles would spend driving independently, and c_{th} is a threshold that needs to be overcome to consider it worthwhile to form a platoon. Conveniently, in expanding the terms in Equation (4.3), most terms cancel each other out. Namely, since the roll resistance and gravitational force are only dependent on the road topography, platoon formation does not affect these forces. Whether vehicles merge or not, the vehicles still need to overcome the road friction, and therefore the terms corresponding to the roll resistance and gravitational force in Equation (4.3) cancel each other out for such comparison. Furthermore, the acceleration term can be neglected with the assumption that the initial and final velocities (v_s and v_f, respectively) are the same, i.e.,

$$\int mv(s)\frac{\mathrm{d}v}{\mathrm{d}s}\,\mathrm{d}s = m\int v\,\mathrm{d}v = m\frac{v_f^2 - v_s^2}{2} = 0. \tag{4.4}$$

Thus, only the term corresponding to the air drag force remains from Equation (4.2) when making a comparison as in Equation (4.3). Thus, the speed profiles and the air drag ratio are the relevant factors in a platoon formation decision.

4.1.2 Optimization problem

Based on a few assumptions, as shown in the previous section, the main factors that influence a platoon formation decision are the speed profiles and air drag ratio (essentially how much air drag is reduced during platooning). Consider a time instant at which two vehicles are already on the road, leading to the situation in Figure 4.1. Here, s_s represents the initial distance between two vehicles, whereas s_f denotes their common destination. The nominal case is where the lead and follower vehicles are driving independently at speeds $v_{\text{nom},1}$ and $v_{\text{nom},2}$, respectively, to their destination. When forming a platoon, there are two phases; a merging phase where the vehicles merge at some point s_m and a platooning phase where both vehicles drive together. For simplicity, let us assume that only the follower vehicle experiences reduced air drag and only when it is in a platoon, i.e., there is no transient phase where the air drag ratio incrementally decreases as the relative distance between the two vehicles decreases. This is motivated by the observation that the merging phase is short in comparison to the total traveled distance. We can formulate an optimization problem, by taking the fuel cost of each vehicle driving to merge at s_m and from there platoon to s_f, as

$$\min_{v_1, v_2, v_p, s_m} \underbrace{\int_{s_s}^{s_m} k_a v_1^2(s)\,\mathrm{d}s + \int_{0}^{s_m} k_a v_2^2(s)\,\mathrm{d}s}_{\text{merge phase}} + \underbrace{\int_{s_m}^{s_f} k_a v_p^2(s)\phi_p\,\mathrm{d}s}_{\text{platoon phase}}, \tag{4.5}$$

where v_1, v_2, and v_p denote the speed of lead vehicle, follower vehicle, and platoon, respectively, and the air drag ratio of the platoon is denoted by $\phi_p \in [1, 2]$[1]. The formulation in Equation (4.5) only considers the fuel cost. However, as a platoon formation takes place in both time and space, the timing of the merge needs to be formulated, which is defined as

$$\int_{0}^{t_m} (v_2(t) - v_1(t))\ \mathrm{d}t = s_s, \tag{4.6}$$

where t_m is the time it takes to merge the vehicles.

The optimization problem in Equation (4.5) is difficult to solve in general, since the merging point and time (s_m and t_m, respectively) depends on the velocity of the vehicles and, consequently, on the road topography. As our aim is to coordinate vehicles to form platoons, and not to control the instantaneous velocity of each vehicle, we simplify the problem by assuming constant (or average) speeds on both the merging and platooning phase. This constant speed can be interpreted as a guidance speed that the vehicle or platoon should maintain in average in order to form platoons. This speed is sent to a look-ahead control (Hellström, 2010; Alam et al., 2013; Turri et al., 2015), which takes the road topography into account to drive fuel efficiently while maintaining the travel time based on the set speed. This aligns with the hierarchical architecture as described in Section 3.4. By using average speeds on each phase, we can reformulate the optimal formation problem (4.5)-(4.6)

[1] The air drag ratio of a platoon is the sum of each individual vehicle's air drag ratio that they experience while in a platoon.

for two HDVs as

$$\begin{aligned}
\min_{v_1,v_2,v_p,s_m} \quad & v_1^2(s_m - s_s) + v_2^2 s_m + v_p^2(s_f - s_m)\phi_p && \text{(4.7a)}\\
\text{s.t.} \quad & t_f \geq \frac{s_m - s_s}{v_1} + \frac{s_f - s_m}{v_p}, && \text{(4.7b)}\\
& \frac{s_m}{v_2} = \frac{s_m - s_s}{v_1}, && \text{(4.7c)}\\
& v_1, v_2, v_p \in [v_{\min}, v_{\max}], && \text{(4.7d)}\\
& s_m \in [s_{\min}, s_f], && \text{(4.7e)}
\end{aligned}$$

where $t_f = \min\left((s_f - s_s)/v_{\text{nom},1}, s_f/v_{\text{nom},2}\right)$ denotes the tightest time constraint. We suppose $v_{\min} > 0$ and $s_{\min} \geq s_s$. The first term in the cost function (4.7a) represents the cost for the lead vehicle to merge, the second term the cost for follower vehicle to merge, and the third term the total cost for both vehicles to platoon. The first constraint (4.7b), which is a time constraint, ensures that the time to reach the destination when coordinating and forming a platoon should be less than or equal to the nominal case. If the lead vehicle slows down, it has to increase the speed once the platoon is formed in order to make up for the time loss. The second constraint (4.7c) is the time to the merging point, which ensures that both vehicles are at the same spot at the same time. The third constraint (4.7d) and the lower bound of the fourth constraint (4.7e) can be adapted depending on the scenario, e.g., if the vehicles are on different roads but the road will merge at some point, then the earliest point where the vehicles can form a platoon is at the junction $s_{\min}$. Note that $s_m \leq s_f$ forces the merge to occur before the vehicles reach the destination. This means that v_2 is always larger than v_1, more precisely, $v_2(1 - s_s/s_f) \geq v_1$.

The cost function (4.7a) should be less than the nominal cost, which is

$$v_{\text{nom},1}^2(s_f - s_s) + v_{\text{nom},2}^2 s_f, \tag{4.8}$$

as in Equation (4.3), with the assumption that $c_{\text{th}} = 0$. In order to make the comparison simple, we assume that $v_{\text{nom},1} = v_{\text{nom},2} = v$ for the nominal case. By including the second constraint (4.7c) into the cost function, we can rewrite problem (4.7) as the following platoon formation problem

$$\begin{aligned}
\min_{v_1,v_2,v_p} \quad & r_s \frac{v_1^3}{v_2 - v_1} + r_s \frac{v_2^3}{v_2 - v_1} + v_p^2\left(1 - r_s \frac{v_2}{v_2 - v_1}\right)\phi_p\\
\text{s.t.} \quad & \frac{1 - r_s}{v} \geq \frac{r_s}{v_2 - v_1} + \frac{1 - r_s \frac{v_2}{v_2 - v_1}}{v_p},\\
& v_1, v_2, v_p \in [v_{\min}, v_{\max}],\\
& r_s \frac{v_2}{v_2 - v_1} \in \left[\frac{s_{\min}}{s_f}, 1\right],
\end{aligned} \tag{4.9}$$

where $r_s = s_s/s_f$.

The platoon formation problem can easily be extended to form larger platoons from either two platoons or one vehicle and a platoon, by just multiplying the first term with ϕ_1 and second term with ϕ_2 in the cost function, such that ϕ_i would represent the total air drag ratio of vehicle/platoon i. We use a nonlinear solver (*fmincon* in Matlab) to solve the non-convex problem (4.9).

4.1.3 Special cases of single vehicle acting

Before solving the full platoon formation problem (4.9), we investigate two special cases in which only one of the vehicles acts. These catch-up and slow-down scenarios give more insight in the platoon formation problem.

Catch-up scenario

A catch-up is where the follower vehicle drives faster and merges with the lead vehicle, while the lead vehicle maintains its nominal speed v. Once the platoon is formed, the platoon keeps driving at the nominal speed. Hence, $v_1 = v_p = v$ and the objective function of (4.9) becomes

$$\min_{v_2} \frac{v^3}{v_2 - v} + \frac{v_2^3}{v_2 - v} - v^2 \frac{v_2}{v_2 - v} \phi_p. \tag{4.10}$$

The optimum can be found through the extreme points by taking the derivate of Equation (4.10) and setting it to zero and are given by the solutions to

$$2r_v^3 - 3r_v^2 + \varphi = 0, \tag{4.11}$$

where $r_v = v_2/v$ and $\varphi = \phi_p - 1$. This gives us one solution with $\varphi \in [0, 1]$ and $r_v \geq 1$. The result is shown in Figure 4.2 for different values of φ. The solution only holds if we guarantee that the vehicles merge before the destination (final constraint in (4.9)), i.e., $v_2(1 - r_s) \geq v$. Otherwise the follower vehicle has to drive faster in order to guarantee that a platoon is formed.

Slow-down scenario

Contrary to a catch-up scenario, the lead vehicle can slow down in order for the follower vehicle to merge at its nominal speed. In order to get an insight in how such slow-down occurs, we ignore the time restriction (constraint (4.7b)) of the problem, and assume that only the lead vehicle acts while the follower vehicle drives at nominal speed v throughout the whole process, hence, $v_2 = v_p = v$. This means that the lead vehicle has the same delivery time as the follower vehicle. The objective function (4.9) can then be written as

$$\min_{v_1} \frac{v_1^3}{v - v_1} + \frac{v^3}{v - v_1}(1 - \phi_p). \tag{4.12}$$

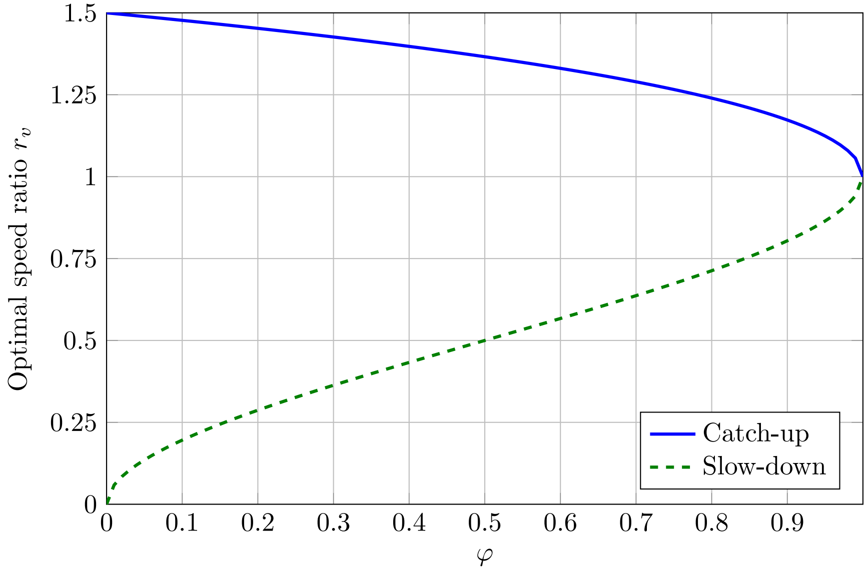


Figure 4.2: Optimal speed ratio for a pure catch-up and slow down, respectively, when only one vehicle acts.

This gives us the same third order equation as in Equation (4.11) to solve (where $r_v = v_1/v$). However the solution differs since we are now considering a slow down within the boundaries $r_v \in [0, 1]$. The optimal speed is shown in Figure 4.2. Note that although we ignore the time restriction, the lead vehicle does not stop and wait for the follower vehicle (unless the follower vehicle experiences no air drag at all, i.e., for $\varphi = 0$). Note also that the slow-down coordination is always more fuel efficient than the nominal case, since the average speed is lower due to the removed time constraint.

A realistic air drag reduction while platooning is 32 % ($\varphi = 0.68$) (Alam, 2014), which corresponds to about 10 m gap between the vehicles when platooning. This means that for a pure catch-up, the follower vehicle would need to drive 30 % faster to form a platoon. For a pure slow down, the lead vehicle would need to reduce its nominal speed by 38 % for a platoon formation.

4.1.4 Cooperative formation

We now show how cooperative platoon formation, where both vehicles act, compares to a pure catch-up, where only the follower vehicle acts. The slow-down scenario is not considered since it is not the same problem (due to the removed time constraint). Recall the platoon formation problem (4.9), where we solve this nonconvex problem using *fmincon* in Matlab. We set the initial guess of v_1, v_2, and v_p as the optimal solution from the special cases, i.e., if we assume $\phi_p = 1.68$ (no air drag reduction for

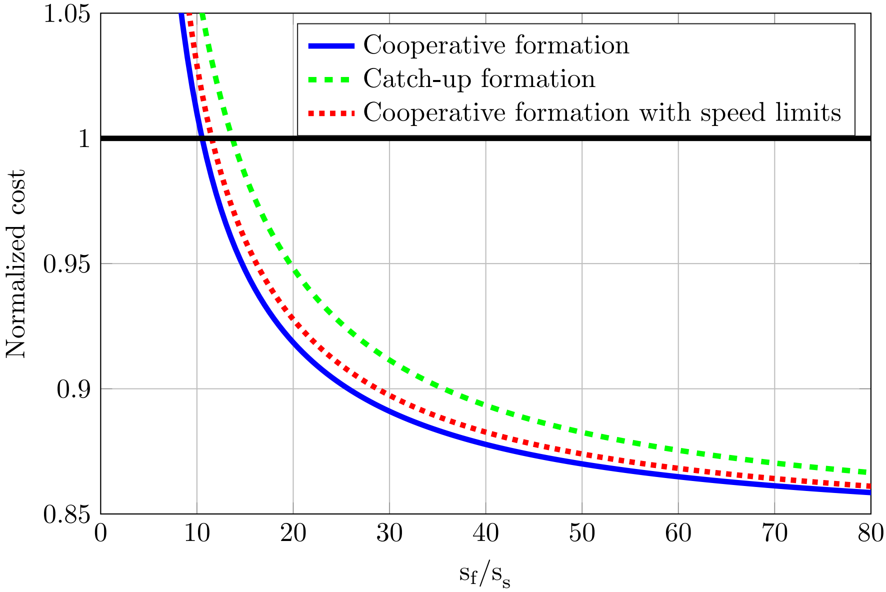


Figure 4.3: The normalized costs of the objective function value from Equation (4.7) for cooperative formation compared to a pure catch-up coordination from Equation (4.10) and compared to cooperative formation with speed limits set to ±12.5 % from nominal speed.

the lead vehicle and a 32 % air drag reduction for the follower vehicles in the platoon), our initial guess is $v_1^0 = 0.68v$, $v_2^0 = 1.32v$, and $v_p^0 = v$. We consider two cases, namely, an unbounded cases (i.e., $v_{\max}$ unbounded) and a bounded case, to take into account for physical speed limitations and driver's conveniency to not drive too slow on the highway. We set $\phi_p = 1.68$, $s_{\min} = s_s$, $v_{\min} = 0$, and the speed constraints to ±12.5 % of the nominal speed, which represent a realistic highway speed of $v = 80$ km/h with $v_{\min} = 70$ km/h and $v_{\max} = 90$ km/h. We solve the optimization problem for different initial values of the relative location r_s. The solutions for both the bounded and unbounded case are depicted in Figure 4.3 and 4.4. The cost is normalized with $v^2(2s_f - s_s)$, which is the nominal case and the speeds v_1, v_2, and v_p are normalized with respect to the nominal speed v.

We define a break-even ratio as the ratio of the distance to destination (or split) over the initial distance between the vehicles, i.e., s_f/s_s, for which the fuel cost is equal whether the vehicles form a platoon or drive independently. When s_f/s_s is larger than the break-even ratio, it is beneficial to form a platoon. In Figure 4.3, the break-even ratio for cooperative formation is 10.5. This essentially gives us a measure of how far each vehicle should look around for a possible candidate to form a platoon with. If there is another vehicle within a $\frac{100}{10.5}$ % of the distance to the

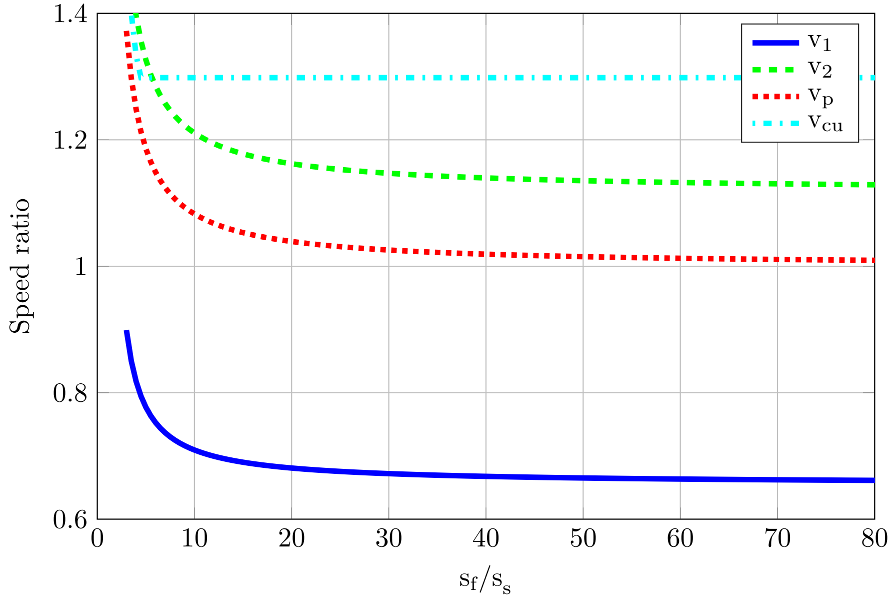


Figure 4.4: The optimal speed ratios (speeds normalized with v) for cooperative formation (v_1,v_2,v_p) compared to a pure catch-up coordination (v_{cu}) for different distance ratio s_f/s_s.

destination, then it is a possible candidate, given that both vehicles cooperate to form a platoon.

If we compare the results of cooperative formation with the pure catch-up coordination, we see in Figure 4.3 that the break-even ratio is 10.5 and 13.5, respectively. This follows the intuition as if both vehicles act to form a platoon, the platoon can be formed earlier and the vehicles can platoon for a longer distance compared to if only one vehicle acted. In Figure 4.4, we see the speeds for both cases and note that the speed up (v_2) of the cooperative formation is considerably lower than the pure catch-up speed (v_{cu}) due to the fact that the lead vehicle assists the platoon formation by slowing down (v_1). Although the cooperative formation is more fuel efficient than a catch-up, as the distance ratio s_f/s_s grows, the savings converge to the same value, which is $\phi_p/2$. If we now look at the results of cooperative formation with speed constraints in Figure 4.3, we see that the normalized cost does not differ too much from the unbounded cooperative formation problem, making this approach applicable in practice.

4.2 Cooperative formation for N HDVs

In this section, we extend the platoon formation problem to N vehicles, where the vehicles have the possibility to form small sub-platoons or longer platoons. As the number of vehicles grows, the complexity grows out of hand quickly and therefore it is not evident how such formation should be done. We continue assuming that the vehicles are on the same road and present an algorithm that enables platoon formations without looking into all possible combinations of platoon formations.

4.2.1 Coordination algorithm

The coordination of two vehicles to form a platoon is quite straightforward; either the platoon formation is executed or it is not, depending on whether fuel savings are obtainable. However, when several vehicles with different destinations are involved, the decision-making is no longer an easy task. By only considering different configurations of platoon formations and not how they are executed, there are a total of $\sum_{k=2}^{N}\binom{N}{k}$ different configurations. This does not include the possibility to form several sub-platoons, making the number of possibilities even larger. Even by considering a simpler scenario in which all vehicles have the same destination, there are a total of $2^{N-1}-1$ different platoon configurations (assuming no overtaking), including the possibility for sub-platoons, that can be executed. This gets quickly out of hand with increased number of vehicles. We therefore suggest a coordination algorithm based on heuristic that only considers the relevant candidates and in which the complexity grows in a gentler manner.

The obtained results from cooperative platoon formation for two HDVs gave us two insights that serve as the main idea for the coordination algorithm. The first insight is the break-even ratio, which describes how far around (in space) a vehicle should search for potential platooning candidates. Secondly, the closer a candidate is, the higher potential fuel savings can be achieved, given the same destination. From these insights, we propose a coordination algorithm, as illustrated in Figure 4.5. The algorithm handles single vehicles forming a platoon as well as platoons forming larger platoons. A platoon's destination is defined as where the platoon splits up. Also, vehicles and platoons that are in the process of forming a (larger) platoon are not considered as possible candidates for formation until the platoon has been formed. We first describe the coordination algorithm from top to bottom then describe the sidestep on the right side.

Let H be any ordered set of all the vehicles and platoons. Calculate the break-even ratio (for the unbounded problem in Equation (4.9)) for all $h_i \in H$, i.e., $\frac{100}{10.5}$ % of the distance to the destination. This break-even ratio serves as a horizon (in space) of interest in which each vehicle looks for possible platooning candidates. Note that the horizon shrinks as the vehicle travels closer to the destination. Select the first unit in H and find the closest neighboring (both back and front) vehicles within the horizon of interest. Calculate the potential fuel savings from a cooperative formation (4.9) and if the candidate also find h_i to be the closest fuel-saving partner, then these two vehicles are considered as a possible pair. This is repeated for all $h_i \in H$. The set H can be represented as a graph network, where each vehicle $h_i \in H$ is a node in the graph. An edge between the nodes are established only if there is a fuel saving neighbor within the horizon of interest, i.e., the possible platooning pair,

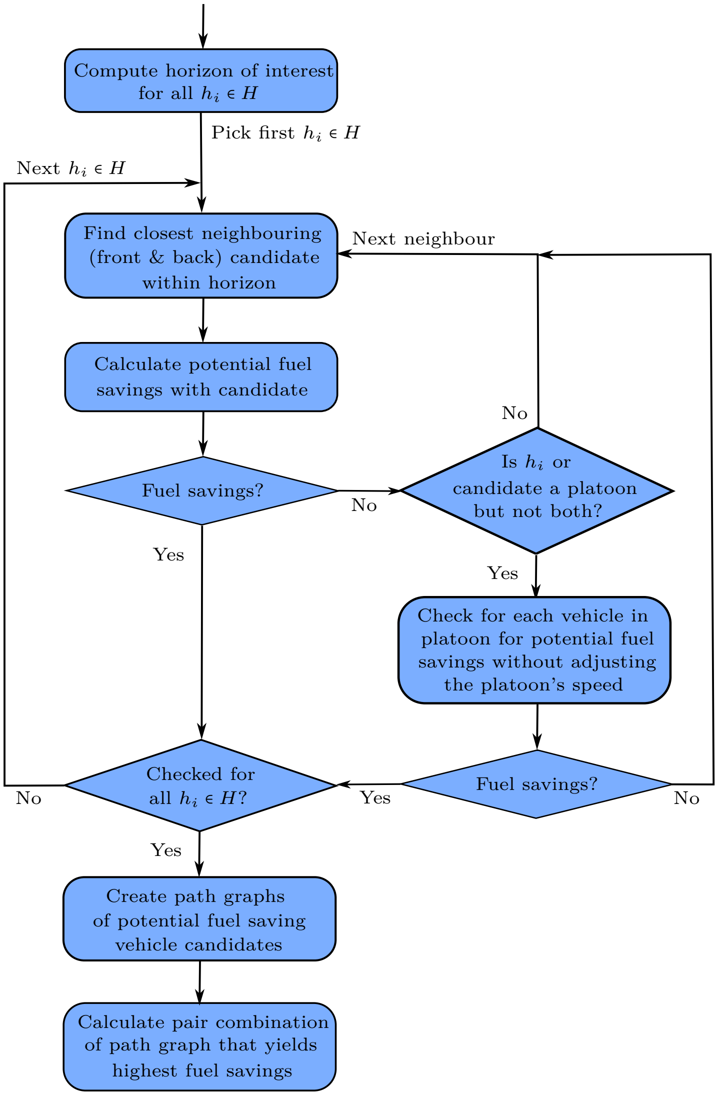


Figure 4.5: Flowchart of the coordination algorithm.

with the edge weight represented by the potential fuel savings. Therefore, the graph network may consist of several disjoint path graphs. The number of nodes in a path graph can vary from 2 to N nodes depending on how many vehicles are within each other's horizon of interest that are possible pairs with each other. Note that each vehicle h_i can have up to two candidates, one in the front and one in the back. This is also reflected in the path graph with each node having a maximum of two other

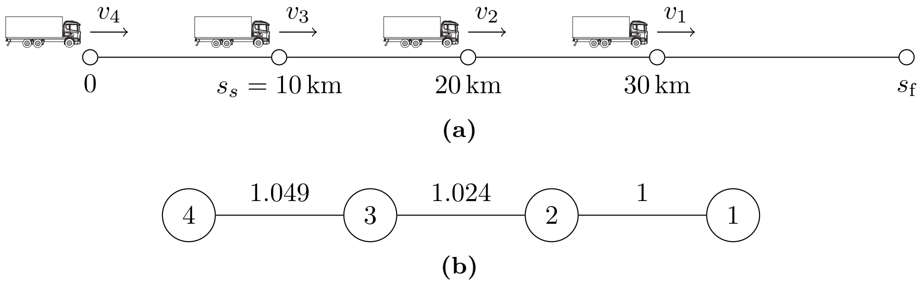


Figure 4.6: Four vehicles equidistantly from each other with the same destination. The algorithm represents this scenario as a path graph with the potential fuel savings as edge weights.

nodes connected by an edge each. For each path graph, the best pair combinations are easily calculated through dynamic programming (Bertsekas, 2012) (which the complexity grows linearly for such problem) for highest savings, since a node (h_i) can only pair up with the candidate in front or behind, but not both.

If a unit h_i does not find any fuel savings with a candidate (sidestep in Figure 4.5), then we check if either (but not both h_i and its candidate) is a platoon. If either h_i or its candidate is a platoon, then we check for each vehicle in the platoon if there are potential fuel savings when coordinating with one of the vehicles in the platoon given that we do not adjust the platoon's speed. For example, this can be when the platoon needs to split soon, however one of the vehicles travels to the same destination as h_i. Notice that we do not adjust the platoon's speed only when we cannot find any fuel savings before the platoon's split point. This allows us to still coordinate platoons with platoons in order to form larger platoons given that they can save fuel before their respective split points. If we cannot find any fuel savings before the platoon's split point, then we check if there are any fuel savings if any single vehicle acts by itself.

4.2.2 Examples

We give three examples to illustrate the strengths and weaknesses of our proposed algorithm in different scenarios. Note that the algorithm in Figure 4.5 can be executed several times and as soon as a vehicle or platoon enters the road or when a platoon is formed or split.

