Fuel-Efficient Distributed Control for Heavy Duty Vehicle Platooning

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KTH Electrical Engineering

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Abstract

Freight transport demand has escalated and will continue to do so as economies grow. As the traffic intensity increases, the drivers are faced with increasingly complex tasks and traffic safety is a growing issue. Simultaneously, fossil fuel usage is escalating. Heavy duty vehicle (HDV) platooning is a plausible solution to these issues. Even though there has been a need for introducing automated HDV platooning systems for several years, they have only recently become possible to implement. Advancements in on-board and external technology have ushered in new possibilities to aid the driver and enhance the system performance. Each vehicle is able to serve as an information node through wireless communication; enabling a cooperative networked transportation system. Thereby, vehicles can semi-autonomously travel at short intermediate spacings, effectively reducing congestion, relieving driver tension, improving fuel consumption and emissions without compromising safety.

This thesis presents contributions to a framework for the design and implementation of HDV platooning. The focus lies mainly on establishing and validating real constraints for fuel optimal control for platooning vehicles. Nonlinear and linear vehicle models are presented together with a system architecture, which divides the complex problem into manageable subsystems. The fuel reduction potential is investigated through simulation models and experimental results derived from standard vehicles traveling on a Swedish highway. It is shown through analytical and experimental results that it is favorable with respect to the fuel consumption to operate the vehicles at a much shorter intermediate spacing than what is currently done in commercially available systems. The results show that a maximum fuel reduction of 4.7-7.7% depending on the inter-vehicle time gap, at a set speed of 70 km/h, can be obtained without compromising safety. A systematic design methodology for inter-vehicle distance control is presented based on linear quadratic regulators (LQRs). The structure of the controller feedback matrix can be tailored to the locally available state information. The results show that a decentralized controller gives good tracking performance, a robust system and lowers the control effort downstream in the platoon. It is also shown that the design methodology produces a string stable system for an arbitrary number of vehicles in the platoon, if the vehicle configurations and the LQR weighting parameters are identical for the considered subsystems.

With the results obtained in this thesis, it is argued that a vast fuel reduction potential exists for HDV platooning. Present commercial systems can be enhanced significantly through the introduction of wireless communication and decentralized optimal control.

To my mother, my wife and my brother.

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Chapter 1

Introduction

"In theory, theory and practice are the same. In practice, they are not." Albert Einstein

The world population has currently reached 6.9 Billion inhabitants. Projections recently issued by the United Nations suggest that the world population will reach 7.6 Billion by the year 2020 (United Nations Population Division, 2010). Hence, the world population is growing rapidly. Inherently the traffic intensity is escalating in most part of the world, making traffic congestion a growing issue. In parallel, to facilitate the continuously advancing needs for goods, the demand for transportation services is increasing. Congruently, the 2006 mid-term review of the White Paper 2001 of the European Commission (European Commission, 2006) states that goods transport in Europe is projected to increase by 50% between 2000 and 2020.

1.1 The Need for Fuel-Efficient Freight Transports

Freight transport demand has escalated and will continue to do so as economies grow. An increase in traffic naturally corresponds to higher fossil fuel usage and inherently a higher emission of harmful exhaust gas as well as more complex traffic situations. The drivers of today are already faced with several challenging scenarios each time they venture out on the road—challenges that will become harsher with increasing traffic intensity. Hence, governments, non-governmental agencies, the private sector, and individuals around the world are trying to find ways to reduce the emissions and design systems to aid the driver in handling difficult situations. Complex traffic scenarios can have a devastating impact: more than 1.3 million people die every year in road accidents. If nothing is done, this number might rise to 1.9 million deaths per year according to the International Transport Forum (ITF), which is a strategic think tank for the transport sector (ITF, 2011). In parallel, the growing traffic intensity have led to that almost every weekday morning and evening, the main roads saturate throughout the major cities in the world.

In addition, harmful emissions have proved to result in severe long term consequences. Working toward the development of a low-carbon economy is vital for averting climate change. Combating climate change and rooting out its main causes, a problem due to increase in greenhouse gases, are among the top priorities in Europe. The ITF reported that the transport-sector CO_2 emissions represent 23 % globally and 30 % within the OECD countries of the overall CO_2 emissions from fossil fuel combustion. The sector accounts for approximately 15 % of overall greenhouse gas emissions (ITF, 2010). Road sector emissions dominate transport emissions globally. Similar results were presented by the Community Research and Development Service (CORDIS), which is part of the European Commission. They reported that road freight accounts for approximately 35 % of transport CO_2 emissions. Considering the high emission of greenhouse gases arising from fossil fuel combustion, especially in freight transports, legislation and policies have been set. Thus, vehicle manufacturers are facing increasingly difficult emission challenges.