Four vehicles forming a large platoon

Consider the scenario depicted in Figure 4.6a with four HDVs that are equidistantly s_s from each other and the last vehicle is a distance s_f from the common destination. Let us assume that s_f = 430 km, $v_{\min}$ = 70 km/h, $v_{\max}$ = 90 km/h, and nominal speed v = 80 km/h.

The first step is to compute each vehicle's horizon of interest, which is a factor of 1/10.5 (obtained from the unbounded platoon formation problem (4.9) for two vehicles) of the total distance to destination. In this case the horizons are 38, 39, 40, and 41 km respectively for vehicles 1 to 4, meaning that all vehicles are within each other's horizon of interest. Starting with vehicle 1, the closest candidate is vehicle 2 at the back and none in front. The distance ratio between vehicle 1 and 2 is 41, which according to Figure 4.3 will yield fuel savings. Let us assume that the coordination yields one unit of saved fuel. Next, we check vehicle 2 who has vehicle 1 and 3 as its nearest neighbors. The fuel saving between vehicle 1 and 2 has already been calculated. For vehicle 2 and 3, the distance ratio is 42 and therefore the fuel savings (obtained from Figure 4.3) yields 1.024 units. Continuing with the rest of the vehicles, we obtain a path graph as depicted in Figure 4.6b. From this, the most fuel-saving pair combination is to pair vehicle 1 with 2 and vehicle 3 with 4 to achieve a total of 2.049 units fuel saved. While all four vehicles are coordinating, they are not considered in the algorithm until the platoons have been formed, which in this example occurs at the same time. Once the platoons have been formed, the next platoon formation is executed. At this point, the first and second platoon are 365 km and 385 km, respectively, away from the destination. Both platoons are within each other's horizon of interest. By calculating the fuel savings, it is more efficient to form a larger platoon. This can be done by multiplying the first term in Equation (4.9) with $\phi_{p,1} = 1.68$ (32 % air drag reduction for follower vehicle in platoon) and second term with $\phi_{p,2} = 1.68$ and set $\phi_p = 3.04$ and solving the platoon formation problem.

Four vehicles forming two sub-platoons

Consider the same scenario as in the previous example, but instead with $s_f = 330$ km. In this case, the resulting path graph is similar to that in Figure 4.6b with just slightly higher numbers, hence the algorithm also pairs vehicle 1 with 2 and vehicle 3 with 4. Again, the algorithm reiterates once the platoons have been formed. Once the platoons have been formed, the first platoon is 265 km away from the destination and the second platoon is 20 km behind. With these conditions, the algorithm does not find it beneficial to a form a larger platoon and the sidestep of the algorithm is ignored since both vehicle pairs are in platoons. Hence the algorithm stops with two sub-platoons. This is more clear in Figure 4.7 where the cost of forming a large four-vehicle platoon (in two steps, as in previous example) compared to two sub-platoons is depicted. The cost is equal when the distance ratio $s_f/s_s = 38$, meaning that for lower distance ratio values, forming two sub-platoons is more fuel efficient than forming a larger platoon of four vehicles and vice versa.

Three vehicles with different destinations

Consider the scenario in Figure 4.8 where each vehicle has a different destination denoted by their respective numbers. Let us assume that $s_{s,2} = 20$ km, $s_{s,1} = 30$ km,

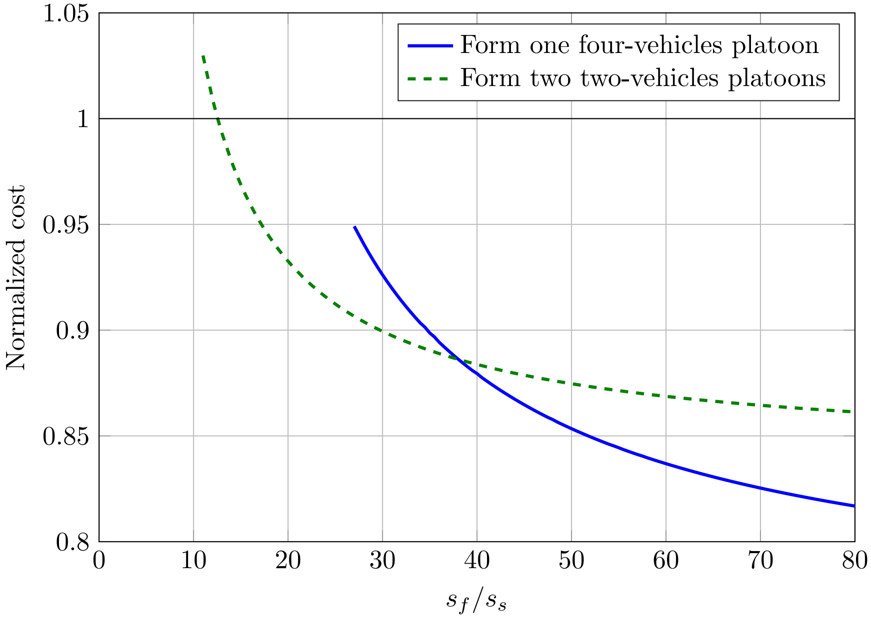
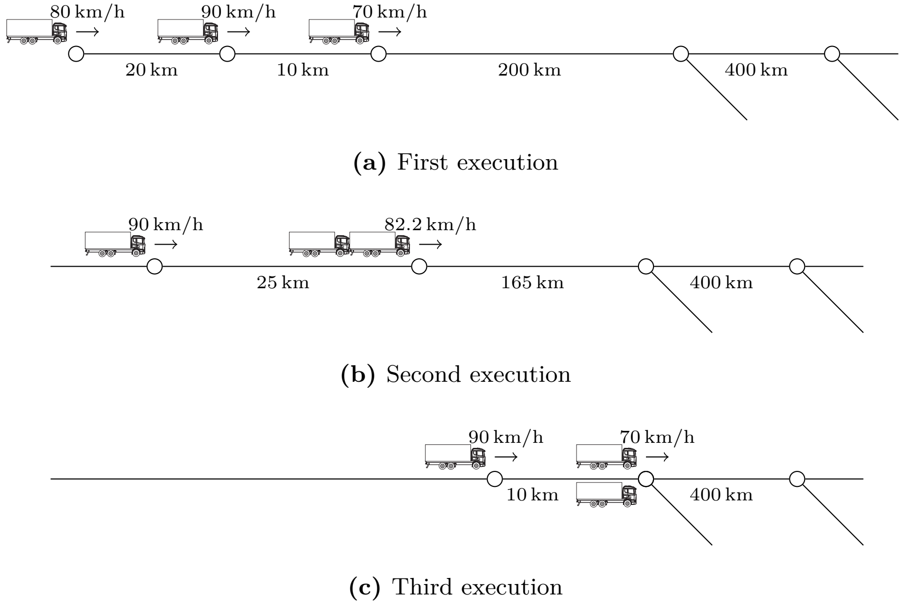


Figure 4.7: Four vehicles forming a large platoon in two steps (first forming two two-vehicles platoon followed by forming a four-vehicles platoon) compared to only forming two sub-platoons based on the scenario depicted in Figure 4.6a with boundary values $v_{\min} = 70\,\text{km/h}$, $v_{\max} = 90\,\text{km/h}$, and $v = 80\,\text{km/h}$. The distance ratio s_f/s_s, where s_f is the distance to destination for last vehicle and s_s is the last vehicle's distance to the vehicle ahead. It is assumed that all the vehicles are initially equidistantly spaced from each.

Figure 4.8: Three scattered vehicles on the road with different destinations denoted by their respective numbers.

$s_{f,1} = 230\,\text{km}$, $s_{f,2} = 630\,\text{km}$, $v_{\min} = 70\,\text{km/h}$, $v_{\max} = 90\,\text{km/h}$, and $v = 80\,\text{km/h}$. Looking at the distance ratio between the vehicles, we have a distance ratio of $210/10 = 21$ between vehicle 1 and 2, $230/20 = 11.5$ between vehicle 2 and 3, and $630/30 = 21$ between vehicle 1 and 3. We know from Figure 4.3 that, given the conditions with speed limits, the break-even ratio is 11.5, which is exactly what the distance ratio between vehicle 2 and 3 is. This means that the potential fuel savings between vehicle 2 and 3 are 0 %. So vehicle 3's nearest fuel-saving candidate is vehicle 1. However, vehicle 1 also checks its nearest fuel-saving candidate, which



(a) First execution

(b) Second execution

(c) Third execution

Figure 4.9: A sequence of each moment where the coordination algorithm makes a decision for the scenario depicted in Figure 4.8.

is vehicle 2. As vehicle 1 and 2 are mutual candidates, vehicle 1 does not consider vehicle 3 as it is further away behind vehicle 2. Therefore, the only possible pair is vehicle 1 and 2. Thus, in this step, only vehicle 1 and 2 forms a platoon while vehicle 3 maintains its speed (see the first execution in Figure 4.9a). While vehicle 1 and 2 are merging, they are not considered in the algorithm until the platoon has been formed. Once vehicle 1 and 2 have merged into a platoon, the platoon has 165 km before they split and vehicle 3 is 25 km behind the platoon. Thus, the distance ratio between the platoon and vehicle 3 is 190/25 = 7.6 and there is no fuel savings when coordinating vehicle 3 with the platoon to the split point. However, vehicle 3 is not a platoon, therefore the algorithm calculates if there are any fuel savings by coordinating with any of the vehicles within the platoon. Since vehicle 1 travels the same road as vehicle 3 for a long stretch, there are potential fuel savings even without adjusting the platoon's speed and if only vehicle 3 acts. Therefore, vehicle 3 will drive faster to catch up with the platoon while the platoon maintains its speed, see second the execution in Figure 4.9b. Once the platoon splits at the splitting point the algorithm is recomputed. At this point, vehicle 1 slows down (as vehicle 3 is already driving faster) so the platoon is formed faster, see the third execution in Figure 4.9c. With these actions, the algorithm allowed the vehicles to totally save 5.52 % compared to if no coordination was executed at all. If we look closer, vehicle 3 could have actually started catching up while vehicle 1 and 2 where merging to form a platoon. So instead of vehicle 3 maintaining its speed (80 km/h), it could have driven faster (90 km/h) to not increase the gap between the vehicles and then merge even earlier than our suggested actions. With this action, the vehicles could have saved up to 5.81 %. Our proposed algorithm is close the that saving despite just considering pairwise coordination compared to a more sophisticated coordination that is required to achieve that saving.

4.3 Simulation evaluation

In this section, we validate our approach for cooperative platoon formation using an advanced vehicle model used at Scania. The purpose is to evaluate the assumptions we made to formulate our platoon formation problem (4.9) and if the savings are aligned with the advanced model, such that the decision to platoon is made correctly. Note that we did not implement the platoon formation algorithm in the advanced model, but set up the conditions so we could compare the results. First, we describe the setup of the simulation and the simulation model itself. Then, we simulate the vehicles on a moderate hilly road in which we compare the results with.

4.3.1 Simulation setup

The setup is to coordinate two HDVs, each with a 6×2 configuration and 480 hp engine with a 12 speed gearbox, to form a platoon driving from Södertälje to Jönköping in Sweden and compare the fuel cost to if the vehicles were driving alone. The road is approximately 280 km long. The altitude and the slope of the road are depicted in Figure 4.10. This is considered as a moderately hilly road.

We evaluate for the distance ratio $s_f/s_s = 23$, which corresponds to an initial distance of 12.2 km between the vehicles. According to our theoretical results (with $v_{\min} = 70$ km/h, $v_{\max} = 90$, and $v = 80$ km/h), we should achieve 8.4 % air drag reduction in average compared to if the vehicles were driving alone. The vehicles are calculated to merge approximately after the first vehicle has driven 44.7 km (56.9 km for the second vehicle). Note that our fuel-optimal speed (obtained from the platoon formation problem) dictates the average speed the vehicle should drive in order to form a platoon. However, a dedicated cruise control (CC) aimed at maintaining an average speed over a longer distance has not been implemented. Therefore, we simply set the CC set speed as the fuel-optimal speed.

4.3.2 Simulation model

To evaluate the experiment, we simulate the scenario using a validated simulation model from Scania that produces reliable results and replicates the real-life behavior of an HDV (Sandberg, 2001). The model was constructed in Dymola, based on the Modelica modeling language. The simulation model considers individual parts in the powertrain such as the engine, clutch, gearbox, auxiliary systems, axles, among others, which are modeled in detail. The model also includes the full braking system,

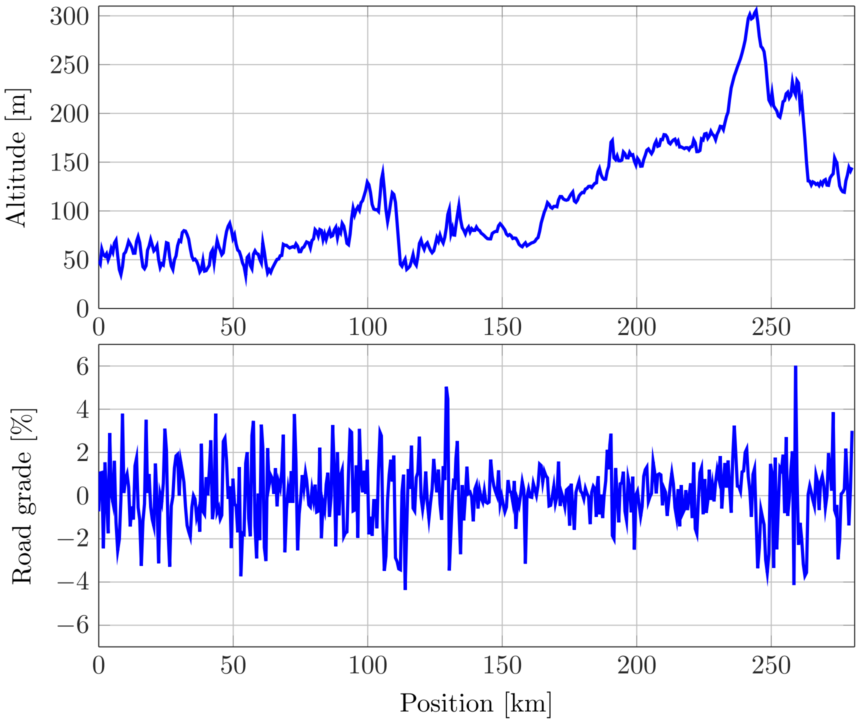


Figure 4.10: The road profile with altitude (top) and road grade (bottom) of Södertälje – Jönköping.

taking into account the nonlinear behavior of the system, including internal brake friction, and the complex model of roll resistance, which depends on the dynamics of the tires, such as tire temperature, vehicle speed, and wheel radius. The braking system includes the exhaust brake, retarder brake, and service brake (wheel brake). The air drag reduction is modeled as a constant, set at 0 % reduction when driving alone and 32 % reduction when driving behind another HDV without any transient phase. The gear shifting logic behind the gearbox is controlled by software used in real-life HDVs. A controller area network (CAN) system is also modeled, which describes the interaction between electronic control units (ECU), actuators, and physical properties of the HDV. The model consists in total of 4482 variables, 943 equations, and 441 states describing a single HDV. The model includes different driver models and features such as CC and downhill speed control (DHSC).

4.3.3 Södertälje – Jönköping road profile

We set both vehicles to the same weight, and simulated for three different vehicle masses; 20 t, 40 t, and 60 t. Although our decision-making with the platoon formula-

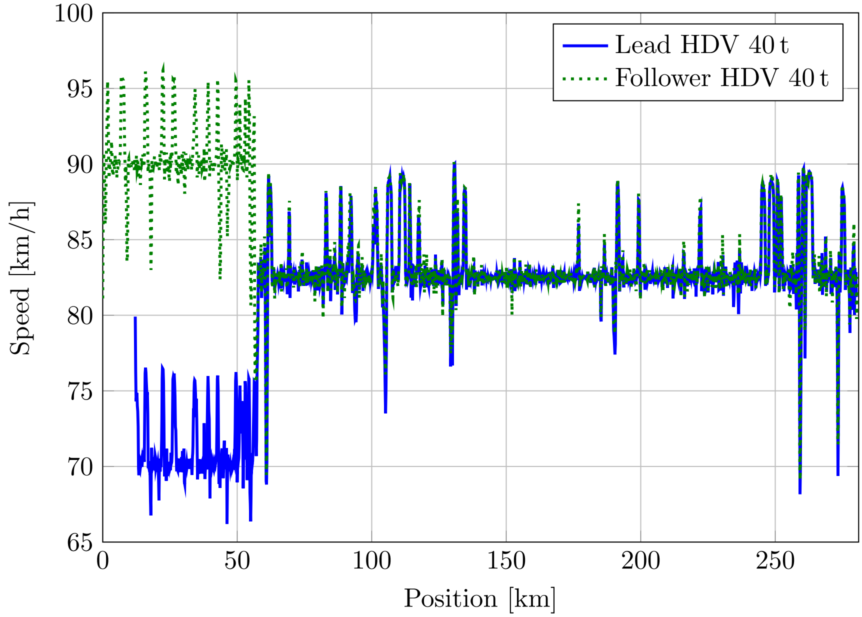


Figure 4.11: Speed profiles when executing a cooperative formation on the Södertälje – Jönköping road when $s_f/s_s = 23$.

tion problem (4.9) does not depend on the vehicle mass, the actual fuel saving (in percent) and the simulation model does, thus, the different values of vehicle masses. For each weight we simulated twice, with and without platoon formation, in order to see the savings that we obtain. The speed profiles of a cooperative formation for two 40 t HDVs are depicted in Figure 4.11. We see that both vehicles start at 80 km/h. Then the lead vehicle slows down to 70 km/h while the follower vehicle drives faster at 90 km/h. At position 57 km, we see that the follower vehicle slows down to match the speed of the lead vehicle before they accelerate and drive at 82.5 km/h to ensure that the lead vehicle is not delayed. The merging maneuver are depicted for all vehicle masses in Figure 4.12. For this particular road, if an HDV were to drive exactly at 80 km/h throughout the whole stretch, the air drag would constitute of 59 %, 42 %, and 32 % of the total force for 20 t, 40 t, and 60 t vehicle mass, respectively. This gives an estimated energy savings of 4.9 %, 3.5 %, and 2.7 % for 20 t, 40 t, and 60 t, respectively.

Table 4.1 shows the simulation results for the three different vehicle masses. We note that the merge point deviated from our theoretical expectations for all three setups. This is due to the road topography causing the vehicles to deviate from their set speeds, which can be noted in the average speeds. The average speeds in general for almost all cases were higher than recommended, which leads to a delayed merge point except for the 20 t case. That is because we assumed that once the follower

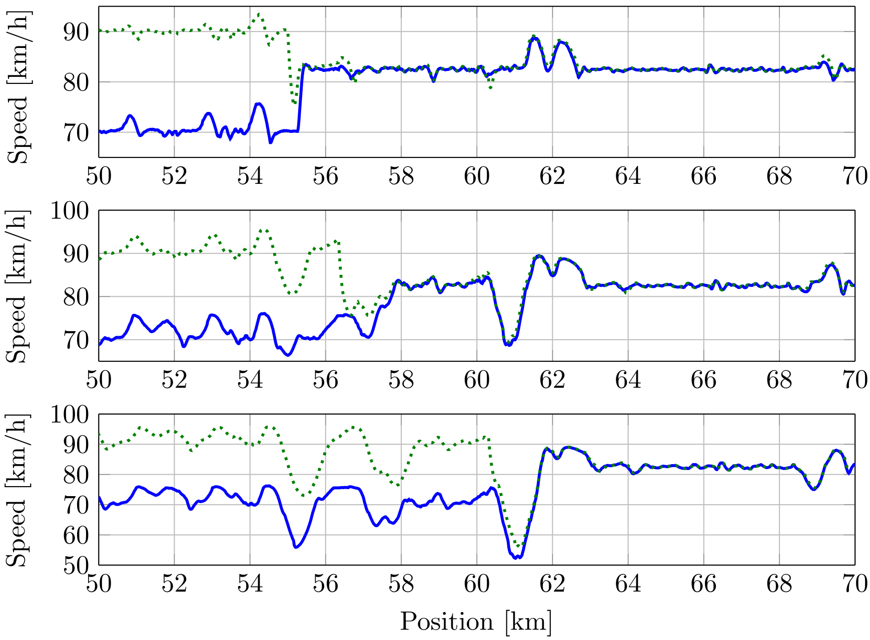


Figure 4.12: The merging maneuver for 20 t (top), 40 t (middle), and 60 t (bottom) vehicles when executing a cooperative formation. The merging point differs between the vehicle masses due to the variation of road slope that affected the speed of the vehicles.

Table 4.1: The results from making a platoon formation compared to the nominal case of not coordinating for $s_f/s_s = 23$.

Södertälje–Jönköping	20 t	40 t	60 t
$\bar{v}_1$ [km/h]	70.6	71.2	70.9
$\bar{v}_2$ [km/h]	90.2	90.3	88.7
$\bar{v}_p$ [km/h]	82.8	82.8	82.1
Merge point [km]	56.6	58.0	61.7
Energy savings [%]	3.8	2.2	1.7

vehicle starts to slow down to match the speed of the lead vehicle, the coordination phase is over, which occurred when the vehicles are approximately 100 m away from each other. In our theoretical results, the merging point is when the vehicles are at the same position. For the 60 t case, the road was too hilly for the follower vehicle to be able to maintain 90 km/h. We note that all three setups saved energy when executing a platoon formation. The energy savings might be a little bit less than we anticipated and this is due to two reasons. One is that the vehicles were not driving at 80 km/h the whole stretch, but varied in speed, which leads to increased energy use. Secondly, the merge occurred later than expected, which meant less time spent as a platoon.

4.4 Summary

We investigated how to form platoons of two or more HDVs through on-the-fly coordination without delaying the transport with the aim of minimizing the total fuel consumption. For the two vehicle case, we formulated the problem as an optimization problem based on average speeds (nominal speed, coordination speed, and platooning speed) as well as on the air drag reduction the HDVs experience once the platoon is formed. The optimal solution is for both the vehicles to adjust their speeds. The lead vehicle slows down while the follower vehicle increases its speed in order to execute a fuel-efficient platoon formation. Once the platoon has been formed, the platooning speed is adjusted to match the delivery time. In practice, where there are traffic and physical constraints (that can be modeled as speed constraints), the resulting optimal merging speeds are in most cases on the constraint boundaries, with a platoon speed that matches the time constraint. When considering platoon formation of several vehicles, a pairwise coordination, which is to coordinate with the closest fuel-saving neighbor, is a sufficiently good strategy that yields noticeable fuel savings. Once the paired vehicles have formed a platoon, one can then consider making a new pairwise coordination if more potential fuel savings exist. In this way, the platoon formation algorithm is scalable. Lastly, we evaluated our coordination approach with an advanced model used in Scania, which suggested that our results are applicable in practice.

Chapter 5

The influence of traffic on platoon formation

"Why do we call it rush hour when nothing moves?"
Robin Williams

Heavy-duty vehicle (HDV) platooning is a means to reduce the fuel consumption and increase the traffic capacity. However, as many HDVs have different start locations, destinations, and time constraints, many vehicles will drive solo. One way to increase the number of platoons is to coordinate the vehicles on the fly and adjust their speeds in order to form platoons. An algorithm to form platoon with the closest fuel-saving neighbor was proposed in the previous chapter. As the HDVs are not the only ones driving on the road, there are traffic and other road users that need to be considered, as they may delay when platoons are formed. The longer the delay is, the less fuel the platoon will save and if the delay is too large, the formed platoon may not save any fuel. Furthermore, if the lead vehicle slows down to form a platoon, then at some point it needs to abort the formation in order guarantee its own transport assignment. If the platoon formation is aborted during execution then the overall fuel cost would be higher than if the vehicles were driving independently to their destinations. It is therefore important to estimate where the platoon will be formed with respect to the current traffic condition, in order to guarantee that the platoon formation saves fuel and still delivers the cargo in time, despite some disturbances from surrounding traffic. For clarity, we use the term (passenger) car for the vehicles that we cannot control and that we do not consider in our platoon formation. They act as a disturbance to our platoon formation.

The outline of this chapter is as follows. In Section 5.1, we describe an HDV that is driving slower than the rest of the traffic as a moving bottleneck. In Section 5.2, we extend the idea of moving bottleneck to two HDVs in order to predict how the traffic conditions evolve in time and space to estimate when the HDVs merge. In Section 5.3, we compare our estimation with the results from a microscopic traffic simulation. Lastly, a summary in Section 5.4 concludes this chapter.

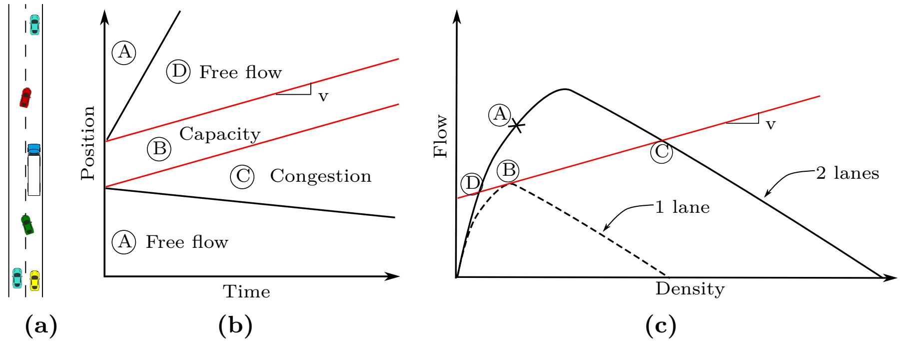


Figure 5.1: (a) An HDV is a moving bottleneck on the highway blocking one lane. (b) The HDV's movement in space and time and the evolution of traffic condition caused by the HDV. (c) Fundamental diagram of a 2-lane road and the corresponding diagram when one lane is blocked by the HDV (dashed), which we assume is half of the 2-lane diagram. The different traffic conditions that are caused by the moving bottleneck are indicated in the space-time domain and the fundamental diagram.

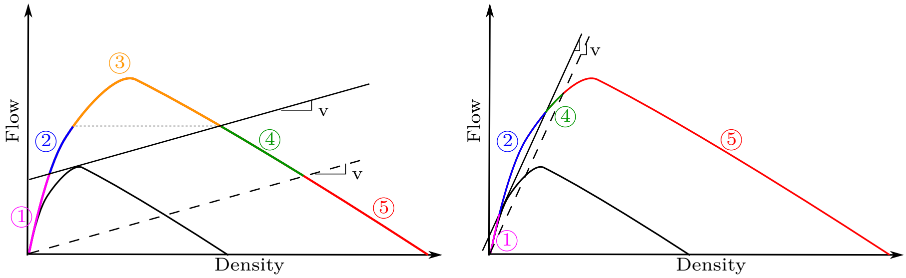
5.1 Moving bottleneck

Recall from Section 3.3 that the average state of the traffic can be described on a macroscopic level as flow, density, and speed. The relation of the variables is

$$q = ku, \tag{5.1}$$

where q denotes the flow, k the traffic density, and u the average traffic speed. The relation is often described using a fundamental diagram. HDVs, however, do not behave the same as passenger cars, due to their large mass and physical limitations. HDVs accelerate and decelerate slower, they cannot maintain their speed as they lose speed during ascents and gain speed during descents, and their speeds are limited due to legislations, thus moving slower than the rest of the traffic. Additionally, as an HDV is moving slower than the rest of the traffic and is occupying one lane, it throttles the overall traffic throughput. This can be modeled using the macroscopic density-flow relation and considering the HDV as an entity in the flow. The HDV in such case is also known as a moving bottleneck (Newell, 1998; Leclercq et al., 2004).

Consider the scenario in Figure 5.1a where an HDV is traveling on the rightmost lane of a 2-lane road. Assume that the current traffic condition is A when the HDV enters the road at a constant speed v that is slower than the rest of the traffic. The HDV is essentially blocking one lane such that the segment just beside the HDV on the left lane is at full capacity, see Figure 5.1c. This is also represented by area B in the space-time plot in Figure 5.1b. This limited capacity leads to a separation in traffic condition behind and ahead of the HDV (recall the shockwave theory in Section 3.3.4). There is a free flow downstream (D) of the moving bottleneck and a congestion upstream (C) of the moving bottleneck. Cars driving in the upstream



(a) Slow moving bottleneck

(b) Fast moving bottleneck

Figure 5.2: Five different zones when considering a moving bottleneck. Depending on where the current traffic state is in the five zones when an HDV (the moving bottleneck) enters the road, a congestion can appear upstreams of the HDV. Zone 3 does not exist for a fast moving bottleneck.

congestion drive slower due to the throttled flow by the HDV (the slope from C to the origin) and once the cars pass the HDV, they are able to drive faster (at their own desired speeds). The shockwave speed that separates the free flow (D) and congestion (C) is the HDV speed v itself. Note that the HDV speed (red line) is tangent to the scaled-down version of fundamental diagram. The evolution in time and space for shockwaves between other traffic conditions are obtained by the same slope as the line between the traffic conditions in the fundamental diagram.

By knowing the traffic state as the HDV enters the highway, we can predict how the traffic will evolve in time and space. Figure 5.2a illustrates five different zones in the fundamental diagram with an HDV driving at speed v and is considered as a slow moving bottleneck. If the current traffic condition is in zone 1 when the HDV enters the highway, there will be no congestion created upstream of the HDV as the traffic is very light and cars can easily pass by the HDV. In zone 2, the traffic is still considered light, however, the amount of cars coming behind the HDV is higher than the amount of cars passing the HDV, leading to a small but not persistent congestion. A persistent congestion is where the congestion grows backwards (in absolute position) from where the shockwave started, i.e., where the HDV entered the road. Note that a non-persistent congestion can still grow in size over time although the back of the congestion does not propagate backwards. In zone 2, the congestion is not persistent as the congestion moves forward. If the traffic condition is in zone 3, then when an HDV enters the road there will be a persistent congestion that will continue to grow upstreams. In zone 4 with heavy traffic, the HDV is driving slightly slower than the rest of the traffic, however no queue or congestion appears behind the HDV as the traffic is already in a congested state. Lastly, in zone 5, the traffic is so congested that the traffic speed is lower than v, thus the HDV cannot drive at speed v but instead follows the speed of the traffic flow (i.e., we assume that the vehicle speed is equal to the traffic speed), and no queue caused by the vehicle appears upstream.

If the moving bottleneck is moving faster such that the upstream condition intersects the fundamental diagram before the critical density, as illustrated in Figure 5.2b, then zone 3 does not exist. All other zones remain the same as for a slow moving bottleneck. Thus, for a fast moving bottleneck, persistent congestion does not appear.

5.2 Merge estimation

In a platoon formation, at least two HDVs are involved and they are each a moving bottleneck along the road. For simplicity, let us assume that the traffic condition is initially homogenous throughout the highway when the HDVs enter at different segments of the road. Each HDV separates the traffic condition into a free flow region downstream and a congestion region upstream the vehicle (unless the vehicles are already in a congestion). The separation and shockwave may differ between the HDVs as they may drive at different speeds. In the previous chapter, we suggested to form platoons pairwise, hence we consider two HDVs when describing the merge estimation of a platoon formation.

In a platoon formation, the surrounding traffic may interfere during the merging maneuver. We try to estimate when the platoon will be formed, that is the merge point, depending on the traffic condition. We treat the HDVs as individual entities while the surrounding traffic as flow. We use the theory of moving bottleneck described in previous section to predict how the traffic conditions will evolve in space and time, in order to predict how each HDV will move. The interesting segment is between the HDVs, how the congestion behind the first HDV and the free flow ahead of the follower HDV interact in space and time. This interaction tells us whether the follower HDV will face a congestion or not as it gets closer to the lead HDV.

Consider the case with two HDVs, initially apart, where the lead vehicle is driving at v_1 and the follower vehicle at v_2 under the traffic condition (1) as denoted in Figure 5.3. For simplicity, we assume that both vehicles entered the highway at different segments simultaneously. The interesting segment is the congestion upstream of the lead vehicle (2) and the free flow downstream of the follower vehicle (3). Based on this, we can predict how the traffic will evolve in space and time. Figure 5.4 illustrates four time instances of how the different traffic condition evolve. In Figure 5.4a, each HDV separates the traffic into a free flow and a congestion area. The HDV trajectories are illustrated with red and orange arrowed line. The free flow downstream the lead vehicle and the congestion upstream the follower vehicle do not affect the merging manuever of the platoon, and therefore those shockwaves are dashed. The shockwave color and traffic condition number represent the same color and number in the fundamental diagram in Figure 5.3. In Figure 5.4b, the free flow downstream the follower vehicle (3) catches up to the congestion upstream the lead

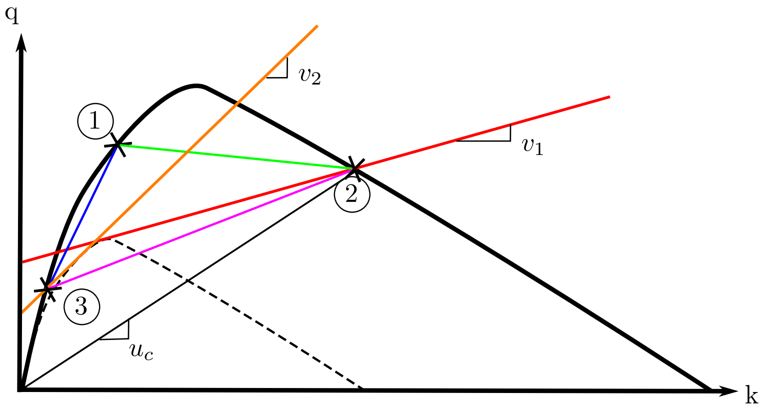


Figure 5.3: Two HDVs (lead vehicle driving at v_1 and follower vehicle at v_2) and the different shockwaves caused by the vehicles. (1) indicates the traffic condition as the HDVs enter the highway, (2) the congestion upstream of the lead vehicle with its corresponding traffic speed u_c, and (3) the free flow downstream of the follower vehicle.

vehicle (2) and this interaction creates a new shockwave (pink line). The congestion shrinks since there are less cars coming due to the follower vehicle throttles the flow. In Figure 5.4c, the follower vehicle catches up to the congestion between the vehicles. As it enters the congestion, it can no longer maintain the speed v_2, and drives at a lower speed u_c together with the rest of the traffic. In Figure 5.4d, the follower vehicle finally catches up to the lead vehicle and completes the platoon formation. This point is the estimated merge point for the two HDVs given the traffic condition is (1). In summary, the lead HDV drives at v_1 at all times, while the follower HDV drives v_2 until it reaches the congestion created by the lead vehicle and then drives u_c until it catches up to the lead vehicle. This is obtained by the following steps

1. Check if both HDVs can maintain their desired speed in the current traffic condition,

2. Calculate shockwaves of the congestion upstream of the lead HDV and the free flow downstream of the follower HDV,

3. Calculate new shockwave of the interaction between congestion and free flow,

4. Calculate when follower HDV reaches the congestion,

5. Calculate when follower HDV driving in congestion driving at lower speed reaches lead HDV.

Note that if the traffic is too dense and the traffic speed is lower than v_1, then the follower HDV will never be able to catch up with the lead HDV.

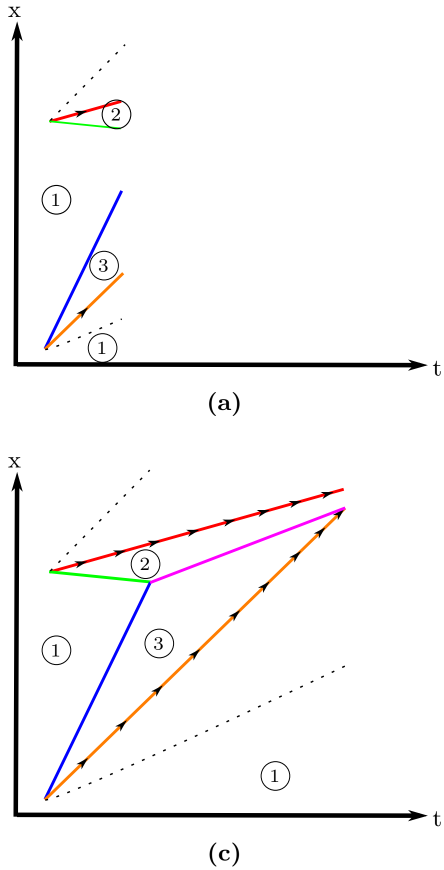


Figure 5.4: The evolution of the traffic condition in time and space when forming a platoon of two HDVs. The arrowed lines indicate the HDVs' profile and the colored shockwaves and numbers are the same as in Figure 5.3. The follower vehicle drives at v_2 until it reaches the congestion caused by the lead vehicle and will drive slower till it reaches the lead vehicle, that is when the platoon formation is completed. The small black cross on the red arrowed line indicate where the HDVs would have merged in absence of traffic.

5.3 Traffic simulation

In order to investigate the interaction between a merging maneuver and traffic, and to verify our merge estimation approach, a simulation is conducted. We use a microscopic traffic simulation tool from Deng and Ma (2015), which we shortly describe here. We kindly refer the interested reader to the paper for more in-depth information regarding the simulation platform.

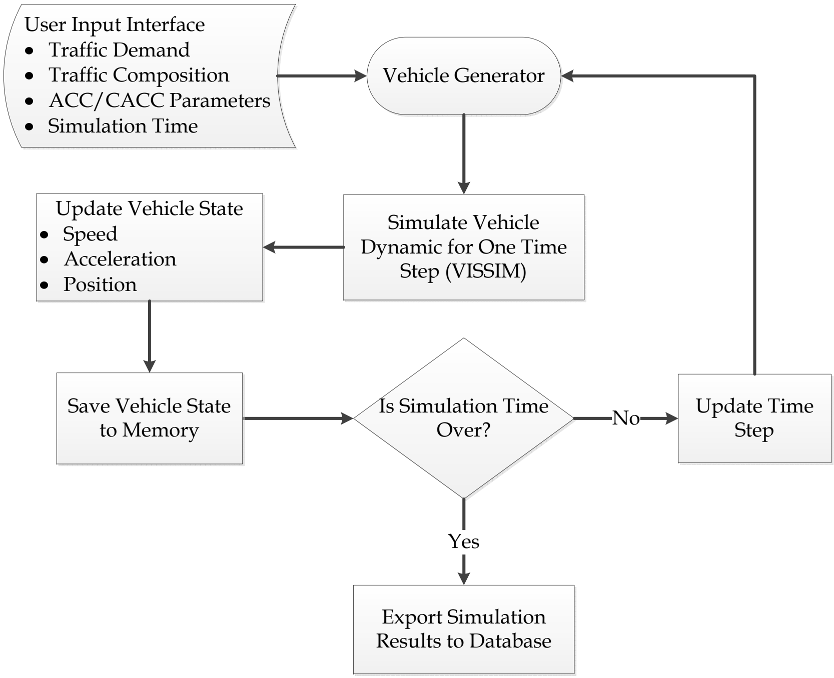


Figure 5.5: Work flow diagram of the simulation platform.

5.3.1 Simulation model

The framework of the simulation platform is implemented using C++ and VISSIM COM server. The framework consists of four major components, namely simulation engine VISSIM (Fellendorf and Vortisch, 2010), user input interface (UII), vehicle generator (VG), and vehicle state updater (VSU). The work flow of the framework is depicted in Figure 5.5. First, we have the UII where we set how the simulation should run. We can set the simulation time of how long it should run, the traffic demand on the road, the desired speeds of the vehicles, whether the vehicle should be driven by a driver model or using (cooperative) adaptive cruise control (ACC/CACC) model, the parameters of ACC/CACC of how the it behaves, among others. These settings serve as inputs to the VG, which overrides VISSIM's own vehicle generator mechanism and loads traffic demand according to the settings in UII. VISSIM plays an important role in simulating vehicle dynamics by its psycho-physical car-following and lane-changing behavior. The state of each vehicle is be recorded by VSU. This component tracks speed, acceleration, and position of each vehicle in the simulation. Aggregated traffic information, such as density, space mean speed, and traffic flow

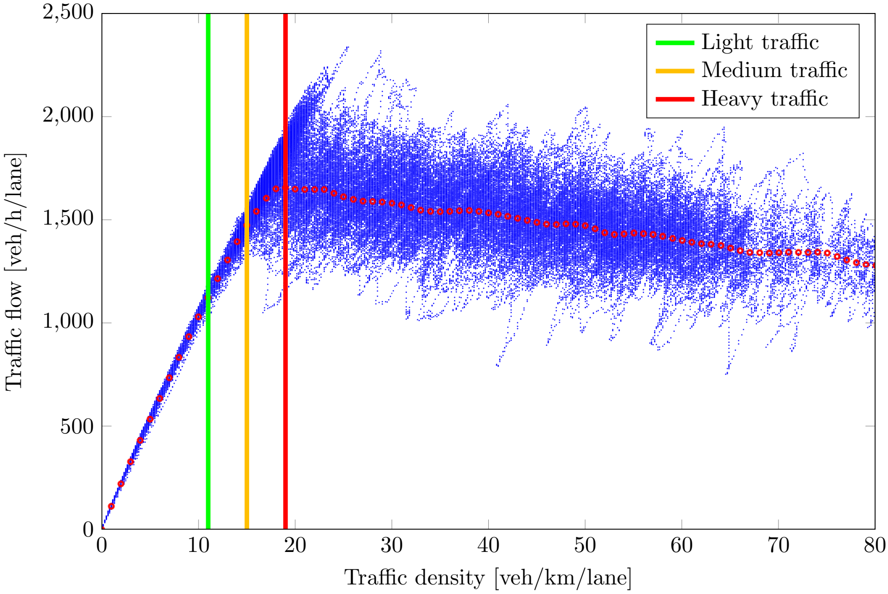


Figure 5.6: The fundamental diagram of the two-lane road with a maximum traffic flow of 2 200 veh/h/lane, which corresponds to traffic density of 21 veh/km/lane. The blue data points are the simulated results while each red data point is the average of all blue data points between i and $i + 1$ where i is an integer number of the traffic density. The green, yellow, and red line corresponds to light, medium, and heavy traffic, respectively, that is used in the simulation.

can be estimated through the individual state saved by the VSU. The simulation results are presented once the simulation run is completed.

5.3.2 Simulation setup

To examine how a merging maneuver of a platoon formation interacts with the traffic, we do our simulations on a 50 km long straight two-lane road. In order to know when there is traffic on the road, we simulate only cars on the road with different traffic densities to establish the fundamental diagram depicted in Figure 5.6. The desired speed of the passenger cars follows a normal distribution with a mean value of 110 km/h and standard deviation of 8 km/h. From Figure 5.6, we note that the maximum traffic flow is approximately 2 200 veh/h/lane, which corresponds to a traffic density of 21 veh/km/lane. At maximum flow, the space mean speed of the vehicles is 105 km/h. The straight line from the origin to the maximum flow is usually referred to as the free flow branch where the vehicles on the road can more or less drive uninterrupted at their desired speeds. The more outspread area (from approximately 21 veh/km/lane in density and above) is often known as the congestion branch. The more right we go on the congestion branch, the more the

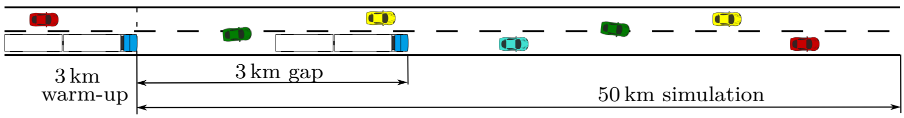


Figure 5.7: The simulation setup, where the HDVs are initially 3 km apart from each other driving on a 50 km long road.

mean speed of the traffic drops and platooning becomes less and less relevant due to insignificant fuel saving from air drag reduction at lower speeds. Therefore, we look at traffic densities up to the density corresponding to the maximum traffic flow where the traffic situation is of interest to study. To verify our merge estimation approach, we use the average values (the red data points) from Figure 5.6.

To study how a merging maneuver is affected by the surrounding traffic, we simulate different speeds of the HDVs and different traffic densities. Both vehicles are driving on the rightmost lane of the road as depicted in Figure 5.7 and are initially 3 km apart. The follower vehicle drives at 90 km/h in order to catch up with the lead vehicle. The lead vehicle slows down with different speeds in order for us to analyze how the merging maneuver is affected by the surrounding traffic and how long it takes to form a platoon. For example, slowing down to 50 km/h may most likely create congestion behind the lead vehicle that will interrupt the merging maneuver for a while, or driving at 80 km/h might cause smaller disruptions in the traffic flow but for a longer time. We simulate slow down speeds of 80, 75, and 70 km/h for the lead vehicle. We consider that the merging maneuver is complete when the vehicles have formed a platoon with a gap less than 30 m and with no cars in between, which is also where the simulation stops. We measure the distance it takes for the HDVs to merge. We compare this to the nominal case of no traffic, which can be calculated by the distance to"collision" for constant speeds. The ideal merging distance d_m (from the perspective of the follower HDV) is defined as

$$d_m = d_s \frac{v_2}{v_2 - v_1}, \tag{5.2}$$

where d_s is the initial gap, v_1 and v_2 the speed of lead and follower vehicle, respectively. There is a 3 km long warm up stretch where we first simulate the cars for a short period of time to create the desired traffic density before loading the two HDVs on the road. The traffic densities we choose to simulate are approximately 11, 15, and 19 veh/km/lane, which we define them as light, medium, and heavy traffic, respectively. We simulate 30 times for each scenario and case.

5.3.3 Simulation results

Figures 5.8 and 5.9 show an example of a simulation run. In an ideal case with the absence of traffic, the follower vehicle maintains a speed of 90 km/h until it reaches the lead vehicle. In the case of traffic, the follower vehicle could maintain 90 km/h for a while until it got closer to the lead vehicle. However, cars have piled up behind

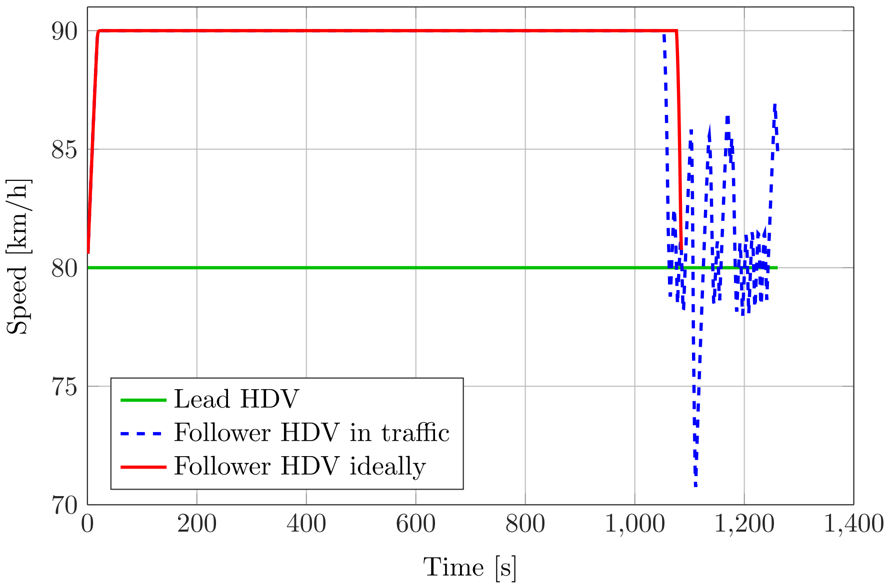


Figure 5.8: A merging maneuver where the HDVs are initially 3 km apart. Ideally when there is no traffic, a merging maneuver takes approximately 1080 s. However, when there is traffic, cars can be driving in between or cut in which can disturb (as shown in Figure 5.9) and delay the platoon formation. In this example, the platoon formation is delayed with almost 200 s.

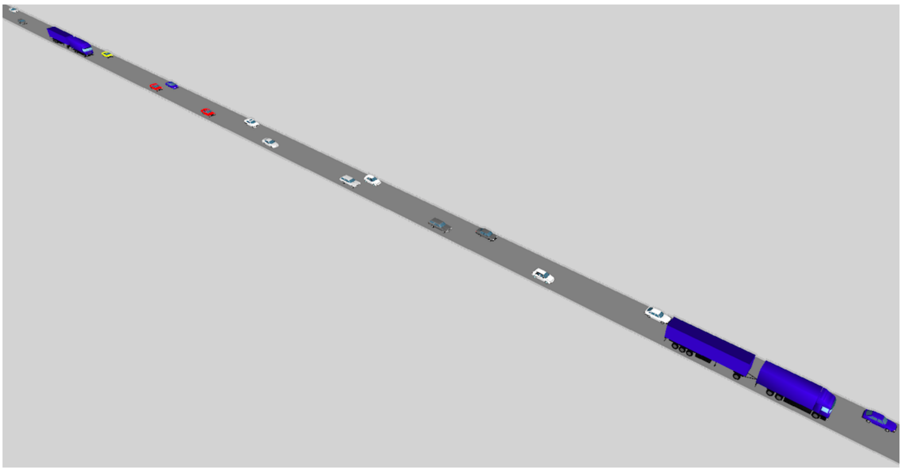
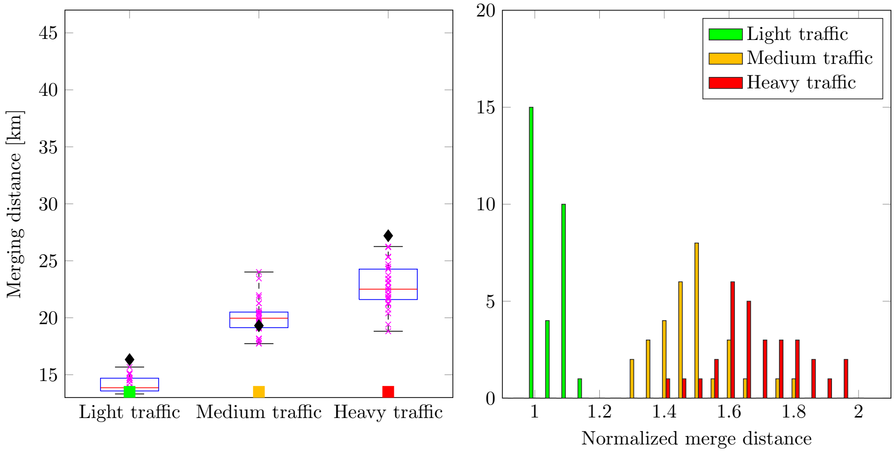


Figure 5.9: An image in VISSIM during the simulation where a pair of HDVs is trying to form a platoon, however cars are driving in between makes it difficult to complete the merging maneuver.



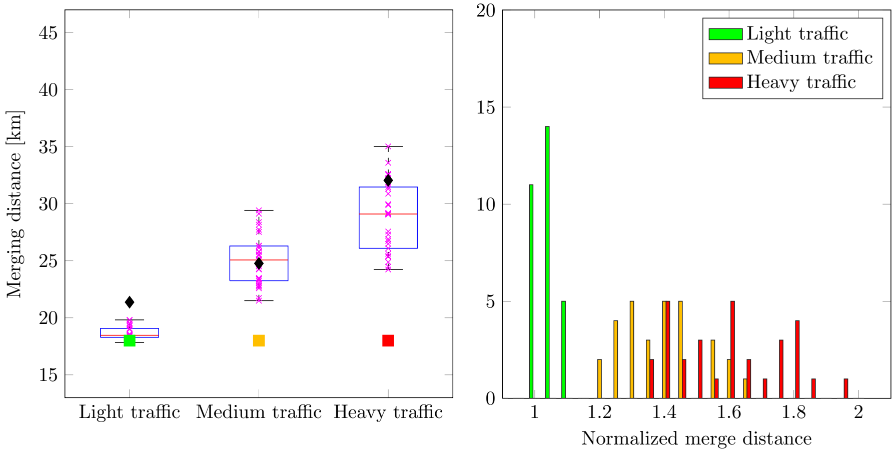
(a) **(b)**

Figure 5.10: A box plot and a histogram of the results for the (70,90) km/h case. The red line in the box is the median of the resulting data, the edges of the box are the 25th and 75th percentiles of the data, and the whiskers outside the box indicates the maximum and minimum value of the data. The result of each individual simulation run is plotted with a purple cross. The colored squares indicate the optimal merge distance without traffic, and the diamond indicate the merge estimation. The x-axis of the histogram is normalized to the optimal merge distance, i.e., 13.5 km in this case.

the lead vehicle, which is seen in Figure 5.9, making it difficult to complete the merging maneuver, and this forced the follower vehicle to accelerate and brake due to cars cutting in or changing lanes. This last part could be represented as driving in a congestion at an average speed of u_c as described earlier in Figures 5.3 and 5.4.

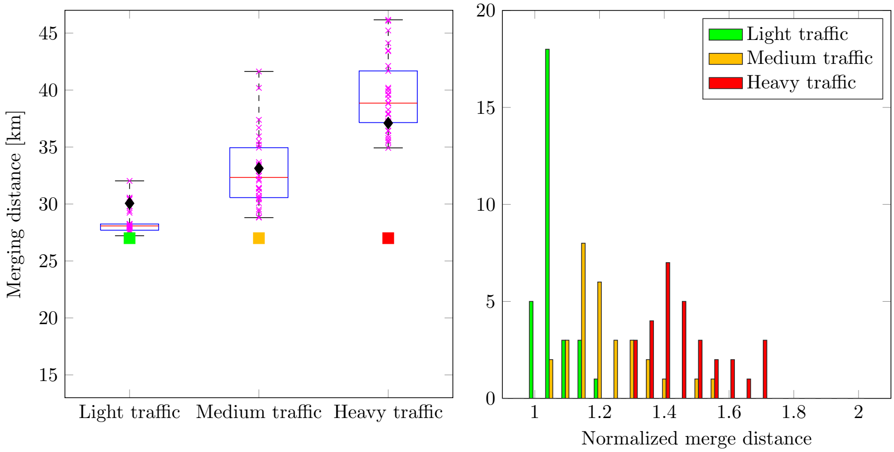
The result of the simulations are depicted as box plots and histogram in Figures 5.10 to 5.12 for the (70,90), (75,90), and (80,90) km/h case, respectively. The notation of (v_1, v_2) stands for the case where the desired speed of the lead vehicles is v_1 and v_2 for the follower vehicle. On each box plot, the red line inside the box is the median of the resulting data, the edges of the box are the 25th and 75th percentiles of the data, and the whiskers outside the box indicates the maximum and minimum value of the data. We also include each individual simulation result with purple cross. Additionally the optimal merging distance is indicated with colored square, and the estimated merge distance in black diamond. The histogram shows the frequency of where the HDVs merged normalized with the optimal merging distance. The colors indicate the traffic intensity.

The optimal merge distance for the (70,90) km/h case is 13.5 km that the follower vehicle has to drive in order to form a platoon in the absence of traffic. Starting with light traffic, we see in Figure 5.10 that the platoon was completely formed between 13.5 to 16 km away for all simulation runs, and with an average merge distance



(a) **(b)**

Figure 5.11: A box plot and a histogram of the results for the (75,90) km/h case. The merge distance is normalized with the the optimal merge distance, which is 18 km for this case.



(a) **(b)**

Figure 5.12: A box plot and a histogram of the results for the (80,90) km/h case. The merge distance is normalized with the the optimal merge distance, which is 27 km for this case.

Table 5.1: A summary of the optimal, average, and estimated merge distance for all cases. The increase column is compared to the optimal merge distance.

Speed (v_1,v_2) and traffic case	Merge distance optimal	average	(increase)	estimate	(increase)
(70,90) km/h light	13.5 km	14.0 km	(+4 %)	16.3 km	(+20.7 %)
(70,90) km/h medium	13.5 km	19.7 km	(+46 %)	19.3 km	(+43.0 %)
(70,90) km/h heavy	13.5 km	22.4 km	(+66 %)	27.2 km	(+101.5 %)
(75,90) km/h light	18.0 km	18.9 km	(+4 %)	21.4 km	(+18.9 %)
(75,90) km/h medium	18.0 km	24.6 km	(+37 %)	24.8 km	(+37.8 %)
(75,90) km/h heavy	18.0 km	28.5 km	(+58 %)	32.0 km	(+78.3 %)
(80,90) km/h light	27.0 km	28.4 km	(+5 %)	30.1 km	(+11.5 %)
(80,90) km/h medium	27.0 km	32.4 km	(+20 %)	33.1 km	(+22.6 %)
(80,90) km/h heavy	27.0 km	39.2 km	(+45 %)	37.1 km	(+37.4 %)

of 14 km. The traffic has almost no influence on the platoon formation, which is to be expected as the traffic intensity is low and therefore the cars could easily overtake and pass the HDVs. The merge estimation approach, that is based on two moving bottlenecks, overestimates the merge distance a bit with the value 16.3 km. It estimated that there would be a noticeable congestion behind the lead HDV. For medium traffic, we note that the merge distance is significantly larger than for the light traffic case. This is due to the lead vehicle blocking a lane, that throttled the flow thus creating a congestion upstream of the lead vehicle. The merging distance spans between 17 to 24.5 km with an average of 19.7 km, which is an increase with 46 % compared to the optimal merge distance. The merge estimation is almost spot on in this case with an estimated merge distance of 19.3 km. Lastly for the heavy traffic case, the merge distance is even larger. This aligns with the expectation that the lead vehicle creates a large congestion behind it making it difficult for the follower vehicle to complete the merge. The merging distance spans between 19 to 26.5 km with an average of 66 % increase compared to the optimal merge distance. The merge estimation estimates the HDVs to start platooning at 27.2 km. In the histogram in Figure 5.12b, we clearly see that the distribution of merge distance grows with traffic density.

The (75,90) and (80,90) km/h cases follow similar trends as in the (70,90) km/h. We therefore summarize all the results in Table 5.1. We note that the normalized merge distance from simulation gets lower the higher v_1 (lead HDV) speed is, especially at higher traffic density. This is also noticeable in Table 5.1 in the average increase column. An explanation is that the congestion behind the lead HDV does not propagate upstream as fast since the cars can easier change lanes to due less speed differences between the two lanes. Additionally, the congestion becomes a smaller part compared to the whole distance driven for higher v_1 speed, since the merge distance is longer. Even though the merge distance (in percent) is larger for lower v_1, the merge itself was completed earlier (in absolute value) and therefore it is important to consider the whole aspect (as in the merging maneuver and platooning together) before deciding which speed strategy is better.

5.4 Summary

In this chapter we investigated how an HDV, that moves slower than the rest of the traffic being a moving bottleneck, throttles the traffic flow and separates the traffic into a free flow area downstream and a congestion area upstream of the HDV. By utilizing shockwave theory we predict how these free flow and congestion evolve in space and time. By extending the idea of moving bottleneck and shockwave theory to two HDVs, that are initially apart, we can estimate when these two vehicles will merge and form a platoon depending on their speeds and the current traffic condition. The interesting aspect is the evolution of traffic between the vehicles, as the free flow downstream the follower vehicle will affect the congestion upstream the lead vehicle. The follower vehicle drives at its desired speed (unless the traffic is too dense) until it reaches the congestion and then drives at that traffic speed of the congestion until it catches up to the lead HDV.

To examine how a merging maneuver of a platoon formation interacts with the traffic and to verify how the performance of our merge estimation approach, we used a microscopic traffic simulation tool. We considered different traffic densities and different speed cases. The higher the speed discrepancy is between the moving bottleneck and the rest of the traffic, the faster the congestion upstream grows and the more difficult it is for the cars in the same lane as the HDV to change lanes. This will delay the merging maneuver significantly. The merge estimation approach has a tendency to overestimate the merge distance for light traffic as it may predict that there is a small congestion behind the lead HDV, while in simulation the cars could easily pass by the vehicle. For the medium traffic cases, the merge estimation almost estimated the same merge distance as in the average outcome. In order to decide which speed strategy to use, depending on the traffic condition, the whole aspect of merging and platooning, as well as the fuel saving potentials must be considered.

Chapter 6

Experimental evaluation of traffic influence

"Prediction is very difficult, especially if it's about the future."
Niels Bohr

Heavy-duty vehicles (HDVs) that are driving on the highway and are relatively close in distance to each other have the possibility to merge and form a platoon. Adjusting the speeds of the HDVs, the follower vehicle can catch up with the lead vehicle. However, as there are other road users, the merging maneuver may be affected and delayed by the surrounding traffic. In order to guarantee that the platoon formation does not yield a fuel loss, a merge prediction is necessary. In this chapter, we present experiments to attempt to form a platoon with two HDVs, initially separated, on a public highway during rush hour. The main purpose of the experiment is to analyze how traffic disturbs and delays the HDVs when forming a platoon. We conduct the experiments during rush hour to capture a variation of traffic densities and with different HDV speeds. In practice, there are always unexpected events such as a car driving persistently behind an HDV and not changing lanes, which causes the merging maneuver to never be completed. This kind of events are of interest to capture. As in the previous chapter, we use the term (passenger) car for the vehicles that we do not consider in our platoon formation. Lastly, we experimentally evaluate and validate the performance of the merge estimation approach presented in Section 5.2.

The outline of this chapter is as follows. In Section 6.1, we describe the experiment setup in detail. In Section 6.2, we present the experiment results. In Section 6.3, we evaluate the performance of the merge estimation approach. In Section 6.4, we discuss the outcome of the experiments and the improvements that can be considered. Lastly, a summary in Section 6.5 concludes this chapter.

(a) Lead vehicle with a trailer. **(b)** Follower vehicle.

Figure 6.1: The two HDVs that are used in the experiment.

6.1 Experiment setup

In this section, we give a detailed description of how the experiments are conducted. We divide it in three parts, the setup of the HDVs, the setup of the experiments, and the traffic data from Stockholm's motorway control system (MCS).

Setup of the HDVs

Two standard Scania tractor HDVs are utilized as depicted in Figure 6.1. The lead vehicke has a 4×2 vehicle configuration with a 480 hp engine and has a trailer with three axles. The total length of the lead vehicle with trailer is 16 m and a total weight of 37.5 t. The follower vehicle has a 6×4 vehicle configuration with a 450 hp engine and has a ballast weight. The total length of the follower vehicle is 6 m and a total weight of 15 t. Both vehicles have standard commercially available equipments, which include doppler radars, global positioning systems (GPSs), front looking cameras (FLCs) and electronic control units (ECUs). A data logger and an additional camera are installed in each vehicle to record and log the experiments. The data logger is directly connected to the HDV's internal controller area network (CAN) and reacts to ignition's on and off to respectively start up and shut down the data logger. The additional camera is installed to record the view in front of the HDV as the FLC is not used for such purpose. We use the doppler radar to measure the relative speed and distance to the vehicles in front. The FLC is used to detect objects in front of the HDV including vehicles and lane markings on the road. The FLC is able to classify the objects it detects into two-wheeler, car, HDV, or unknown depending on the estimated width of the objects. The GPS is used to localize the HDV on the highway and to sync the time between the lead and follower vehicle. The GPS receiver gets an update every second.

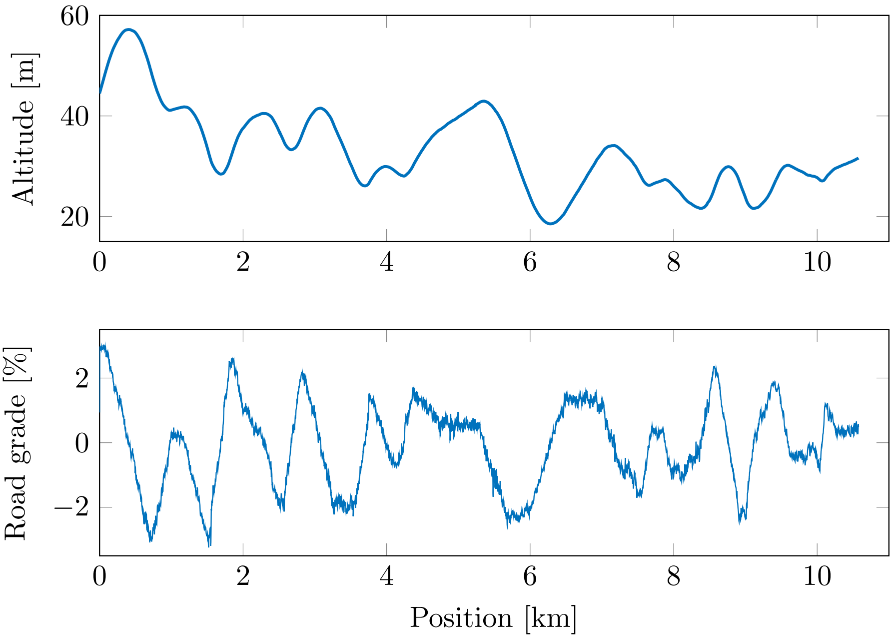
Experiment location and scenarios

The experiments are conducted on the E4 and E20 highway between Hallunda and Moraberg, which are located between Stockholm and Södertälje, as shown in the map of Figure 6.2a. The top plot in Figure 6.2b shows the altitude profile and the bottom plot the corresponding road grade profile. As shown by the road grade profile, the road is fairly hilly with road grade segments of ±3 %. The highway is a three-lane road with a total length of 11 km and a fixed speed limit of 100 km/h. HDVs are only allowed to drive on the middle and the rightmost lanes. Additionally, there is an on- and off-ramp approximately in the middle of the highway stretch (at Salem). The number of cars that enters and leaves at this location is relatively low throughout the day. The experiments took place during four weeks in November 2015. Both vehicles start on the same location at one end of the road, just outside the highway. The lead vehicle starts driving and enters the highway while the follower vehicle waits approximately 40 s in order to open a gap. This corresponds to approximately 800 m that the follower vehicle needs to catch up. The experiment starts when the follower vehicle enters the highway. The drivers are instructed to drive with adaptive cruise control (ACC) with a desired speed and they are allowed to overtake vehicles if needed. Once the follower vehicle catches up to the lead vehicle, they platoon until they reach the other end of the highway stretch. We refer to one such north- or southbound drive as a test-run. The test-runs are conducted during the rush hours, i.e., between 6:00–10:00 in the morning and 14:00–18:00 in the afternoon in order to capture a set of different traffic densities. During the three first days, the afternoon shift was between 15:00–19:00. Three merging maneuver speed pairs are considered, namely (75,85), (75,89), and (80,89) km/h, where (v_1,v_2) denotes the speed of the lead and follower HDV, respectively. We refer to one such pair as a test-scenario. The speeds are set as the desired speed of the ACC, together with a downhill speed control (DHSC) offset of 5 km/h. The DHSC enables the HDV to accelerate on descents and gain speed until the vehicle speed reaches the offset in which the system intervenes by applying brakes to not overspeed.

Stockholm's MCS traffic data

Traffic data are obtained from Stockholm's MCS during the experiment. The collected data are from the time the experiments were conducted, i.e., between 6:00–10:00 and 14:00–19:00 for twenty weekdays. The traffic data are based on measurements from microwave detectors (doppler radars). Each detector measures the number of passing vehicles and the harmonic mean speed within one-minute time intervals. The microwave detectors are mounted on gantries along the highway as shown in Figure 6.3, one detector for each lane. The gantries are placed 200–400 m from each other along the highway. There are a total of 41 and 37 gantries in the north- and southbound directions, respectively, between Moraberg and Hallunda. Each gantry is paired with two outstations, see Figure 6.3 on the left. These outstations connect the gantries with a central system that collects traffic data and change the

(a) Location of the experiment. (Map courtesy of ©mapz.com – Map Data: OpenStreetMap ODbL.)



(b) Altitude and road grade of the road in the northbound direction.

Figure 6.2: The experiment took place between Hallunda and Moraberg, southwest of Stockholm, Sweden.

Figure 6.3: Each gantry of Stockholm's MCS is equipped with microwave detectors (behind the variable speed limit sign) that measure traffic flow and harmonic mean speed on each lane. The big white bulk on the left is an outstation, which connects two gantries with a central system.

Table 6.1: A break down of all the test-runs that are conducted in test-scenarios and directions. Successful merging maneuver are presented in parentheses.

Direction \ Scenario	(75,85)	(75,89)	(80,89)	Total
Northbound	88 (77)	87 (81)	97 (73)	272 (231)
Southbound	75 (71)	83 (77)	89 (68)	247 (216)
Total	163 (148)	170 (156)	186 (141)	519 (447)

variable speed limit (or message) sign according to the gathered traffic data and traffic situation.

6.2 Experiment results

In this section, we first evaluate the merging maneuver and how different traffic condition influences it. Then, we investigate how often car drivers are in between the two HDVs and are reluctant to change lanes, which is often a reason for a delayed platoon formation.

Successful and failed test-runs

In total, there are over 600 test-runs conducted during the four weeks. However, due to traffic accidents and data corruptions some of the data set is filtered away. We end up with 519 test-runs, where 447 of these test-runs are successful formations of a platoon. Table 6.1 summarizes all the test-runs and breaks them down into test-scenarios and directions. Furthermore, we only consider test-runs where the initial distance between the two HDVs is between 400 to 1300 m. To classify a successful merging maneuver, three criteria need to be satisfied:

1. The relative distance between the merged HDVs, based on their GPS positions, must be less than 80 m,
2. The doppler radar must detect a moving object in front of the vehicle, with a similar relative distance as the GPS measurements,
3. The FLC must detect an object in front of the vehicle and classify the object as an HDV.

The 72 failed attempts to merge are due to a too large initial distance combined with a limited road length, highly congested traffic condition, or cars persistently driving behind the lead HDV making it impossible to satisfy all three criteria and complete the merging maneuver. The explanation behind a too large initial distance combined with a limited road length is that during the first week of the experiment (the (80,89) km/h test-scenario), there was road construction work near the entrance to the on-ramp on the northbound direction. The road construction work caused the HDVs to enter the highway with different timing, which resulted in sometimes large initial distance. Figure 6.4 shows all the initial distances between the vehicles as the follower vehicle entered the highway. Note that a failed merging maneuver in this experiment means that the HDVs did not manage to merge before the end of the stretch where the vehicles need to exit. There are over 30 test-runs where the initial distance is more than 1 km. This makes it very difficult to complete a merging maneuver for the (80,89) km/h test-scenario as it takes more than 10 km to merge and the road length is only 11 km. Highly congested traffic causes the follower vehicle to have difficulties to change lanes and overtake other cars to catch up with the lead vehicle. Persistent drivers are discussed separately at the end of the section.

Two examples

The results for two test-runs over the northbound direction for the test-scenario (80,89) km/h are shown in Figure 6.5. Each example consists of a speed profile plot and a relative distance plot. The large speed fluctuations are mainly due to the road topography, cf., Figure 6.2b. In the first example in Figure 6.5a, the HDVs start approximately 950 m apart from each other. The follower vehicle catches up to the lead vehicle just before they reach the end of the road stretch. The test-run is compared to the nominal run, where the merge is completed 50 s later than the nominal run, which is due to minor disturbances from other traffic. The nominal run is the theoretical run where the HDVs keep a constant desired speed and platoon once the relative distance is 50 m. In the second example in Figure 6.5b, the HDVs start with a similar initial distance. However, along the way the follower vehicle cannot maintain its speed due to other road users, which forces the follower vehicle

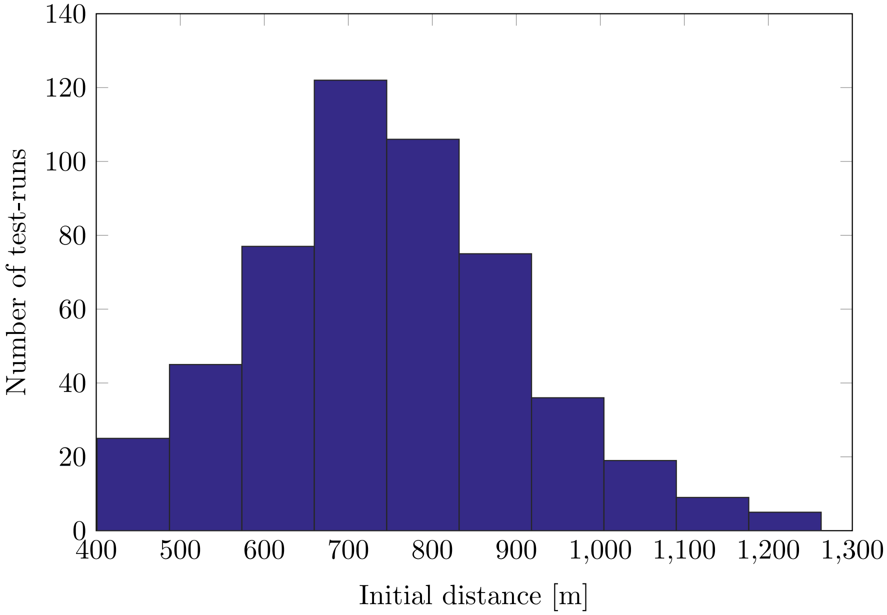
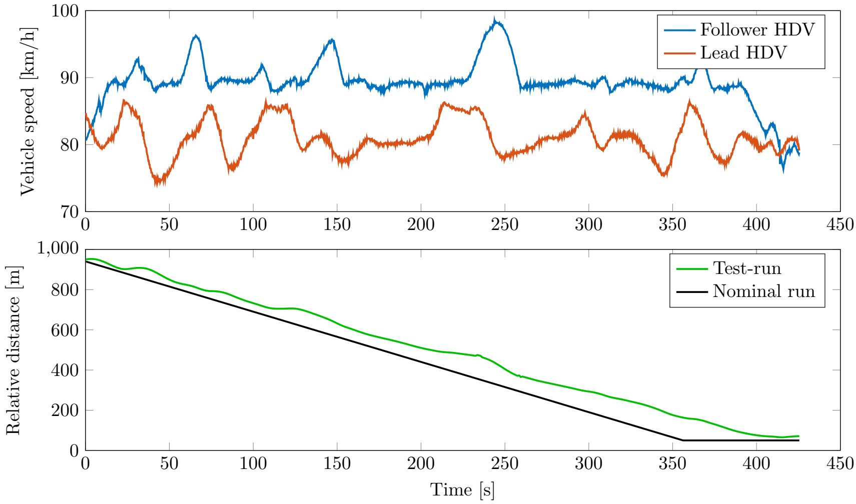


Figure 6.4: The frequency of different initial distances for all test-runs. The average initial distance is 748 m.

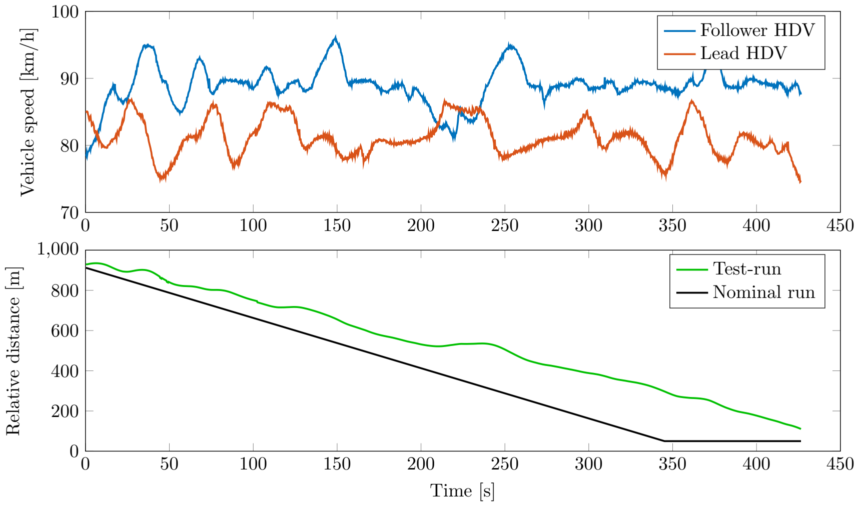
to slow down (at around 200 s and 270 s). From there, the relative distance is too long for the follower vehicle to catch up with the lead vehicle before the end of the road stretch that is used in the experiment and therefore this test-run failed to form a platoon. Note that the failure in this case would have completed the platoon formation if we allowed the vehicles to drive a bit further.

Traffic data and fundamental diagram

Traffic data from the MCS are gathered to understand in what the traffic condition is during the merging experiments. Figure 6.6 shows the fundamental diagram using all data points collected during the entire experiment period and over the whole road length. One blue dot represents an aggregated minute of three microwave detectors together that are mounted on the same gantry, i.e., a one-minute gantry measurement. There are in total over 830 000 gantry measurements in Figure 6.6. The fundamental diagram here is similar to the fundamental diagram from the simulations in Figure 5.6, if the outliers (low traffic flows with low traffic density), mainly caused by accidents, are ignored. The maximum flow is approximately at 2 100 veh/h/lane with a corresponding traffic density at 22 veh/km/lane, resulting in a mean speed of 95 km/h. The free flow branch is a bit more spread compared to the simulated fundamental diagram. Similarly, the congestion branch is more spread but also slightly lower compared to the simulated fundamental diagram. To



(a) Successful merge attempt



(b) Failed merge attempt

Figure 6.5: Two examples of test-runs with speed profiles and relative distance. The nominal run corresponds to both HDVs drive constantly at their set speeds and platoon once the relative distance is 50 m. The first (top) example shows the follower vehicle barely had any disturbances from surrounding traffic and could merge successfully. The second (bottom) example shows that there were some influence from surrounding traffic that made the follower vehicle drop in speed both at 200 s and 270 s and could therefore not complete the merging maneuver before the end of the highway stretch.

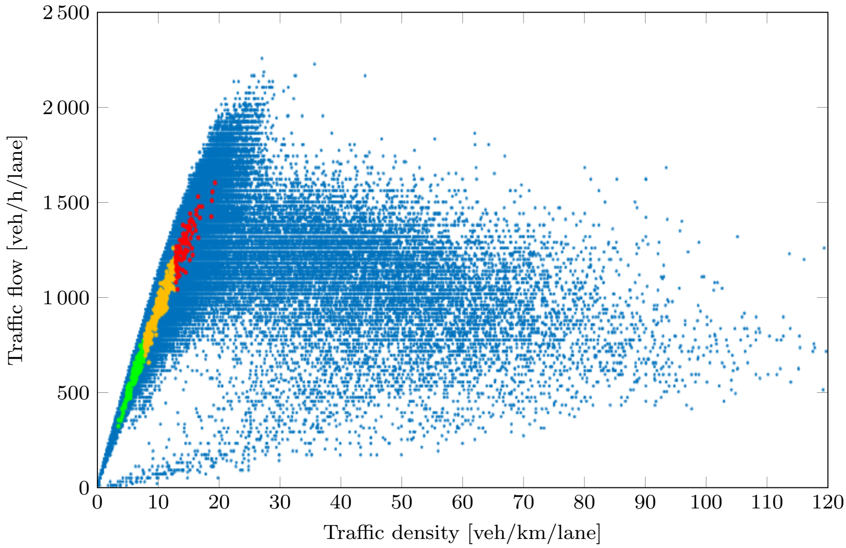


Figure 6.6: Fundamental diagram based on the traffic sensor measurements during the entire experiment period. The green, yellow, and red colored dots represent the traffic conditions (light, medium, and heavy traffic) during the merging maneuver experiments.

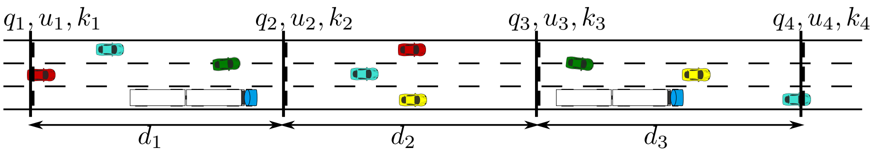


Figure 6.7: An illustration of three-lane highway with gantry measurements. We assume the ith gantry measurement (flow q_i, mean speed u_i, and density k_i) holds for the next d_i distance until the next gantry, $i + 1$.

calculate the traffic density for each test-run, we assume each gantry measurement is constant until the next update and holds along the road until the next gantry on the road, as seen in Figure 6.7. Gantry i measures flow q_i, harmonic mean speed u_i, and density k_i each minute and the distance to the next gantry, $i + 1$, is d_i. The traffic density for each test-run is calculated as soon as both HDVs are on the highway. We consider the weighted measurements from the gantry measurement behind the follower vehicle to the gantry measurement behind the lead vehicle. For example, in Figure 6.7, gantries 1 to 3 is considered, which results in the following traffic measurements

$$k_{\mathrm{tr}} = \frac{\sum_{i=1}^{3} k_i d_i}{\sum_{i=1}^{3} d_i} = \frac{\sum_{i=1}^{3} \tilde{n}_i}{\sum_{i=1}^{3} d_i}, \tag{6.1a}$$

$$u_{\mathrm{tr}} = \frac{\sum_{i=1}^{3} \tilde{n}_i}{\sum_{i=1}^{3} \frac{\tilde{n}_i}{u_i}}, \tag{6.1b}$$

$$q_{\mathrm{tr}} = k_{\mathrm{tr}} u_{\mathrm{tr}}, \tag{6.1c}$$

where subscript tr denotes test-run and $\tilde{n}$ denotes the (estimated) number of vehicles. The traffic densities for each test-run during the experiment are depicted in Figure 6.6 with green, yellow, and red colored dots and varies from 3.5–19.5 veh/km/lane. We divide the test-runs into three categories according to the traffic density. The green dots represent light traffic (lower than 8 veh/km/lane), yellow represents medium traffic (between 8 and 13 veh/km/lane), and red represents heavy traffic (above 13 veh/km/lane). There is a total of 164, 266, and 89 test-runs for light, medium, and heavy traffic, respectively.

Outcome of merge distance

For each test-run, we compare the outcome when the HDVs managed to form a platoon with the nominal run, by normalizing the test-run with the nominal run. The nominal run is when the vehicles maintain their desired speeds and merge at $d_m = d_s v_2/(v_2 - v_1)$ distance from where the follower vehicle starts. We plot the results for each test-scenario in a histogram with each traffic category. Figures 6.8–6.10 and Table 6.2 summarize all the test-scenarios and test-runs. The histograms show that there are a few test-runs that where the merge occurs earlier than the nominal run (below value 1) and a few test-runs where the HDVs drive twice the distance to merge. The earlier merge (compared to the nominal run) indicate that there are cars in front of the lead vehicle causing it to drive slower, thus the platoon is formed earlier. There are also a few test-runs in light and medium traffic that failed to merge. This is mainly due to persistent drivers that keeps driving behind the lead HDV and do not change lanes. Lastly, for all three figures, we see a slight shift in the bars for heavier traffic, indicating that the merge maneuver is slightly prolonged with higher density. This is more evident in Table 6.2 where the mean value of the normalized merge distance is shown for each test-scenario. The mean value of the normalized merge distance increases with higher traffic density.

Persistent drivers

In general, there are drivers that are reluctant to change lanes. This is often not an issue since other cars can change lanes and overtake the reluctant driver. However, for a platoon formation case, these reluctant drivers may be an issue as they may hinder the completion of a platoon formation if they insist driving behind the lead HDV. We call these drivers for persistent drivers. We define the existence of a

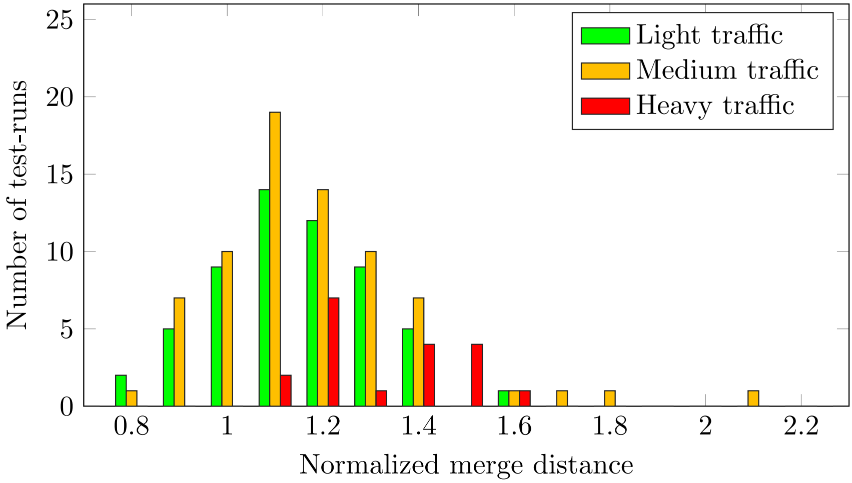


Figure 6.8: Histogram of the (75,85) km/h test-scenario over the actual outcome of merge distance normalized with the nominal merge distance. Values below 1 indicates minor interruption by surrounding traffic on the lead HDV leading to a shorter merge distance.

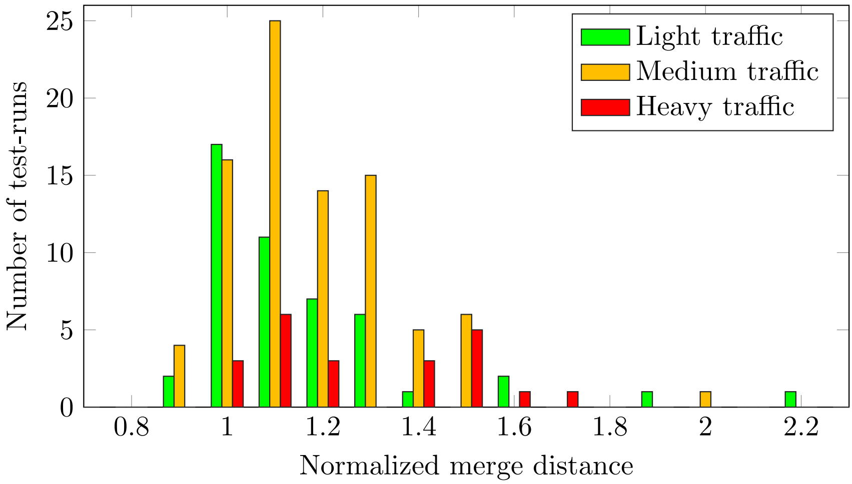


Figure 6.9: Histogram of the (75,89) km/h test-scenario over the actual outcome of merge distance normalized with the nominal merge distance.

persistent driver when it takes over 1 km to complete the merge once the HDVs are less than 80 m from each based on the GPS measurements. In other words, there is a persistent driver that drives behind the lead HDV when it takes over 1 km drive from that the first criterium of successful merging maneuver is satisfied until all three criteria are satisfied. Figure 6.11 shows an example where the relative distance

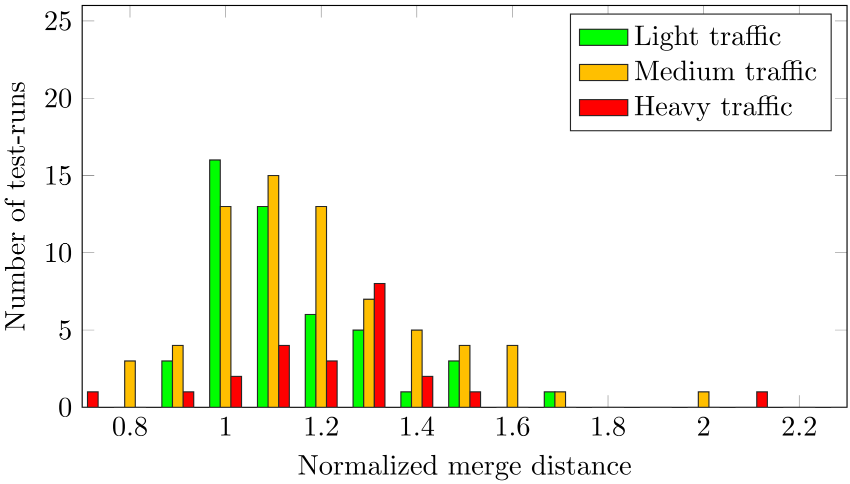


Figure 6.10: Histogram of the (80,89) km/h test-scenario over the actual outcome of merge distance normalized with the nominal merge distance.

Table 6.2: A summary of all the test-scenarios and test-runs conducted. The minimum, maximum, mean, and standard deviation (STD) are indicated for all test-scenarios.

Test-scenario and traffic case	Test-runs total	Test-runs successful	Normalized merge distance min	max	mean	STD
(75,85) km/h light	59	57	0.85	1.56	1.14	0.16
(75,85) km/h medium	83	72	0.79	2.10	1.17	0.21
(75,85) km/h heavy	21	19	1.10	1.61	1.33	0.17
(75,89) km/h light	48	48	0.90	2.19	1.16	0.24
(75,89) km/h medium	94	86	0.93	1.99	1.18	0.18
(75,89) km/h heavy	28	24	1.03	2.60	1.39	0.39
(80,89) km/h light	57	48	0.93	1.66	1.13	0.17
(80,89) km/h medium	89	70	0.83	1.97	1.19	0.23
(80,89) km/h heavy	40	23	0.74	2.10	1.24	0.26

between the HDVs goes below 80 m at time 255 s. However, as there is a vehicle in between the vehicles, the merging maneuver is never completed. Video records confirm that there is a car driving in between the HDVs. Table 6.3 summarizes the results for all test-scenarios. There is a persistent driver in 24 % of the total test-runs and they are the reason behind half of the failed merge attempts in total. This indicates that the possibility of persistent drivers need to be considered in a platoon formation.

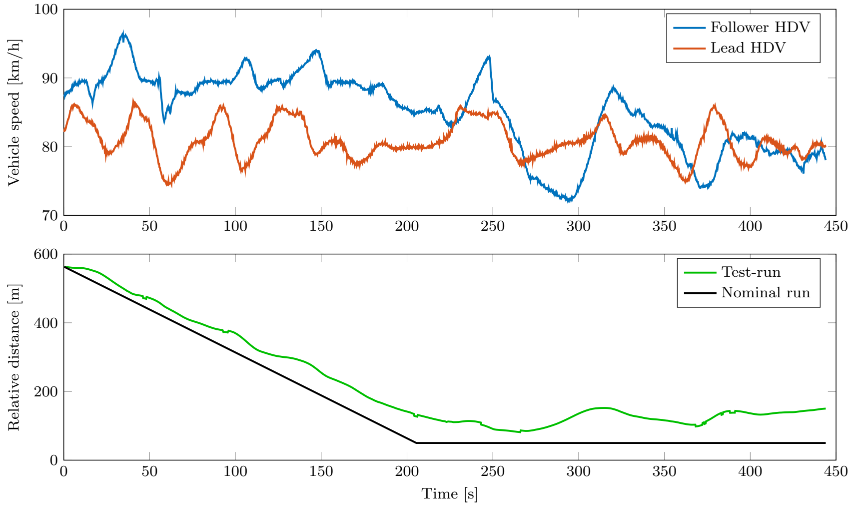


Figure 6.11: An example of a test-run with a persistent driver. The relative distance between the HDVs is below 80 m at time 255 s but due to a car in between, the merging maneuver is incomplete.

Table 6.3: The number of persistent drivers that cause either delayed merge or failed attempts.

Test-scenario and traffic case	Total test-runs	Persistent drivers total	Persistent drivers caused failure
(75,85) km/h light	59	13	0
(75,85) km/h medium	83	22	5
(75,85) km/h heavy	21	7	1
(75,89) km/h light	48	4	0
(75,89) km/h medium	94	21	7
(75,89) km/h heavy	28	9	2
(80,89) km/h light	57	13	5
(80,89) km/h medium	89	19	9
(80,89) km/h heavy	40	18	6

6.3 Performance of merge estimation

In this section, we use a machine learning technique, namely linear regression, on our experiment results to model a merge prediction based on traffic density. We compare the linear regression and the moving bottleneck model presented in Section 5.2 with the outcome of the experiments.

Linear regression model

There are over 500 test-runs conducted from the experiments. The 447 successful test-runs are used to make a merge prediction model, as the remaining failed attempts do not give any information on when the HDVs formed a platoon. A linear regression model is used with a holdout method on the data set. A holdout method is to separate the data into two subsets, where one subset is to train the model and the other subset is to validate the model. Common proportions of the subsets are 70 % as training set and 30 % as validation set. In our case, 130 randomly chosen test-runs are used as the validation set, and the remaining 317 test-runs as the training set. Linear regression models fit a scalar dependent variable (the output of interest, in our case a merge location) with one or more independent variables (inputs that affect the output, in our case for example traffic density) and is often fitted using least squares method. The merge location, where the HDVs successfully merged, is chosen as the dependent variable. Two independent variables are considered for the model, namely traffic density and the nominal merge distance. There are other possible independent variables that we considered, such as using four variables (traffic density, initial distance, desired speeds of lead and follower HDV) or three variables (traffic density, initial distance, speed difference of follower and lead vehicle), however the suggested one gave the least root mean squared error (RMSE) on both the training and validation sets. The linear regression model is described as

$$\hat{d}_m = \alpha_1 + \alpha_2 k + \alpha_3 d_s \frac{v_2}{v_2 - v_1}, \tag{6.2}$$

where $\hat{d}_m$ denotes the predicted merge distance [m], k the traffic density [veh/km/lane], v_1 the desired speed of lead HDV [km/h], v_2 the desired speed of follower HDV [km/h], d_s the initial distance [m], and α_i for $i \in [1, 3]$ the regression parameters. The physical interpretation of the model is that the predicted merge distance linearly depends on the merge distance of the nominal run. If the nominal merge distance is large, then the prediction should naturally predict the merge far away. Additionally, the model describes the the influence of traffic as affine, i.e., the delay increases linearly to the increased traffic density. Lastly, we have a constant bias term α_1 in the model. The values of the regression parameters are

$$\begin{aligned} \alpha_1 &= 490, \\ \alpha_2 &= 95, \\ \alpha_3 &= 0.93. \end{aligned} \tag{6.3}$$

The value of α_3 indicates that the predicted merge scales with 0.93 of the nominal merge distance. In theory this should be 1, since if there is no traffic, the prediction and the nominal merge should be the same. However, since we have a few test-runs where the merge outcome was lower than the nominal merge, we obtain a value α_3 less than one. The value of α_2 shows that the model predicts a 95 m delay for every more vehicles there are per kilometer and per lane. This sounds reasonable as the more vehicles there are on the road, the more vehicles that need to overtake the lead HDV. Lastly, α_1 tells us that there is always a constant bias of 490 m in the prediction.

Moving bottleneck model

Recall the merge estimation approach presented in Section 5.2 based on fundamental diagram, shockwave theory, and moving bottleneck. The fundamental diagram from the MCS traffic data is used as a basis for the merge estimation. The fundamental diagram is divided to two parts, the free flow and the congestion branch, where each part is defined by a polynomial. The division is estimated (by simply estimating with the eyes) to be approximately at 23 veh/km/lane. All the traffic data below 23 veh/km/lane in traffic density are used to fit into a second order polynomial using least squares method. All the traffic date above 23 veh/km/lane are used to fit into a first order polynomial using least squares method. These are described as

$$\begin{aligned} q_f &= -1.4k^2 + 110k, \\ q_c &= -8.5k + 1500, \end{aligned} \tag{6.4}$$

where q_f denotes the traffic flow in free flow, q_c the congestion flow, and k the density. These polynomials intersect each other at $k = 16$. This gives us an equation describing the whole fundamental diagram, which is based on traffic measurements. The equation is

$$q = \begin{cases} -1.4k^2 + 110k & 0 \le k \le 16 \\ -8.5k + 1500 & 16 < k \le 175, \end{cases} \tag{6.5}$$

and it is depicted in Figure 6.12. The validation set of 130 randomly chosen test-runs is used to estimate the merge distance. Note that the scaled-down fundamental diagram, when applying the concept of moving bottleneck, is 2/3 of the original one since it is a three-lane highway and the HDV is only blocking one lane.

Merge prediction

Both the linear regression and moving bottleneck model take the traffic density k, lead vehicle's speed v_1, follower vehicle's speed v_2, and initial distance d_s as inputs and give the merge prediction $\hat{d}_m$ as an output. The results of the merge prediction are divided according to the three test-scenarios and they are compared to the real outcome of the experiments. From the validation set of 130 randomly chosen test-runs, there are 53, 41, and 36 test-runs for the test-scenarios (75,85), (75,89), and (80,89) km/h, respectively.

For the test-scenario (75,85) km/h, each individual prediction are shown in Figure 6.13 for both the linear regression and moving bottleneck model. The predicted merge distance is normalized with the nominal merge distance, i.e., $d_m = d_s v_2/(v_2 - v_1)$. Additionally, the real outcome is shown as well. The test-runs are sorted according to the traffic density, with an ascending order and ranges

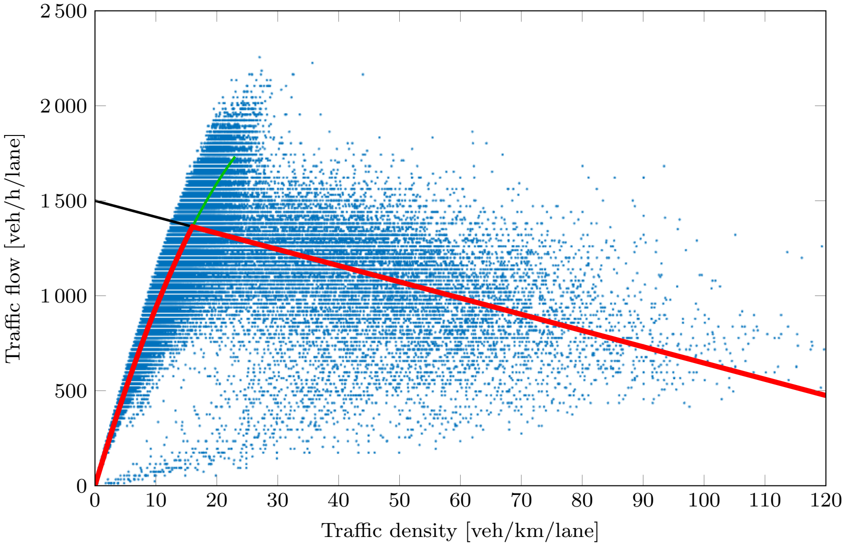


Figure 6.12: Fundamental diagram based on traffic sensor measurement. The fundamental diagram is fitted with an approximation (in red) based on a second order polynomial (in green) for the free flow branch and a first order polynomial (in black) for the congestion branch.

from 3.7 veh/km/lane to 19.1 veh/km/lane. Although the prediction from the moving bottleneck model aligns nicely, there is a large discrepancy when comparing both prediction models with the actual outcome. Almost all of the predictions from the linear regression predict a larger merge distance than the moving bottleneck model and are most often closer to the actual outcome. There are some test-runs where the merge distance of the real outcome occurred much later than the nominal case, such as test-run #7 and 8, despite the low traffic density. This is due to other cars driving in between the HDVs, and in these two cases they were more than one car in between since the first merging maneuver criterium was not satisfied. Note for test-run #53 (the last one), the moving bottleneck model predicts an infinite merge distance, i.e., it is not possible to merge due to the high traffic density (19.1 veh/km/lane). The traffic might not have been as heavy as the traffic sensors measured, or the traffic density might have been high at that particular measurement (minute) and lower later on.

The results for each individual test-run for the test-scenario (75,89) km/h is shown in Figure 6.14. As the previous test-scenario, the test-runs are sorted in ascending traffic density order, ranging from 6.0 to 16.7 veh/km/lane. The majority of the test-runs are overestimated for both prediction models, and this is due to the lead HDV not being able to maintain the set speed of 75 km/h, which is due to the slower cars in front. The results from the moving bottleneck model aligns nicely as in the previous test-scenario. However, at higher traffic density there is a

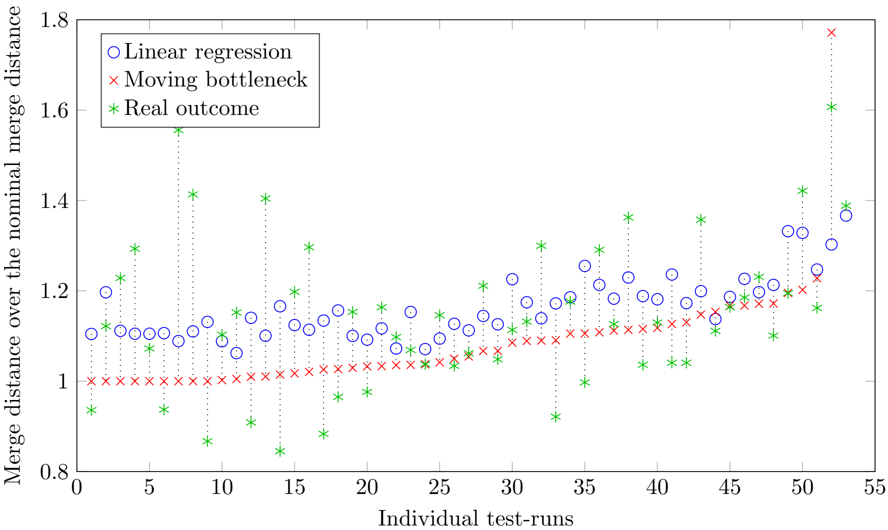


Figure 6.13: The merge predictions, from the linear regression and moving bottleneck models, and the real outcome normalized with the nominal merge distance for each individual test-run for the test-scenario (75,85) km/h. The test-runs are sorted in ascending traffic density order ranging from 3.7 to 19.1 veh/km/lane.

sudden jump in the prediction. This is due to the traffic is congested (in zone 4, in Figure 5.2) in comparison to the lead vehicle's desired speed.

Lastly, for the test-scenario (80,89) km/h, the results are depicted in Figure 6.15, where the traffic density ranges from 4.9 to 15.3 veh/km/lane. Both the linear regression and moving bottleneck models underestimate half the test-runs, especially at lower traffic density values, and overestimate the other half compared to the actual outcome. The differences between both prediction models are relatively small for this test-scenario compared to the other ones. There is a similar behavior for the moving bottleneck as in the previous test-scenario, namely the sudden jump at higher traffic density. This indicates that the moving bottleneck model overestimating the merge distance the higher the traffic density is. The cause of the significant deviation lies in the congested traffic (zone 4) in comparison to the speed of the lead vehicle. Note that the congested traffic, zone 4, appears with lower density values with increased moving bottleneck speed.

The performance results are summarized in Table 6.4. For the overall performance, the linear regression model fits the prediction better than the moving bottleneck when comparing with the real outcome, as the RMSE is lower. This aligns with the expectation of the models as the linear regression is based on the outcome of the experiment (the training set), while the moving bottleneck is based on an average traffic behavior of the road.

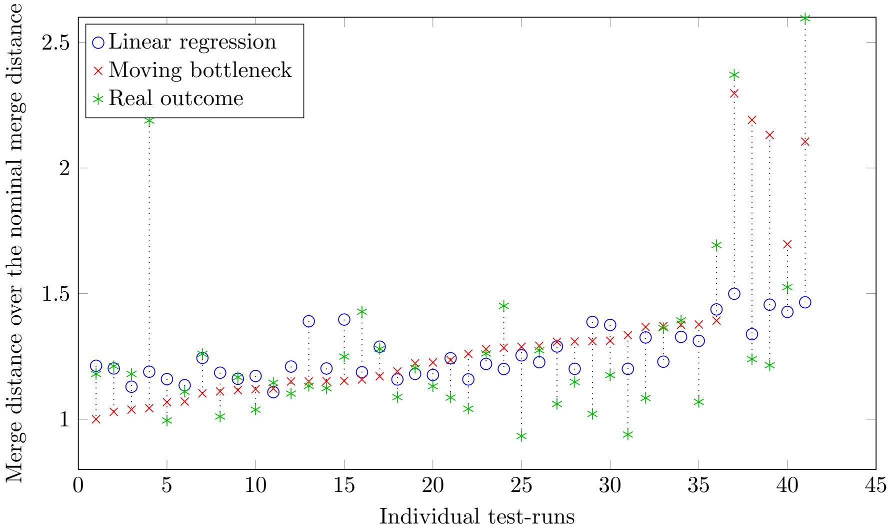


Figure 6.14: The merge predictions, from the linear regression and moving bottleneck models, and the real outcome normalized with the nominal merge distance for each individual test-run for the test-scenario (75,89) km/h. The test-runs are sorted in ascending traffic density order ranging from 6.0 to 16.7 veh/km/lane.

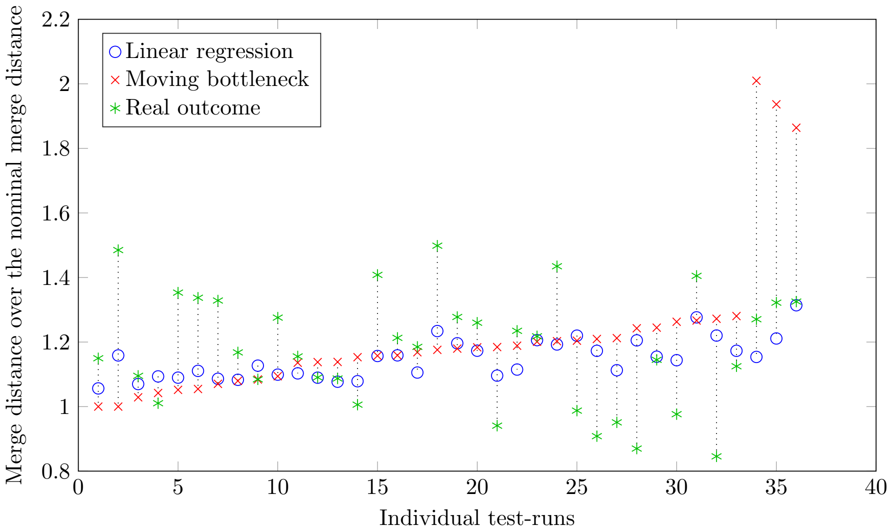


Figure 6.15: The merge predictions, from the linear regression and moving bottleneck models, and the real outcome normalized with the nominal merge distance for each individual test-run for the test-scenario (80,89) km/h. The test-runs are sorted in ascending traffic density order ranging from 4.9 to 15.3 veh/km/lane.

Table 6.4: Comparison between the predicted merge distance from the linear regression and moving bottleneck model with the real merge outcome in meters. Root mean squared error (RMSE), mean value, and standard deviation (STD) of the validation set for both models are indicated.

	Real outcome		Linear regression			Moving bottleneck		
Test-scenario	mean	STD	RMSE	mean	STD	RMSE	mean	STD
(75,85) km/h	7160	1570	970	7220	1060	1040	6780	1280
(75,89) km/h	5880	1530	1280	5850	910	1440	6090	1460
(80,89) km/h	7860	1480	1070	7680	1200	1830	8210	2190
Total	6950	1720	1100	6910	1290	1430	6960	1830

6.4 Discussion

The purpose of a merge prediction model is to obtain an estimate where the platoon formation will occur based on the current traffic condition. This is required to be able to make the correct decision whether or not a platoon should be formed in order to save fuel. The moving bottleneck model predicts how the traffic conditions will evolve in time and space based on a fundamental diagram over the road segment. The fundamental diagram is a static measurement of the average traffic behavior and does not consider dynamic behaviors, which is one of the drawbacks of the prediction model. Individual driver's incentives or reluctancy of changing lanes or overtaking are not considered, which can cause the actual merge to occur much later than predicted. In connection to the fundamental diagram, the traffic behavior varies significantly even for the same traffic density value, especially on the congestion branch where it is more a region than a line (as we approximated it as), which affects the performance of the prediction model. It also depends on how the fundamental diagram is estimated, as different methods such as Theil-Sen estimator, which is less sensitive to outliers, can give different estimates. With different fundamental diagram estimations, the moving bottleneck model will predict the traffic flows and shockwaves differently. A clear example is the test-runs with high traffic density for test-scenario (75,89) and (80,89) km/h in Figures 6.14 and 6.15, where the prediction overestimated noticeably.

The outcome of the experiments indicates that persistent drivers are quite common on the highway, where they are either reluctant to change lanes and overtake HDVs or they are comfortable driving at a lower speed behind an HDV. These persistent drivers need to be considered when predicting a merge distance. The choice of the test-scenarios is an attempt to also study if car drivers have more incentive to change lanes when the HDV is driving slower at 75 km/h on the highway. Unfortunately, the outcome of the results do not indicate such behavior. Furthermore, persistent drivers are not the only one affecting a platoon formation, as other trucks[1] on the highway may also affect it. The trucks may drive slower, which causes the HDV to drive as slow and consider overtaking if the speed is too low. This results in a longer merge distance.

Road inclines affect the speed of an HDV and it also affects the fundamental diagram compared to a flat road. The effect is noticed on the average speed of the lead HDV from the experiments, due to its heavy mass. For car drivers, they tend to maintain a fixed gas pedal position, which results in higher speed in descents and lower speed in ascents. There is a long incline at approximately 5.5–6 km in Figure 6.2b, which affects the heavier lead HDV noticeably. It is a descent on the northbound direction but an ascent on the other direction. The average speed of the lead HDV differs with 1 km/h between the north- and southbound directions on majority of the test-runs. This affect the merge prediction and could be improved by taking it into consideration.

6.5 Summary

A merging maneuver may be affected by the surrounding traffic when forming a platoon of two HDVs. In this chapter we investigated how traffic may delay a merging maneuver by conducting a one-month long experiment. Two HDV drivers attempted to merge the vehicles into a platoon on a public highway during rush hours with varying traffic conditions. We obtained traffic data for that specific highway segment in order to determine the traffic density when the HDVs were driving. Over 500 attempts were conducted with varying traffic condition and vehicle speeds. The results indicated that cars and trucks affect a merging maneuver by driving slower in front the follower HDV causing it to widen the gap between the HDVs. When the HDV driver felt that the vehicle in front drove too slow, the driver could make the decision to change lanes and overtake the slower vehicle. Additionally, it was quite common for a car to persistently drive behind the lead HDV causing the merging maneuver to be incomplete till it changed lanes. This occurred in a fourth of the attempts, more often than we initially expected.

We also investigated the performance of merge prediction based on two different models, namely a linear regression model based on a subset of the experimental results and the merge estimation approach based on shockwave theory and moving bottleneck. Both models predict a merge distance based on the traffic density, initial distance between the HDVs, and the speeds of the HDVs. Both models showed varying but promising predictions for the validation set. The linear regression model had slightly better performance compared to the moving bottleneck model. This, however, is expected as the linear regression model is based on a subset of the results from the experiments, while the moving bottleneck model uses a fundamental diagram based on empirical traffic data measurements.

[1] We call other HDVs, that we do not consider for platoon formation, for trucks for clarity.

Chapter 7

Fuel-potential savings evaluated through sparse probe data

"I didn't fail the test, I just found 100 ways to do it wrong."
BENJAMIN FRANKLIN

The use of fleet management system (FMS) has increased among fleet operators. Each vehicle sends information of the vehicle status and global position periodically to the FMS server. This gives the possibility for the fleet operator to monitor and analyze the condition of their owned heavy-duty vehicles (HDVs) and the status they have during transports. This acts as feedback to the fleet operator and allows the operator to improve future transports. Furthermore, it gives the possibility for the fleet operator to check and monitor the vehicle's condition live and whether the transport is going according to plan or not. With the live position information, it is possible for either a system or the operators themselves to advise their drivers to form platoons with other HDVs in order to save fuel.

We have so far investigated and shown the potentials of forming platoons on the fly when the HDVs are already driving on the road with the influence of surrounding traffic, both in theory and in practice. In this chapter, we analyze platoon coordination possibilities using vehicle probe data acquired from Scania's FMS. We map the position data from the probe data into an underlying road network in order to infer the paths the vehicles have taken between each position sample. Then, we analyze the current platoon situation and investigate how much fuel can be saved through coordinated platoon formations. We use OpenStreetMap (OSM) as our digital road network.

The outline of this chapter is as follows. In Section 7.1, we give a brief background of probe and map data. In Section 7.2, we describe the methodology of map-matching and path inference algorithm, and platoon analysis. In Section 7.3, we present three platoon coordination schemes to increase the fuel savings through platooning. In

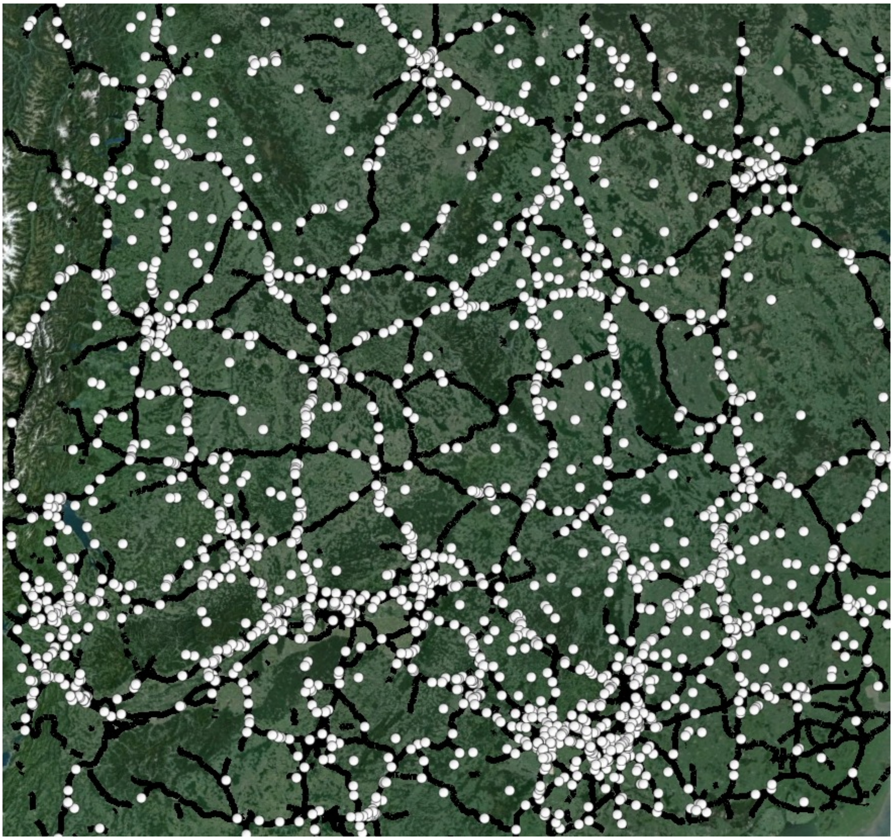


Figure 7.1: A snapshot of all vehicles on the OSM road network. Black lines represent the OSM road network and the white dots represent vehicle probe data.

Section 7.4, we present the results of the analysis. Lastly, a summary in Section 7.5 concludes this chapter.

7.1 Background

We consider a road network with HDVs, see Figure 7.1. A road network is modeled as a graph, consisting of nodes connected by edges. A node in the road network is a geographical point described with a unique id, longitude, and latitude. It has attributes such as altitude or speed sign. A way in the road network is an ordered list of nodes that describes the road and the road type such as a highway or a small street. The way consists of a unique id and at least two nodes. A vehicle traveling on the road network is described with a unique vehicle id and its position is described with a timestamped location with longitude, latitude, and heading.

We use OSM as the digital road network, where the road attributed with `motorway`, `motorway_link`, `trunk` and `trunk_link` were extracted from OSM. This is obtained through a software tool called *osmfilter*. We obtain a data set of probe data from Scania HDVs equipped with GPS units over one whole day in spring 2013 over a 500 000 km^2 region in Europe. The data set contains 7 634 HDVs, which includes both long-haulage and local-distribution HDVs. The probe data consists of timestamped longitude, latitude, heading information, and an id, which is unique for each vehicle with GPS unit. Each vehicle asynchronously sends its position information to the FMS with an interval of 5-10 minutes.

7.1.1 Fuel model and platooning rate

In order to analyze the fuel savings through platooning, we choose a simple fuel model based on speed and distance driven, namely

$$\psi_c = v^2 d\eta_p(d_r), \tag{7.1}$$

where ψ_c denotes the fuel cost, v the velocity, and d the traveled distance. Since platooning leads to reduced fuel consumption, we assume a 10 % lower fuel cost for the follower HDV when platooning, that is

$$\eta_p(d_r) = \begin{cases} 0.9 & \text{if } d_r \le d_p \\ 1 & \text{otherwise,} \end{cases} \tag{7.2}$$

where $d_r > 0$ is the relative distance to the vehicle ahead, hence always positive, and platoon distance d_p is a constant that we set when analyzing the data, which is described later on.

We define platooning rate $\mathcal{P}_{\mathcal{R}}$ as the sum of the distance platooned d_i^p for all $i \in N$ vehicles (including the lead vehicle despite not gaining any fuel savings from platooning) over the sum of total distance d_i driven, i.e.,

$$\mathcal{P}_{\mathcal{R}} = \frac{\sum_{i=1}^{N} d_i^p}{\sum_{i=1}^{N} d_i}. \tag{7.3}$$

7.2 Methodology

In this section, we describe the three steps that are used to analyze the probe data, namely map-matching, path inference, and spontaneous platooning analysis. The map-matching step is inspired from Rahmani and Koutsopoulos (2013). Map-matching is used to find possible road candidates close to a GPS position probe. Path inference is used to infer the vehicle's path from road candidates generated by multiple GPS probes. Spontaneous platooning analysis gives an estimate of the number of vehicles that are ad-hoc platooning (based on the inferred path and timing) and the total fuel saved.

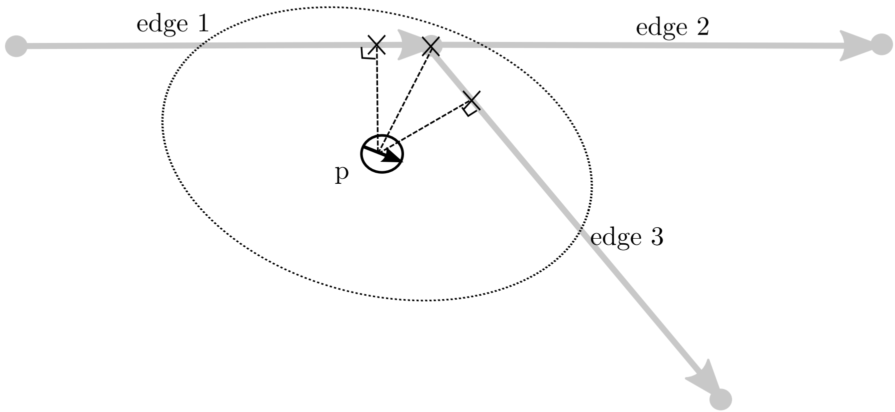


Figure 7.2: An example where the probe data p has three edges intersecting the neighborhood. Each intersected edge gets a projection of the probe data and is a candidate edge for path inference. In our case, at a junction we only keep the exiting edges, hence only edge 2 and 3 are the candidate edges.

7.2.1 Map-matching

Due to errors in the GPS measurement and the digital road network, probe data of a vehicle are usually not located on an edge in the road network. The map-matching process identifies a set of candidate edges within the neighborhood of the probe by looking in a geometrically defined neighborhood around the current position. The choice of shape and size of the neighborhood affects the computational complexity. With larger neighborhood comes more possible candidate edges and with smaller neighborhood comes the risk of not enclosing any edges. Each candidate edge is evaluated by projecting the probe position onto it, see Figure 7.2. We choose a rotated ellipse with respect to the heading of the vehicle probe as our neighborhood with a radius of 50 m in x-direction (the longitudinal direction of the vehicle) and 20 m in y-direction (the lateral direction of the vehicle). The reason behind an ellipse instead of a circle is to avoid capturing parallel roads. We also have a maximum angle difference between the vehicle's and edge's heading, with the threshold set to 30° in order to remove the opposite road direction. Additionally, if there are several candidate edges with the same way id, we only keep the one that has the shortest distance to the probe. Furthermore, if there is a junction (as in Figure 7.2) within the neighborhood, there is at least three candidate edges. The inferred path from some of these edges contains the other edges (as in Figure 7.2, the inferred path from edge 1 also contains edge 2 or 3, depending on which of those goes to the next map-matched probe). Therefore, to reduce the number of candidate edges, only the outgoing edges from a junction are considered as candidate edges. Since we are looking at the highway road network, there will be many GPS probes that are not map-matched into the road network due to the HDVs driving on smaller roads and into the cities. Therefore, to have a consistent good data set, we put a minimum

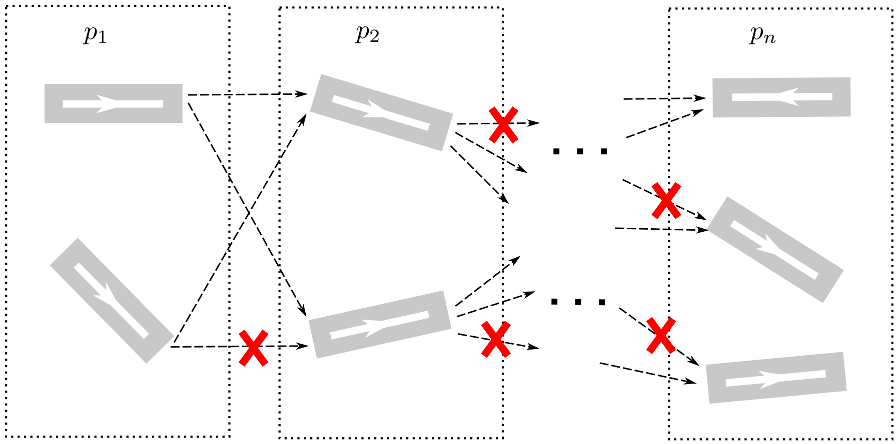


Figure 7.3: An illustration of path inference, where the path is inferred between each consecutive probe pair to obtain the whole path that the vehicle has taken.

threshold of at least ten map-matched points (not necessarily consecutive) needed for each vehicle, otherwise we discard that vehicle data.

7.2.2 Path inference

To infer the path a vehicle has taken between two points, a brute-force method is used since the number of possible paths a vehicle can take on the highway road network are limited. We look at every possible path between two map-matched points and take the shortest path among all of them. We set a limit on how far our brute-force method should search for the next probe, and this limit is based on how far an HDV can travel within the time between two points. We also calculate the average speed between points to ensure that the HDVs did not travel beyond its capability, which is set to 100 km/h. The average speed is used when calculating the fuel cost since the speed between probes is not known.

To infer the path from start to end for each vehicle, each possible combination between the probes has to be checked as seen in Figure 7.3. The more candidate edges there are, the more combinations have to be checked when inferring the path. Since there is a possibility that some probes are not map-matched or the corresponding candidate edges are wrong, the path inference can sometimes fail to yield result between two position probes. Even though it fails to path infer between two consecutive probe pair, the algorithm continues path inferring with the remaining probe data. This results in (at least) two path inferred segments that consist different parts of the whole path the vehicle actually took. To avoid missing segment, we only keep the segment with most probes. If there are several segments with the same number of probes, we keep the segment with the longest driven distance, see Figure 7.4. The segment should at least consist of seven probes,

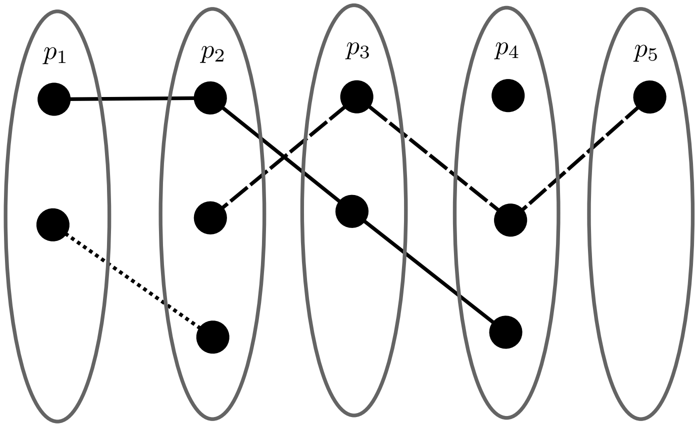


Figure 7.4: An example of path inference for five probes p_i, each node represent a candidate edge. Here we have three different segments; lined, dashed and dotted. Since both the lined and dashed segments are the ones with the most probes, we have to check the traveled distance on each of them and keep the one which is the longest.

Figure 7.5: An example of a vehicle's raw probe data (red pins), map-matched data (yellow pins), and the inferred path (blue line). Notice that some probe data are outside the road network and could therefore not be map-matched, however the path inference managed to find a path between all map-matched points.

otherwise the whole vehicle data set is discarded. In Figure 7.5, we see an example of a vehicle's GPS locations (red pins), map-matched data (yellow pins), and path-inferred data (blue line). We see that all probe data are not map-matched, there are several points (upper left of the figure) where the vehicle is outside the road network. The next point that is map-matched have a much higher timestamp and this means that the average velocity between the two map-matched points is really low. This will most likely yield no platooning possibilities even though it could have platooned in reality until the vehicle exits the highway.

7.2.3 Spontaneous platooning

To be able to study whether the vehicles did platoon with each other or not, we have to check if there are vehicles close to each other. Before analyzing spontaneous platooning, we need to match the timestamps of the vehicles as it is not enough for the vehicles to travel on the same segment, but they need to travel on the segment at the same time. This is what we refer to as spontaneous platooning. This is achieved by discretizing time on one minute-basis and interpolating the path with respect to the time. Since the vehicles are map-matched and path inferred into the road network, it is sufficient to look for vehicles ahead on the same path. We define a distance d_p that we call platoon distance, to determine if the vehicles are platooning. We look at a vehicle's path and if there is another vehicle within d_p ahead at the same time, we assume the vehicles platooned. This has to hold for two consecutive time instances for the vehicles to have platooned over the distance. That is, if there is a vehicle ahead within d_p at time instance t_i and t_{i+1}, then the vehicles have platooned the distance between the time instances. If it only holds for one time instance, for example the platoon splits midway, then we assume that platooning did not occur. Furthermore, the relative speed cannot differ more than 5 km/h at both time instances, otherwise it is not considered as platooning. This is to ensure that the vehicles are most likely driving behind each other. This analysis tells us how many vehicles are platooning today and approximately how much fuel they save compared to if no spontaneous platooning occurs at all (i.e., assuming that all vehicles are driving independently). This result is also compared to the savings when doing platoon coordination.

7.3 Platoon coordination

In order to investigate what the possibilities are to increase the platooning rate and the fuel savings, we consider three coordination schemes, namely catch-up coordination, departure coordination, and transport coordination. We discretize time of the inferred paths to one minute-basis to obtain a finer granularity for the coordination analysis.

7.3.1 Catch-up coordination

Starting with the coordination scheme that we are familiar with from Section 4.1, we consider the possibility for vehicles to catch up to each other to form platoons. A follower vehicle drives faster and merge with the lead vehicle and platoon until their paths split or reach destination. At each time step t_i, we check if there are any vehicles within a horizon (in space) ahead, that we call coordination horizon. For each candidate vehicle within the coordination horizon, we check which of those candidates give the highest fuel savings if a catch-up is made. The catch-up, unlike previously, is just simply driving +15 km/h (with maximum speed of 100 km/h) of the vehicle's own speed profile until merge and then drive at the lead vehicle's speed profile until the platoon splits. After splitting, the follower vehicle resumes with its own speed profile. This is done by finding the common path of both vehicles, and then calculating the fuel cost compared to have maintained its own profile. If it is beneficial to catch-up, we set a flag on the lead vehicle so it does not consider catching up to other vehicles ahead of it. This way, we avoid having a supposed lead vehicle catching up with another vehicle. Furthermore, we only coordinate single vehicle and it can either form a platoon with other single vehicle or platoons, but we do not coordinate vehicles already in a platoon.

7.3.2 Departure coordination

In this coordination scheme, we consider the possibility for the vehicles to adjust their departure time in order to match other vehicles in order to increase the platooning rate. First, we check which vehicles spontaneously platoon (including being a platoon leader) at least once during the day and exclude them from adjusting their departure time. At each time step, each vehicle checks if there are any vehicles within the coordination horizon (similar to the catch-up coordination). For each candidate vehicle within the coordination horizon, we check how long it takes for the follower vehicle to reach the candidate vehicle's current location and also how far they can travel together. The relative velocity has to be within 5 km/h at all times, otherwise we assume that the common path ends. The fuel saving for platooning on common path is calculated. We do this for each time step and for each vehicle and store it as vehicle pairs in a global candidate vehicle list. Notice that a lead vehicle in a platoon is eligible to check for candidate vehicles but all the vehicles in a platoon cannot be candidate vehicle. We then check which vehicle pair (one vehicle can be in several other pairs) saves the most fuel. We remove the vehicle pair from the list and also in any other pair the vehicles might be included in, then we repeat until the list is empty. This coordination scheme also captures that the lead vehicle, instead of adjusting its departure time, is stopping for a break or refueling, or the follower vehicle departures earlier.

7.3.3 Transport coordination

In transport coordination, we consider the coordination problem in a different perspective. Instead of looking at the vehicles, we are looking at the road segments. A road segment often starts and ends in a junction. Since we already inferred the path of the vehicles and have the timestamps, we check when each vehicle enters a road segment. By checking the time a vehicle enters each road segment, if several vehicles enter the same road segment within a time interval, we say that those vehicles platoon the whole road segment despite they not being within the platoon distance. Example, if we set a time interval of one hour, we check each road segment if there are vehicles entering between 00:00–00:59, 01:00–01.59 and so on until 23:00–23:59. If there are more than two vehicles entering the same road segment within the same time interval, we assume they platooned the whole road segment. Furthermore, we do not change the vehicles' time or speed profile, we mainly analyze the possibilities for platooning through possible transport rescheduling. Since this approach is different from the previous two coordination schemes, a different fuel model is used, namely

$$\psi_r = \begin{cases} d_{road}(1 + (N-1)\eta_r) & \text{if } N \geq 1 \\ 0 & \text{if } N = 0, \end{cases} \tag{7.4}$$

where ψ_r is the fuel cost, d_{road} the length of the road segment, N the number of vehicles entering the road, and $\eta_r = 0.9$ is the reduced fuel cost for platooning vehicles.

7.4 Results

After the map-matching and path-inference processes, only 1 773 HDVs remain out of 7 634. The reason for so many discarded vehicle data is due to the probe data containing many local-distribution HDVs that drive on smaller roads. Figure 7.6 depicts in yellow the paths that at least one of the 1 773 vehicles have taken on the road network. The number of actively moving vehicles along the day is shown in Figure 7.7. Note that most of the time we have more than 200 active vehicles. The minimum and maximum distance traveled out of the 1 773 HDVs are 24 and 948 km, respectively. The total distance traveled for all HDVs is 505 945 km, giving us an average of 285 km distance traveled per vehicle.

In order to investigate the spontaneous platooning rate, we set the platoon distance to 100 m. If there are vehicles ahead on the same path within the platoon distance for two consecutive time steps, we assume the vehicles platoon over that time. The spontaneous platooning rate is 1.21 %, which means that 1.21 % of all the vehicles' traveled distances are traveled in platoons. Since only the follower vehicles gain 10 % fuel savings in a platoon, this yields to an overall fuel savings of 0.07 % compared to if the vehicles drive alone and not considering the platooning effect. This is noted in Figure 7.8 were the number of platoons (blue solid line) stayed very low throughout the day, which means that not many vehicles are platooning in the current data set. The reason for fluctuations is that the distance to the vehicle ahead fluctuated around 100 m. Which part in the region where the vehicles platooned is shown in Figure 7.6 (red lines). We increase the platoon distance to 1 km in order to see if there are vehicles nearby for possible coordination. So if there is a vehicle within 1 km on the same path as the follower vehicle at two consecutive time steps, then the follower vehicle gains the platooning benefit. The fuel saving and platooning rate increased to 0.27 % and 4.85 %, respectively. This does not consider velocity changes to coordinate and form platoons, it just merely indicates that there are vehicles close by that could possibly platoon with.

Since increasing the platoon distance to 1 km indicates a higher possible fuel savings, it would be interesting to see the actual fuel savings where the follower vehicle increases velocity in order to catch up and merge. For the catch-up coordination, we investigate four different coordination horizons; 1, 5, 10, and 20 km. The coordination horizon is the horizon length where we search for possible vehicle candidates to form platoons with. The follower vehicle only obtains the 10 % fuel saving when

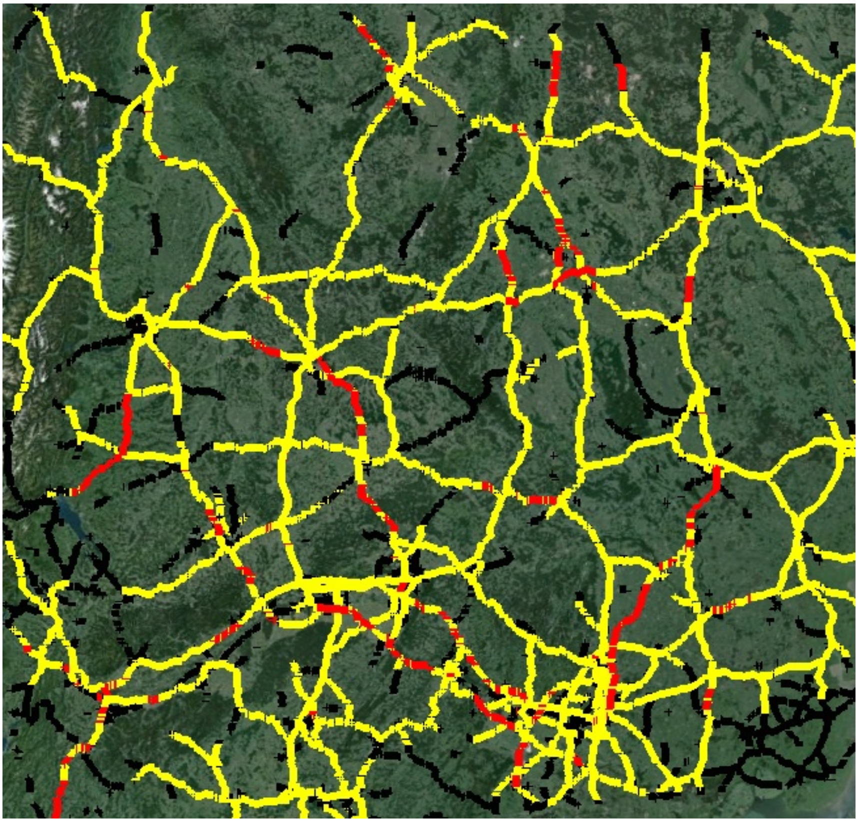


Figure 7.6: The path-inferred vehicles on the OSM road network. Black lines represent the road network, the yellow lines the path-inferred vehicles and the red lines the distances where the vehicles spontaneously platoon. The vehicles covered most of the highway road network.

the relative distance to the lead vehicle is within the platoon distance of 100 m at two consecutive time steps. This also applies when calculating the platooning rate. However, we do not consider coordinating vehicles already in a platoon. The results are presented in Table 7.1.

From Table 7.1, we note that with a longer coordination horizon, the more possible candidate vehicles there are to platoon with. Thus giving more catch-up possibilities, which increased both the platooning rate and the fuel saving. The fuel saved is compared to vehicles driving alone and not considering any platooning benefits. The fuel saving is an average over all vehicles and not the average of the vehicles that platooned, which would be much greater since most vehicles are not in a platoon. We notice that the results between 5, 10, and 20 km do not differ significantly, this means that most of the beneficial catch-ups are done with vehicles near by. This is reasonable considering that catching up with vehicles that are far

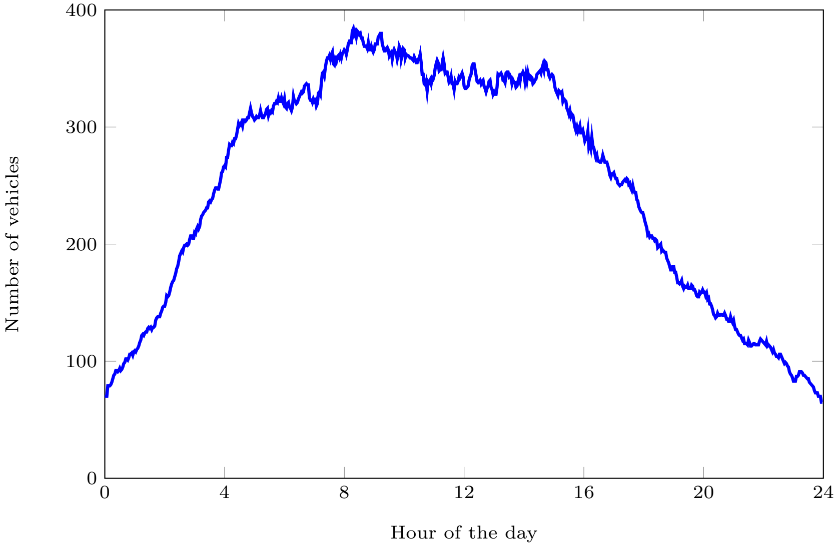


Figure 7.7: Number of vehicles moving at a given point throughout the 24-hour period.

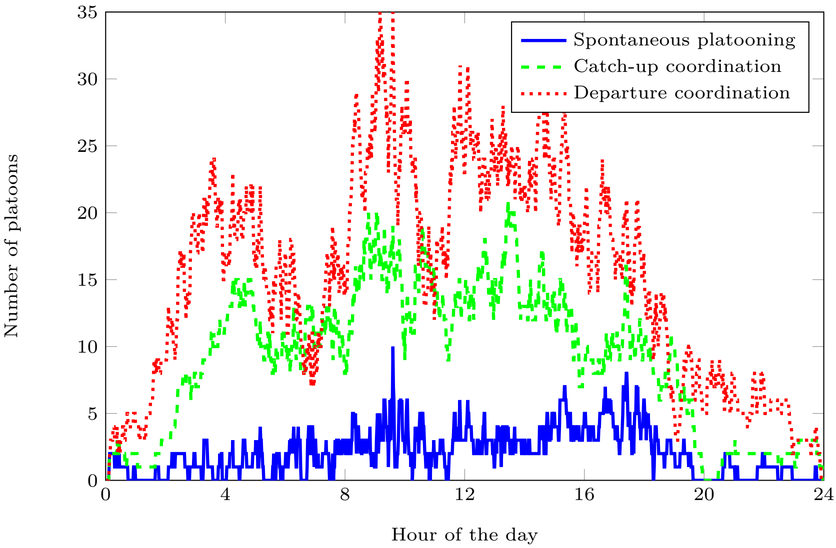


Figure 7.8: Number of spontaneous platoons and platoons through catch-up coordination and departure coordination throughout the day. The platoon distance and coordination horizon is set to 100 m and 20 km respectively. The number of platoons overall increases with roughly five and eight times through catch-up coordination and departure coordination, respectively, compared to spontaneous platooning.

Table 7.1: Results with catch-up coordination. As the coordination horizon is increased, the more possible candidate vehicles there are, however most catch ups have been made with candidate vehicles that are relatively close, hence the insignificant differences between 10 and 20 km coordination horizon.

Coordination horizon	Fuel saved	Platooning rate	Catch-ups made	Minutes saved
1 km	0.17%	4.66%	157	158
5 km	0.21%	6.59%	204	245
10 km	0.22%	6.94%	209	267
20 km	0.22%	6.97%	210	268

Table 7.2: Results with departure coordination. As the coordination horizon is increased, the more possible candidate vehicles there are that can adjust departure time in order to form platoons.

Coordination horizon	Fuel saved	Platooning rate	Vehicles adjusting their departure	Average minutes adjusted
1 km	0.11%	2.08%	105	2.6
5 km	0.27%	4.91%	319	5.5
10 km	0.42%	7.56%	434	7.2
20 km	0.60%	10.76%	529	11.3

away means that it has to platoon longer to gain back the additional fuel cost. This is reflected back in Chapter 4, that the distance ratio (distance to destination over distance between the vehicles) is an important factor when a catch-up is beneficial. The number of platoons during the day is depicted in Figure 7.8 (green dashed line). We note that it has increased overall by an average of approximately five times compared to spontaneous platooning.

We also analyze departure coordination with the same coordination horizon as in the catch-up coordination. A vehicle is allowed to adjust its departure only if it does not spontaneously platoon at all throughout the transport delivery. Notice that these two coordination analyses are done separately. Also notice that a coordination horizon of 20 km corresponds approximately to 15 minutes drive of highway speed, which is shifted in departure time. The results are presented in Table 7.2.

Similarly to catch-up coordination, we note that the longer coordination horizon is, the higher platooning rate and fuel saving. Furthermore, a departure coordination gives a much higher fuel saving compared to catch-up coordination. This is mainly due to that a catch-up coordination consumes additional fuel during the catch up and has to win that back through platooning before starting to save fuel. Contrary, the departure coordination allows the vehicle to form platoons with no additional fuel cost but in expense of delaying departures. Hence, the departure coordination does not saturate with longer coordination horizon as it does for catch-up coordination.

Table 7.3: Results with transport coordination. The higher the time interval is, the higher the chance of vehicles entering the road segment for platoon formation is.

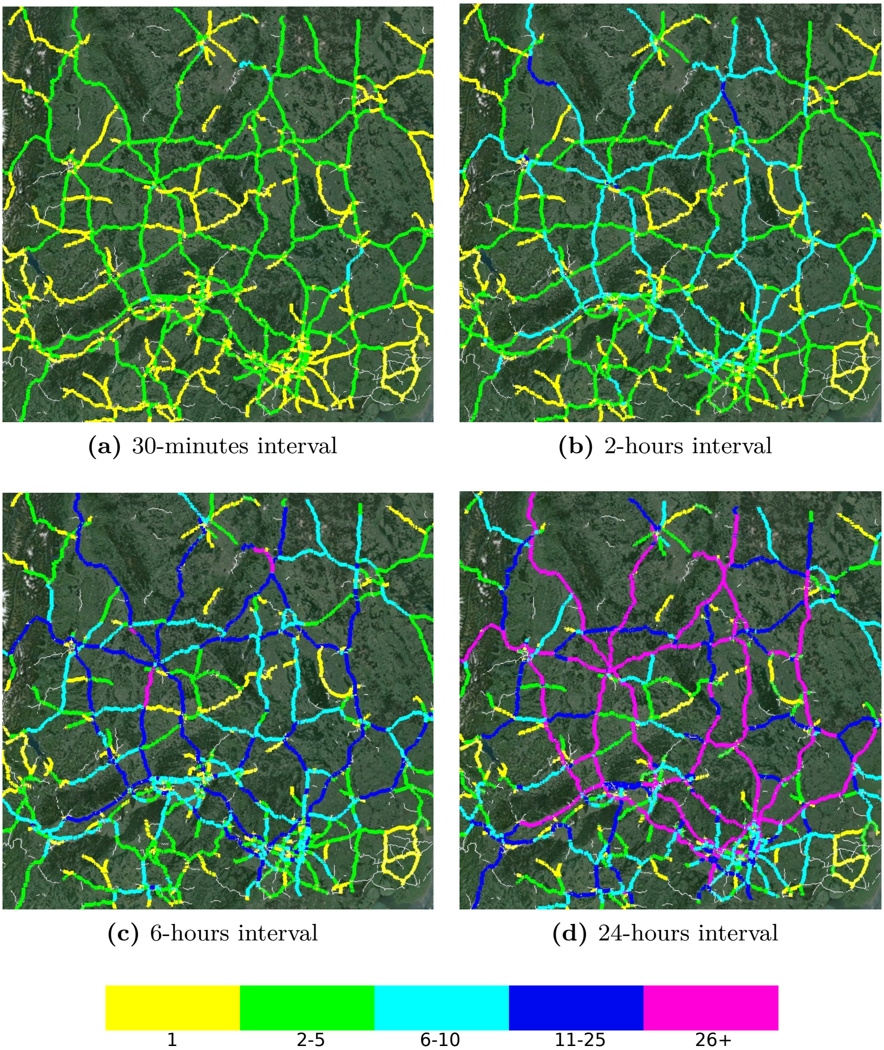
Time interval	Fuel saved*	Platooning rate
5 min	0.68%	13.22%
10 min	1.19%	22.41%
15 min	1.64%	30.26%
30 min	2.74%	47.58%
1 hr	4.31%	68.07%
2 hr	5.94%	83.23%
3 hr	6.87%	89.93%
6 hr	8.06%	95.67%
12 hr	8.85%	98.38%
24 hr	9.37%	99.38%

*Different fuel model used compared to the two previous coordination schemes.

Although the departure coordination adjusts the departure time, it is only changed by a few minutes, which in most cases are acceptable and within the time frame of transports. The number of platoons during the day has increased even more compared to catch-up coordination, which is seen in Figure 7.8 (red dotted line).

We notice that the departure coordination shows promising fuel saving the more we let the vehicles adjust their departure time. This gives us incentive to further study the transport coordination and check the fuel saving potentials. The transport coordination scheme analyzes when vehicles enter the same road segment within the same time interval. We choose several different time intervals and the results are shown in Table 7.3.

We see that with higher time interval, the more opportunities there are for vehicles to platoon with each other. Let us take 24-hours time interval for clarification. This means that we allow any vehicle to reschedule their transport to any time on the day and try to maximize the fuel saving by letting every vehicle travel together at the same time. For 12-hour time interval, there are two time slots. This means that there are slightly less vehicles, traveling on the same road segment within the time interval, to platoon with. This is illustrated in Figure 7.9 with four different time intervals, it shows the time slot with the highest number of platoons on each road segment. This is related to Figure 7.6 where we see paths where the vehicles platooned (in red), however in this case it is the number of vehicles entering the road segment. For the 30-minutes time interval (Figure 7.9a), we see that most platoons consist of 2–5 vehicles while as for the 24-hours time interval (Figure 7.9d) the platoons consist of several vehicles. This explains why the fuel saving for 24-hours time interval is more than three times higher than 30-minutes time interval while the platooning rate only doubled, this is due to that the first vehicle does not reduce its



(a) 30-minutes interval

(b) 2-hours interval

(c) 6-hours interval

(d) 24-hours interval

Figure 7.9: Highest number of platoons with transport coordination illustrated with line colors on the road network for four different time intervals, where the line colors represent the number of vehicles entering the road segment within the same time interval. There are more possibilities to form more and longer platoons if all the vehicles can travel at the same time (d) compared to allowing small adjustments (a).

fuel consumption in a platoon. Notice that 5-minutes and 10-minutes time interval are closely related to 5 km and 20 km coordination horizon departure coordination, but the fuel saving and platooning rate differ noticeably. This is because with departure coordination, we adjust the vehicles' departure and do not adjust the vehicles that spontaneously platoon at least once during its transport even if it is only for a short distance. There could have been possibilities that if the vehicle (that platooned at least once) adjusted its departure, the fuel saving would be even higher. For transport coordination, we do not consider changing the vehicles' speed or time profile, we only check when those enter a road segment. In practice, the vehicles need to adjust their profiles which would affect the future road segment entrances. We consider that the departure coordination gives us a lower bound and the transport coordination gives us an upper bound of possible fuel saving and platooning rate.

7.5 Summary

In this chapter, we studied the platooning rate of Scania HDVs during a 24-hour period in a region in Europe through their low-sampled GPS positions. This was done with the help of a map-matching algorithm to infer the path the vehicles have taken. Unfortunately the vehicles do not platoon spontaneously with each other that often. Only two, three active platoons out of 200–350 active vehicles throughout the day. This is of no surprise considering that a commercial platooning system does not yet exist unless the adaptive cruise control (ACC) is considered as one. Hence, the drivers are either using the ACC or driving manually close behind another vehicle. However, there are vehicles within a reasonable distance that one could possibly coordinate with. We showed with catch-up coordination that it could increase the fuel savings and platooning rate by a factor of three and six, respectively. However, due to the fact that a significant part of the coordination is the catch-up phase, the fuel savings got reduced compared to the platooning rate. We therefore analyzed the possibility to adjust departure time instead. With adjusting a few minutes, we increased the fuel savings and platooning rate nine times compared to spontaneous platooning. Although the fuel saving of 0.60 % for departure coordination seems quite low, this corresponds to approximately a total of 640 000 liter diesel fuel saved yearly for the 1 773 vehicles based on average fuel consumption of 0.3 liter/km and HDV traveling 200 000 km per year.

Notice that the spontaneous platooning rate might not be accurate since the HDVs might platoon with other non-Scania HDVs or vehicles not equipped with GPS. This only gives an indication that the spontaneous platooning rate is quite low today and can be increased manifold through platoon coordinations, either on the fly or through transport planning.

Chapter 8

Conclusions and future outlook

"The future belongs to those who believe in the beauty of their dreams."
Eleanor Roosevelt

Vehicle platooning is becoming important in the transport industy. Heavy-duty vehicle (HDV) platooning is a means to mitigate the environmental impacts from road freight transports, as well as a means to reduce fuel consumption, increase safety, and increase the throughput on congested highways. In this thesis, we showed how platoon formation of scattered HDVs can be achieved by adjusting the vehicle speeds, and how this leads to increased fuel savings. However, the surrounding traffic can disturb and delay the merging maneuver, which resulted in lower fuel savings. We investigated how traffic affects a merging maneuver and proposed a merge estimation approach based on a fundamental traffuc diagram, shockwave theory, and moving bottlenecks. The approach predicts where two HDVs merge, which depends on the current traffic condition, initial distance between the vehicles, and the desired speeds of both vehicles. We validated our approach using a microscopic traffic simulation tool. Additionally, we conducted experiments on a public highway, where we obtained traffic data on that specific highway segment, and attempted to merge two HDVs during rush hour. Lastly, we investigated the fuel-saving potentials on a larger road network with hundreds and thousands of HDVs involved. This was analyzed using probe data obtained from a fleet management system.

This chapter summarizes the thesis by detailing the conclusions that follow from the obtained results, in Section 8.1, and outlines directions for possible future work in this area, in Section 8.2.

8.1 Conclusions

The work presented in this thesis tackles the problem of forming platoons of scattered HDVs by adjusting vehicle speeds and considering the influence of the surrounding traffic. In Chapter 4, we studied the platoon formation of two HDVs, where both vehicles have the possibility to adjust their own speed. If the follower vehicle decides to drive faster in order to catch up with the lead vehicle, it consumes additional fuel during the merging maneuver but the loss is recovered from platooning. If the lead vehicle decides to slow down to let the follower vehicle catch up, it loses transport time that needs to be compensated by driving faster once the platoon is formed or drive faster after the platoon splits. A combination of both lead and follower vehicle adjusting their speeds allows for faster platoon formation and therefore also higher fuel savings. We introduced the term break-even ratio, which defines a distance measure of a horizon (in space) a vehicle should consider for a platooning candidate in order to save fuel. Based on the break-even ratio, we proposed a coordination algorithm that considers N HDVs to form platoons that yields large fuel savings without the need to compute each possible combination to form platoons. The concept is to coordinate HDVs pairwise and to form platoons with the closest fuel saving candidate.

In Chapter 5, we investigated how traffic influence a platoon formation of two HDVs. An HDV is generally driving slower than the rest of the traffic due to traffic regulations and therefore it throttles the throughput of the road since it is occupying a lane. This is known as a moving bottleneck and causes the traffic to separate into a free flow region downstream the vehicle and a congestion region upstream. Based on the current traffic condition and the speed of the vehicle, the free flow and congestion region evolve differently in time and space and this is predicted using a fundamental diagram. For example, if the traffic is very light then the cars can easily overtake and pass the HDV without the flow being throttled and therefore a congestion upstream will not appear. We considered the two HDVs as two separate moving bottlenecks and studied the interaction of these in order to predict the traffic condition in the area between the vehicles, where the free flow downstream of the follower vehicle affects the congestion upstream of the lead vehicle. This allowed us to predict and estimate where the merge will occur depending on the traffic density, the relative distance between the vehicles, and the desired speeds of the vehicles. An accurate prediction of the merge point is very valuable when making a coordination decision. If traffic delays the platoon formation, it might result in lower fuel savings, or in worst case fuel loss, and this can be avoided if the merge point can be predicted. We used a traffic simulator to validate our approach.

In Chapter 6, we investigated the traffic influence on platoon formation further by conducting experiments on a Swedish highway. The experiments consisted of forming a platoon with two HDVs in different traffic conditions. We obtained traffic data for that specific highway for the duration of the experiment in order to determine the traffic density. The HDV drivers were allowed to overtake other cars and trucks if they deemed them to be driving too slowly. This happened a few times every day, especially for the follower HDV that tried to catch up. This resulted in a longer merge distance than the optimal merge distance, where the HDVs maintain constant speeds. In some of the test-runs, the effect was the other way around. There were slowly moving cars in front of the lead HDV causing it to drive slower, which led to an earlier merge than expected. Another driver behavior was observed, where drivers persistently drive behind an HDV. The driver was either comfortable driving behind an HDV or reluctant to change lanes and overtake the HDV. A fourth of the test-runs had a persistent driver driving behind the lead HDV making it impossible for the follower HDV to complete the merging maneuver. We introduced two merge prediction models, namely a linear regression model and a moving bottleneck model, which we compared with the outcome of the experiment. The performance of both models were good, with the linear regression model being better as the root mean squared error was lower. The linear regression model was also much closer to the real outcome for majority of the individual test-runs. However, this is expected as the linear regression model is based on a subset of the results from the experiments, while the moving bottleneck model uses a fundamental diagram based on empirical traffic data measurements.

Lastly, in Chapter 7 we analyzed real-world data obtained from Scania's fleet management system. We had low-sampled GPS position data for 1 800 vehicles over a $500\,000\,\mathrm{m}^2$ area in Europe during a 24-hour period. We inferred the paths the vehicles had taken on an underlying road network based on OpenStreetMap. During the majority of the day there were 200–350 active vehicles transporting goods. With this low number of vehicles, the platooning possibilities are few. Despite the low number of active vehicles, we had two or three platoons most of the time throughout the day. This gave us an average fuel saving of 0.07 % and a platooning rate of 1.27 %, meaning that more than 1 % of the total traveled distance was in a platoon. With catch-up coordination we managed to increase the fuel savings and platooning rate to 0.22 % and 6.97 %, respectively. This also increased the number of platoons to over ten active platoons over the majority of the day. The low increase in fuel savings compared to platooning rate are due to the additional fuel cost of driving faster and catching up. Therefore, we continued with investigating the possibility to adjust departure times, where we tried to match the departure such that the single vehicle (vehicles that do not spontaneously platoon at all over the whole day) can platoon with other vehicles. With adjusting the departure time of only 11 minutes in average, we increased the fuel savings and platooning rate by a factor of nine compared to spontaneous platooning. By either coordinating on the fly, like our catch-up coordination, or by adjusting the departure time slightly, we increased the fuel savings and the number of platoons on the road. Further fuel savings are obtained by coordinating transport missions. This indicates that planning the transport mission ahead of time has significantly higher fuel saving potentials compared to platoon coordination on the fly.

8.2 Future outlook

Some research remains to be done as the conducted work regarding HDV platoon formation is limited. We present some possible extension of our work and possible directions as future outlook.

Our study of cooperative formation for a pair of vehicles do not consider all practical issues, such as speed limits of the road or vehicle constraints. Additionally, a driver has to respect the driving and resting time regulations; in Europe for instance, a driver is not allowed to drive more than 4.5 hours without taking a break. Such constraints need to be considered in practical use. Investigation with different and more sophisticated fuel models is also of interest. Furthermore, we believe that lower level cooperative control of vehicles and platoons is necessary for merging, platooning, and splitting and needs to be investigated further. More research is still required on how to cooperatively drive a platoon as fuel efficiently as possible under various disturbances, such as road grade and other traffic. Additionally, as we focused on platoon formation with the nearest neighbor, other types of coordinated platoon formation are open for research. Planning ahead of time who to platoon with before the departure is an example and requires a systematic way to handle hundreds, thousands, or more vehicles for coordination.

Merge predictions based on varying road properties is a possible extension. Our study on the influence of traffic on a merging maneuver is performed based on simplifications that the road is flat and straight. Fundamental diagrams are usually based on empirical observations of the average traffic behavior and that often varies with different road grades, curvature, and speed limits. As platoon formation extends to long distances, the road infrastructure varies (such as on- and off-ramps, lane merging, and lane splitting), which affects the fundamental diagram. As this work focused on a moving bottleneck model, other merge prediction models are interesting to study to compare the performances between the models. Other traffic models include multi-class model, where the model describes two different flows that interact with each other such as a highway with high proportion of cars and HDVs, or a hybrid traffic model. For example, a macroscopic model can be used for the merging maneuver, however, as soon as the follower vehicle interacts with the congestion (caused by the lead vehicle), a microscopic model is used. Another consideration is to utilize the static traffic data (fundamental diagram) and combine it with the experiment outcome for a more sophisticated model. A merge time and fuel cost predictions are as equally important to analyze as the merge distance prediction. A merging maneuver occurs both in space and time, therefore the merging time needs to be evaluated. Traffic may cause the vehicle to accelerate and brake often leading to a higher fuel consumption. Thus, a possible extension is to cope all three aspects (merge distance, time, and fuel cost) in order to develop a complete merge predictor. Furthermore, as merging maneuver and platooning extend over long distances, chances are low that a well-built infrastructure exists outside metropolitan cities where the platooning has the highest benefits. Therefore a non-infrastructural solution to measure traffic conditions needs to be explored.

The data analysis on the potentials of platoon coordination through vehicle probe data shows promising results. A possible future work is to extrapolate or gather more data to better represent reality and use machine learning techniques and clustering to find fleet owners who can benefit from platooning with others. A highly unexplored research area is to investigate how to optimize goods transport and departures between different fleet companies, in order to decrease the fuel cost. This involves logistics and scheduling to find goods to reallocate to other HDVs and to find platooning opportunities. We believe that high fuel savings can be achieved by planning transport missions ahead of time and working on the top layer of the transport system architecture described in Chapter 3.

Nomenclature

Acronyms and abbreviations

ACC	Adaptive cruise control
AID	Automatic incident detection
CC	Cruise control
CACC	Cooperative adaptive cruise control
CAN	Controller area network
CAM	Cooperative awareness message
CFD	Computational fluid dynamics
DENM	Decentralized environment notification message
DHSC	Downhill speed control
ECU	Electronic contorl units
FLC	Front looking camera
FMS	Fleet management system
GCDC	Grand cooperative driving challenge
GPS	Global positioning system
HDV	Heavy-duty vehicle
IaaS	Infrastructure as a service
ICT	Information and communication technology
ITS	Intelligent transportation systems
MCS	Motorway control system
MPC	Model predictive control
OSM	OpenStreetMap
PaaS	Platform as a service
PID	Proportional-integral-derivative
RMSE	Root mean squared error
SaaS	Software as a service
STD	Standard deviation

UII	User input interface
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle to vehicle and/or infrastructure
VG	Vehicle generator
VMS	Variable message sign
VSL	Variable speed limit
VSU	Vehicle state updater
WLAN	Wireless local area network

Bibliography

5G PPP. 5g automotive vision. White paper, 5G Infrastructure Public Private Partnership (2015).

ACEA. European motor vehicle parc 2014, European automobile manufacturer association (2014). ANFAC report.

A. Alam. *Fuel-efficient distributed control for heavy duty vehicle Platooning*. Licentiate thesis, KTH Royal Institute of Technology (2011).

A. Alam. *Fuel-efficient heavy-duty vehicle platooning*. Ph.D. thesis, KTH Royal Institute of Technology (2014).

A. Alam, B. Besselink, V. Turri, J. Mårtensson, and K. H. Johansson. Heavy-duty vehicle platooning for sustainable freight transport. *IEEE Control Systems Magazine* (2015).

A. Alam, A. Gattami, K. H. Johansson, and C. J. Tomlin. Guaranteeing safety for heavy duty vehicle platooning: Safe set computations and experimental evaluations. *Control Engineering Practice*, 24 (2014).

A. Alam, A. Gattami, and K.-Y. Liang. *Metod i samband med fordonståg, och ett fordon som använder metoden*. Swedish patent grant number SE 537185 (filed 2011).

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Apparatus and method for regulating a vehicle comprised in a vehicle train*. International patent application number PCT/SE2014/051120 (filed 2013*a*).

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Ett system och en metod för korrigering av kartdata och positionsdata för fordonståg*. Swedish patent grant number SE 537469 (filed 2013*b*).

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Metod och system för gemensam körstrategi för fordonståg*. Swedish patent grant number SE 537482 (filed 2013*c*).

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Metod och system för gemensam körstrategi för fordonståg*. Swedish patent grant number SE 537578 (filed 2013*d*).

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Metod och system för gemensam körstrategi för fordonståg*. Swedish patent grant number SE 537618 (filed 2013*e*).

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Metod och system för organisering av fordonståg*. Swedish patent grant number SE 537598 (filed 2013*f*).

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *A system and a method for correction of map data and position data for a vehicle platoon*. European patent application number 14848197.1 (filed 2014*a*).

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *A system and a method for correction of map data and position data for a vehicle platoon*. International patent application number PCT/SE2014/051114 (filed 2014*b*).

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Method and system for common driving strategy for vehicle platooning*. International patent application number PCT/SE2014/051117 (filed 2014*c*).

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Method and system for common driving strategy for vehicle platoon*. International patent application number PCT/SE2014/051112 (filed 2014*d*).

A. Alam, K. H. Johansson, K.-Y. Liang, J. Mårtensson, and H. Pettersson. *Method and system for handling of obstacle for vehicle platoon*. International patent application number PCT/SE2014/051111 (filed 2014*e*).

A. Alam and K.-Y. Liang. *Anordning och förfarande för utvärdering av framfart inbegripande fordonstågsformering*. Discontinued, Swedish patent application number SE 1251407-1 (filed 2012).

A. Alam and K.-Y. Liang. *Device and method for the evaluation of progress comprising the formation of platoons*. European application number 13862945.6 (filed 2013*a*).

A. Alam and K.-Y. Liang. *Device and method for the evaluation of progress comprising the formation of platoons*. International application number PCT/SE13/051382 (filed 2013*b*).

A. Alam and K.-Y. Liang. *Method, device and system for supporting the formation of platooning*. International patent application number PCT/SE15/050419 (filed 2014*a*).

A. Alam and K.-Y. Liang. *Metod, anordning och system innefattande anordningen för att stödja skapandet av fordonståg*. Swedish patent application number SE1450433-6 (filed 2014*b*).

A. Alam, K.-Y. Liang, and H. Pettersson. *Metod och system för hantering av hinder för fordonståg*. Swedish patent grant number SE 537603 (filed 2013*g*).

A. Alam, K.-Y. Liang, and H. Pettersson. *System and method for regulating a vehicle platoon with two different strategies*. European patent application number PCT/SE2014/051122 (filed 2013*h*).

A. Alam, K.-Y. Liang, and H. Pettersson. *System and method for regulating a vehicle platoon with two different strategies*. International patent application number 14849834.8 (filed 2013*i*).

A. Alam, K.-Y. Liang, and H. Pettersson. *System och metod för att reglera ett fordonståg med två olika körstrategier*. Swedish patent grant number SE 537466 (filed 2013*j*).

A. Alam, K.-Y. Liang, and H. Pettersson. *System och metod för att reglera fordonståg med en gemensam positionsbaserad körstrategi*. Swedish patent grant number SE 537985 (filed 2013*k*).

A. Alam, K.-Y. Liang, and H. Pettersson. *Styrenhet och metod för att reglera hastigheten på ett fordon i ett avståndsreglerat*. Swedish patent grant number SE 537992 (filed 2014*f*).

A. Alam, K.-Y. Liang, and H. Pettersson. *System and method relating to vehicle platooning*. European patent application number 14847454.7 (filed 2014*g*).

A. Alam, K.-Y. Liang, and H. Pettersson. *System and method relating to vehicle platooning*. International patent application number PCT/SE2014/051119 (filed 2014*h*).

A. Alam, K.-Y. Liang, and H. Pettersson. *Steuereinheit und Verfahren zum Regeln der Geschwindigkeit eines Fahrzeugs in einer abstandsgeregelten Fahrzeugkolonne bei einer Bergfahrt*. German patent application number DE 102015010559.0 (filed 2015).

A. Alam, J. Mårtensson, and K. H. Johansson. Look-ahead cruise control for heavy duty vehicle platooning. In *Proceedings of the 16th International IEEE Annual Conference on Intelligent Transportation Systems*. Hague, The Netherlands (2013).

L. Alvarez and R. Horowitz. Safe platooning in automated highway systems. Report No. USC-ITS-PRR-97-46, California PATH (1997).

T. Bellemans, B. De Schutter, and B. De Moor. Model predictive control for ramp metering of motorway traffic: A case study. *Control Engineering Practice*, 14 (2006).

D. Bertsekas. *Dynamic programming and optimal control: approximate dynamic programming.* Athena Scientific optimization and computation series. Athena Scientific (2012).

B. Besselink, V. Turri, S. van de Hoef, K.-Y. Liang, A. Alam, J. Mårtensson, and K. H. Johansson. Cyber-physical control of road freight transport. *Proceedings of the IEEE*, 104(5) (2016).

R. Bishop, D. Bevly, J. Switkes, and L. Park. Results of initial test and evaluation of a driver-assistive truck platooning prototype. In *IEEE Intelligent Vehicles Symposium*. Dearborn, Michigan, USA (2014).

S. Bitam and A. Mellouk. ITS-cloud: Cloud computing for intelligent transportation system. In *IEEE Global Communications Conference*. Anaheim, California, USA (2012).

C. Bonnet and H. Fritz. Fuel consumption reduction in a platoon: Experimental results with two electronically coupled trucks at close spacing. In *Future Transportation Technology Conference & Exposition*, 724. SAE (2000).

F. Browand, J. McArthur, and C. Radovich. Fuel saving achieved in the field test of two tandem trucks. Report No. UCB-ITS-PRR-2004-20, California PATH (2004).

C. Canudas de Wit, F. Morbidi, L. L. Ojeda, A. Y. Kibangou, I. Bellicot, and P. Bellemain. Grenoble traffic lab: An experimental platform for advanced traffic monitoring and forecasting [applications of control]. *IEEE Control Systems*, 35(3) (2015).

K. Chang, W. Li, P. Devlin, A. Shaikhbahai, P. Varaiya, J. Hedrick, D. McMahon, V. Narendran, D. Swaroop, and J. Olds. Experimentation with a vehicle platoon control system. In *Vehicle Navigation and Information Systems Conference* (1991).

C. Chien, Y. Zhang, and C. Cheng. Autonomous intelligent cruise control using both front and back information for tight vehicle following maneuvers. *IEEE Ttransactions on Vehicular Technology*, 48(1) (1999).

A. Davila. Report on fuel consumption. Deliverables, SARTRE (2013).

Q. Deng and W. Boughout. The impacts of heavy-duty vehicle platoon spacing policy on traffic flow. In *Transportation Research Board 95th Annual Meeting* (2016).

Q. Deng and X. Ma. A simulation platform for autonomous heavy-duty vehicle platooning in mixed traffic. In *Transportation Research Board 94th Annual Meeting* (2015).

I. B. Dhaou. Fuel estimation model for eco-driving and eco-routing. In *IEEE Intelligent Vehicles Symposium*. Baden-Baden, Germany (2011).

ETSI. Intelligent transport systems (ITS); European profile standard for the physical and medium access control layer of intelligent transport systems operating in the 5 GHz frequency band. ETSI EN 202 663 V1.1.0, European Telecommunication Standards Institute (2009).

ETSI. Intelligent transport systems (ITS); framework for public mobile networks in cooperative ITS (C-ITS). ETSI TR 102 962 V1.1.1, European Telecommunication Standards Institute (2012).

ETSI. Intelligent transport systems (ITS); vehicular communications; basic set of applications; part 2: Specification of cooperative awareness basic service. ETSI EN 302 637-2 V1.3.2, European Telecommunication Standards Institute (2014*a*).

ETSI. Intelligent transport systems (ITS); vehicular communications; basic set of applications; part 3: Specification of decentralized environmental notification basic service. ETSI EN 302 637-3 V1.2.2, European Telecommunication Standards Institute (2014*b*).

ETSI. Intelligent transport systems (2016). URL `http://www.etsi.org/technologies-clusters/technologies/intelligent-transport`. Accessed: March 22, 2016. ©European Telecommunications Standards Institute 2016. Further use, modification, redistribution is strictly prohibited.

European Commission. Roadmap to a single European transport area - towards a competitive and resource efficient transport system. White paper, European Commission (2011).

European Commission. Trends to 2050: Reference scenario 2013 (2013). ISBN: 978-92-79-33728-4.

European Commission. EU transport in figures: Statistical pocketbook 2015 (2015). ISBN: 978-92-79-43915-5.

European Truck Platooning Challenge. Creating next generation mobility (2016). URL `https://www.eutruckplatooning.com/default.aspx`. Accessed: April 19, 2016.

European Union. EU directive 2010/40/EU (2010). URL `http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:207:0001:0013:EN:PDF`. Accessed: March 24, 2016.

Eurostat. Energy, transport and environment indicators - 2015 edition (2015). ISBN: 978-92-79-49471-0.

S. Ezell. *Explaining international IT application leadership: intelligent transportation systems*. The Information Technology & Innovation Foundation (2010).

F. Farokhi and K. H. Johansson. A game-theoretic framework for studying truck platooning incentives. In *Proceedings of the 16th International IEEE Annual Conference on Intelligent Transportation Systems*. Hague, The Netherlands (2013).

F. Farokhi, K.-Y. Liang, and K. H. Johansson. Cooperation patterns between fleet owners for transport assignments. In *IEEE Conference on Control Applications*. Sydney, Australia (2015).

M. Fellendorf and P. Vortisch. Microscopic traffic flow simulator VISSIM. In J. Barceló, editor, *Fundamentals of Traffic Simulation*, volume 145, chapter 2 (2010).

General Motors. The 1939 New York world's fair (1939). URL `http://www.1939nyworldsfair.com/worlds_fair/wf_tour/zone-6/general_motors.htm`. Film *To New Horizons* available at: `http://www.archive.org/details/ToNewHor1940`. Accessed: March 30, 2016.

T. D. Gillespie. *Fundamentals of vehicle dynamics*. SAE International (1992). ISBN: 1-56091-199-9.

M. Gordon and R. E. Turochy. Evaluation of the effects of driver assistive truck platooning on freeway traffic flow. *Transportation Research Record: Journal of the Transportation Research Board* (2016).

H. Hadj-Salem, J. Bloseeville, and M. Papageorgiou. ALINEA: a local feedback control law for on-ramp metering; a real-life study. In *Third International Conference on Road Traffic Control*. London, United Kingdom (1990).

J. Hedrick, M. Tomizuka, and P. Varaiya. Control issues in automated highway systems. *Control Systems, IEEE*, (December) (1994).

A. Hegyi, B. De Schutter, and J. Hellendoorn. Optimal coordination of variable speed limits to suppress shock waves. *IEEE Transactions on Intelligent Transportation Systems*, 6(1) (2005).

E. Hellström. *Look-ahead control of heavy vehicles*. Ph.D. thesis, Linköpings University (2010).

Highways Agency. M25 controlled motorways. Summary report, Executive Agency of the Department for Transport (2004).

S. Hoogendoorn and V. Knoop. Traffic flow theory and modelling. In *The Transport System and Transport Policy: An Introduction*. Edward Elgar Publishing Limited (2012).

Z. Hou, J.-X. Xu, and H. Zhong. Freeway traffic control using iterative learning control-based ramp metering and speed signaling. *IEEE Transactions on Vehicular Technology*, 56(2) (2007).

H. L. Humphreys, J. Batterson, D. Bevly, and R. Schubert. An evaluation of the fuel economy benefits of a driver assistive truck platooning prototype using simulation. Technical report, SAE Technical Paper 2016-01-0167 (2016).

L. Immers and S. Logghe. Traffic flow theory (2002). URL `https://www.mech.kuleuven.be/cib/verkeer/dwn/H111part3.pdf`. Accessed: April 6, 2016.

ITF. Transport CO2 emissions. Statistics, International Transport Forum (2008). URL `http://www.internationaltransportforum.org/jtrc/environment/CO2/World.pdf`. Accessed: March 14, 2016.

E. Kaplan and C. Hegarthy. *Understanding GPS - principles and applications*. Artech House (2006). ISBN: 978-1-58053-895-4.

M. Khatir and E. Davison. Decentralized control of a large platoon of vehicles using non-identical controllers. In *American Control Conference*. Boston, Massachusetts, USA (2004).

R. Kianfar, P. Falcone, and J. Fredriksson. A distributed model predictive control approach to active steering control of string stable cooperative vehicle platoon. In *7th IFAC Symposium on Advances in Automotive*. Tokyo, Japan (2013).

M. P. Lammert, A. Duran, J. Diez, K. Burton, and A. Nicholson. Effect of platooning on fuel consumption of class 8 vehicles over a range of speeds, following distances, and mass. In *SAE Commercial Vehicle Engineering Congress*. Rosemont, Illinois, USA (2014).

C. Lank, M. Haberstroh, and M. Wille. Interaction of human, machine, and environment in automated driving systems. *Transportation Research Record: Journal of the Transportation Research Board*, 2243 (2011).

J. Larson, C. Kammer, K.-Y. Liang, and K. H. Johansson. Coordinated route optimization for heavy-duty vehicle platoons. In *Proceedings of the 16th International IEEE Annual Conference on Intelligent Transportation Systems*. Hague, The Netherlands (2013).

J. Larson, K.-Y. Liang, and K. H. Johansson. A distributed framework for coordinated heavy-duty vehicle platooning. *IEEE Transactions on Intelligent Transportation Systems*, 16(1) (2015).

E. Larsson, G. Sennton, and J. Larson. The vehicle platooning problem: Computational complexity and heuristics. *Transportation Research Part C: Emerging Technologies*, 60 (2015).

L. Leclercq, S. Chanut, and J.-B. Lesort. Moving bottlenecks in Lighthill-Whitham-Richards model: A unified theory. *Transportation Research Record: Journal of the Transportation Research Board*, (1883) (2004).

W. Levine and M. Athans. On the optimal error regulation of a string of moving vehicles. *IEEE Transactions on Automatic Control*, 11(3) (1966).

K.-Y. Liang, A. Alam, and A. Gattami. The impact of heterogeneity and order in heavy duty vehicle platooning networks. In *IEEE Vehicular Networking Conference*. Amsterdam, The Netherlands (2011).

K.-Y. Liang, Q. Deng, J. Mårtensson, X. Ma, and K. H. Johansson. The influence of traffic on heavy-duty vehicle platoon formation. In *IEEE Intelligent Vehicles Symposium*. Seoul, South Korea (2015).

K.-Y. Liang, J. Mårtensson, and K. H. Johansson. When is it fuel efficient for a heavy duty vehicle to catch up with a platoon? In *7th IFAC Symposium on Advances in Automotive*. Tokyo, Japan (2013).

K.-Y. Liang, J. Mårtensson, and K. H. Johansson. Fuel-saving potentials of platooning evaluated through sparse heavy-duty vehicle position data. In *IEEE Intelligent Vehicles Symposium*. Dearborn, Michigan, USA (2014).

K.-Y. Liang, J. Mårtensson, and K. H. Johansson. Experimental evaluation of platoon formation on E4/E20 highway (2016*a*). In preparation.

K.-Y. Liang, J. Mårtensson, and K. H. Johansson. Heavy-duty vehicle platoon formation for fuel efficiency. *IEEE Transactions on Intelligent Transportation Systems*, 17(4) (2016*b*).

K.-Y. Liang, S. van de Hoef, H. Terelius, V. Turri, B. Besselink, J. Mårtensson, and K. H. Johansson. Networked control challenges in collaborative road freight transport. *European Journal of Control* (2016*c*). To appear.

M. J. Lighthill and G. B. Whitham. On kinematic waves. ii. a theory of traffic flow on long crowded roads. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 229(1178) (1955).

X.-Y. Lu and S. E. Shladover. Automated truck platoon control and field test. In *Road Vehicle Automation*, 247–261. Springer (2014).

J. Mårtensson, A. Alam, S. Behere, A. Khan, J. Kjellberg, K.-Y. Liang, H. Pettersson, and D. Sundman. The development of a cooperative heavy-duty vehicle for the GCDC 2011: Team Scoop. *IEEE Transactions on Intelligent Transportation Systems*, 13(3) (2012).

P. Meisen, T. Seidl, and K. Henning. A data-mining technique for the planning and organization of truck platoons. In *Proceedings of the International Conference on Heavy Vehicles*. Paris, France (2008).

F. Moosmann and C. Stiller. Velodyne SLAM. In *IEEE Intelligent Vehicles Symposium*. Baden-Baden, Germany (2011).

G. Newell. A moving bottleneck. *Transportation Research Part B: Methodological*, 32(8) (1998).

A. Nissan. *Evaluation of variable speed limits: empirical evidence and simulation analysis of Stockholm's motorway control system*. Ph.D. thesis, KTH Royal Institute of Technology (2010).

A. Nissan and K. L. Bang. Evaluation of impacts of the motorway control system (MCS) in Stockholm. In *European Transport Conference* (2006).

D. Norrby. *A CFD study of the aerodynamic effects of platooning trucks*. M.Sc. thesis, KTH Royal Institute of Technology (2014).

C. Nowakowski, S. E. Shladover, X.-Y. Lu, D. Thompson, and A. Kailas. Cooperative adaptive cruise control (CACC) for truck platooning: Operational concept alternatives. Research reports, California PATH (2015).

M. Papageorgiou, E. Kosmatopoulos, and I. Papamichail. Effects of variable speed limits on motorway traffic flow. *Transportation Research Record: Journal of the Transportation Research Board*, (2047) (2008).

M. Papageorgiou and A. Kotsialos. Freeway ramp metering: an overview. In *Proceedings of IEEE Conference on Intelligent Transportation Systems*. Dearborn, Michigan, USA (2000).

PATH. Vehicle platooning and automated highways (1997). URL `http://www.path.berkeley.edu/PATH/Publications/Media/FactSheet/VPlatooning.pdf`. Accessed: February 20, 2014.

L. E. Peppard. String stability of relative-motion PID vehicle control systems. *IEEE Transactions on Automatic Control*, 19(5) (1974).

M. Pillado, D. Gallegos, M. Tobar, K. H. Johansson, J. Mårtensson, X. Ma, S. Eilers, T. Friedrichs, S. S. Borojeni, M. Adolfson, and H. Pettersson. COMPANION - towards co-operative platoon management of heavy-duty vehicles. In *18th International Conference on Intelligent Transportation Systems*. Canary Islands, Spain (2015).

L. A. Pipes. An operational analysis of traffic dynamics. *Journal of Applied Physics*, 24(3) (1953).

M. Rahmani and H. N. Koutsopoulos. Path inference from sparse floating car data for urban networks. *Transportation Research Part C: Emerging Technologies*, 30 (2013).

Regiolab Delft. Regiolab Delft: Traffic monitoring on motorways, urban and provincial roads (2016). URL `http://www.citg.tudelft.nl/fileadmin/Faculteit/CiTG/Over_de_faculteit/Afdelingen/Afdeling_Transport_en_Planning/`

`Traffic_management_and_traffic_flow_theory/Dynamisch_Verkeers_Management/Monitoring/doc/Regiolab.pdf`. Accessed: March 30, 2016.

P. I. Richards. Shock waves on the highway. *Operations Research*, 4(1) (1956).

T. Robinson, E. Chan, and E. Coelingh. Operating platoons on public motorways : An introduction to the SARTRE platooning programme. In *Proceedings of the 17th ITS World Congress*. Busan, Korea (2010).

M. Roeth. Cr england Peloton technology platooning test nov 2013. *North American Council for Freight Efficiency* (2013).

R. Rothery, R. Silver, R. Herman, and C. Torner. Single-lane bus flow. *Operations Research*, 12(6) (1964).

P. Sahlholm. *Distributed road grade estimation for heavy duty vehicles*. Ph.D. thesis, KTH Royal Institute of Technology (2011).

T. Sandberg. *Heavy truck modeling for fuel consumption simulations and measurements*. Licentiate thesis, Linköping University (2001).

Scania CV AB. Annual report (2014).

M. Schittler. State-of-the-art and emerging truck engine technologies for optimized performance, emissions and life cycle costs. In *9th Diesel Engine Emissions Reduction Conference* (2003).

P. Seiler, B. Song, and J. Hedrick. Development of a collision avoidance system. In *SAE World Congress*. Detroit, Michigan, USA (1998). SAE paper 980853.

E. Shaw and J. K. Hedrick. String stability analysis for heterogeneous vehicle strings. In *American Control Conference*. New York, USA (2007).

M. S. Shehata, J. Cai, W. M. Badawy, T. W. Burr, M. S. Pervez, R. J. Johannesson, and A. Radmanesh. Video-based automatic incident detection for smart roads: The outdoor environmental challenges regarding false alarms. *IEEE Transactions on Intelligent Transportation Systems*, 9(2) (2008).

S. E. Shladover. Recent international activity in cooperative vehicle - highway automation systems. Report No. FHWA-HRT-12-033, California PATH (2012).

S. E. Shladover, C. Nowakowski, X.-Y. Lu, and R. Hoogendoorn. Using cooperative adaptive cruise control (CACC) to form high-performance vehicle streams. Research report UCB-ITS-PRR-2014-7, California PATH (2014).

S. E. Shladover, D. Su, and X.-Y. Lu. Impacts of cooperative adaptive cruise control on freeway traffic flow. *Transportation Research Record: Journal of the Transportation Research Board*, (2324) (2012).

D. Srinivasan, X. Jin, and R. L. Cheu. Adaptive neural network models for automatic incident detection on freeways. *Neurocomputing*, 64 (2005). Trends in Neurocomputing: 12th European Symposium on Artificial Neural Networks 2004.

Y. J. Stephanedes and A. P. Chassiakos. Freeway incident detection through filtering. *Transportation Research Part C: Emerging Technologies*, 1(3) (1993).

D. Swaroop and J. K. Hedrick. String stability of interconnected systems. *IEEE Transactions on Automatic Control*, 41(3) (1996).

Trafik Stockholm. CTS: centralt tekniskt system [*central technical system*]. (2016). URL `http://www.trafikstockholm.com/etapp/etapp_fixed.html`. Accessed: March 30, 2016.

S. Tsugawa. An overview on an automated truck platoon within the Energy ITS project. In *7th IFAC Symposium on Advances in Automotive*. Tokyo, Japan (2013).

V. Turri, B. Besselink, and K. H. Johansson. Cooperative look-ahead control for fuel-efficient and safe heavy-duty vehicle platooning. *Pre-print* (2015). ArXiv:1505.00447.

V. Turri, B. Besselink, J. Mårtensson, and K. H. Johansson. Look-ahead control for fuel-efficient heavy-duty vehicle platooning. In *53rd IEEE conference on decision and control*. Los Angeles, California, USA (2014).

B. van Arem, C. J. G. van Driel, and R. Visser. The impact of cooperative adaptive cruise control on traffic-flow characteristics. *IEEE Transactions on Intelligent Transportation Systems*, 7(4) (2006).

S. van de Hoef, K. H. Johansson, and D. V. Dimarogonas. Coordinating truck platooning by clustering pairwise fuel-optimal plans. In *18th International Conference on Intelligent Transportation Systems*. Canary Islands, Spain (2015*a*).

S. van de Hoef, K. H. Johansson, and D. V. Dimarogonas. Fuel-optimal centralized coordination of truck platooning based on shortest paths. In *American Control Conference*. Chicago, Illinois, USA (2015*b*).

F. van der Veen and H. Taale. Evaluation of ramp metering on the A10 Amsterdam ring road. Document EEG/11/7, EasyWay project (2011).

E. van Nunen, M. R. J. A. E. Kwakkernaat, J. Ploeg, and B. D. Netten. Cooperative competition for future mobility. *IEEE Transactions on Intelligent Transportation Systems*, 13(3) (2012).

Velodyne. Velodyne LiDAR$^{\text{TM}}$ (2016). URL `http://velodynelidar.com`. Accessed: April 5, 2016.

VTI. The effects of long and heavy trucks on the transport system. VTI report 605a, The Swedish National Road and Transport Research Institute (2008).

H. Wolf-Heinrich and S. Ahmed. *Aerodynamics of road vehicles* (1998).

D. Yanakiev and I. Kanellakopoulos. Variable time headway for string stability of automated heavy-duty vehicles. In *Proceedings of 34th Conference on Decision and Control*. New Orleans, LA, USA (1995).

M. Zabat, N. Stabile, S. Farascardoli, and F. Browand. The aerodynamic performance of platoons: Final report. Technical report, UC Berkeley (1995).

J. Zhang and P. Ioannou. Control of heavy-duty trucks : Environmental and fuel economy considerations. Technical report, California PATH program (2004).

W. Zhang, X. Ma, and E. Jenelius. Planning of heavy-duty vehicle platoon formulation: basic scheduling problem considering travel time variance. In *Transportation Research Board 95th Annual Meeting* (2016).

"*Do not go where the path may lead,*
go instead where there is no path
and leave a trail."
Ralph Waldo Emerson

TRITA-EE 2016:068
ISSN 1653-5146
ISBN 978-91-7729-004-9