Along with challenges regarding safety and emission policies, the vehicle manufacturers also experience an increase in fuel prices. Transportation constitutes the main part of the increase in oil consumption during the last three decades and the growth is expected to continue. As the fuel price increases, the strain on operating costs grows for a heavy duty vehicle (HDV) fleet provider. This issue has a major impact within the transport industry. Road transport serves as the backbone of the economy in many countries. With the rise in fuel prices, road transportation becomes less economically viable. Figure 1.1 shows the main operational costs for an HDV in Europe. Fuel cost constitutes approximately one third of the total life cycle cost in European long haulage HDVs. An HDV fleet provider generally owns many vehicles that travel over 200 000 km per year. With an average fuel consumption of 0.3 liter/km and the current diesel fuel price in Sweden being 13.74 kr/liter, only the fuel cost amounts to over $80k \in$ per year for a single HDV. Hence, the HDV fleet industry is extremely fuel price sensitive and reducing only a few percent in fuel consumption has a substantial impact for the HDV customer and inherently for HDV manufacturers. Thus, there is a strong need for fuel-efficient freight transports solution.

Vehicle manufacturers' responses to the emission challenges and the life cycle cost issues have mainly been technical. Vast research efforts have been dedicated to combustion engines to the extent that it is difficult to improve them further. Aftertreatment systems have been developed as a natural next step. As an example, exhaust gas recirculation has been used to reduce NO_X formation. However, there is a trade-off between NO_X emission and fuel efficiency, as most methods to suppress NO_X formation reduce the engine's thermal efficiency. An alternative approach for diminishing greenhouse gases by car manufacturers is to reduce the weight of the vehicle and thereby lower the fuel consumption. So far, development has mostly been focused on making the powertrain more energy efficient. Attention spent on



Figure 1.1: Life cycle costs of class 8 HDVs in Europe over a 4 year period (Schittler, 2003). The fuel cost ratio is similar for a Scania HDV (Scania CV AB, 2010)

reducing greenhouse gases and fuel-efficiency have to a vast extent been focused on electric cars, hybrid vehicles, fuel efficient tires, and alternative fuels such as hydrogen, solar cells, etc. Most of these approaches demand a reconstruction of the powertrain, which is costly and still does not improve the global issues of traffic congestion and safety.

HDV platooning serves as a possible solution to reduce fuel consumption and exhaust gas emissions. The concept of platooning for congestion and energy reduction is not new. Many experienced HDV drivers have for a long time noticed that when driving at a short intermediate distance to a vehicle ahead, it results in a lower required throttle action to propel the vehicle forward. This fact have also been observed in terms of lowered effort in professional bicycling and high velocity race driving. It is due to a lowered air drag that occurs when operating in such a formation, as illustrated in Figure 1.2. Hence, vehicle platoons (Figure 1.3), operating as a cooperative system, have become an important research area, which addresses the issues of safety, traffic congestion, fuel consumption and harmful exhaust emissions. By packing HDVs close to each other, the total road capacity can be increased and



Figure 1.2: Change in air drag coefficient c_D with respect to distance between the vehicles in a platoon. The top curve shows the air drag reduction for the last vehicle in a three HDV platoon. Middle curve shows the air drag reduction for the second vehicle. The lead vehicle also experiences a lowered air drag, as shown by the bottom curve. Adapted from (Wolf-Heinrich and Ahmed, 1998). Similar findings have been established by the fluid dynamics department at Scania CV AB and in (Bonnet and Fritz, 2000).



Figure 1.3: HDVs traveling in a platoon can achieve significant fuel reduction. It is fuel-efficient for the lead vehicle to utilize the gravitational force and coast along the downhill. However, when coasting, the speed might increase due to its extensive mass. Thus, the intermediate distance and the air drag will increase if the second vehicle is not able to maintain or increase its speed when facing an uphill. Alternatively, the second vehicle must produce a higher control effort to maintain the relative distance. Furthermore, the fourth vehicle, traveling along a downhill, might have to apply its brakes in order not to collide with the third vehicle, which is not fuel-efficient. Hence, a cooperative control strategy is advantageous for all vehicles traveling in a platoon.

emissions can be reduced. Additionally, governing vehicle platoons by an automated control strategy, the overall traffic flow is expected to improve.

1.2 Enabling Platooning Technologies

Vehicle platooning has been widely recognized as a means to reduce energy consumption. However, with increasing traffic density and traffic network complexity, more pressure is put on the driver performance. Driving a vehicle at a close intermediate spacing is a very strenuous task for the driver. The driver has to be alert at all times, constantly adjusting the velocity and relative distance according to the behavior of the vehicle ahead. The response time of human drivers are insufficient to navigate the vehicle under such conditions with respect to safety and fuel efficiency. Often the driver fails to react in time causing unnecessary harsh braking and acceleration or at times even an accident. Due to recent advances in technology, systems as depicted in Figure 1.4 can be developed to aid the driver in platooning applications.

Electronic control systems and sensors within vehicles have been increasing rapidly in numbers over the last decades. They enable additional functionality in terms of software and smart control logic. Thereby, advanced driver assistance systems (ADAS) have been developed over time to aid the driver and relieving certain driving tasks. For instance, the lane departure warning system is such a functionality that issues a warning if it detects that the driver is drifting off the lane. It utilizes a camera often mounted in the front window to determine the vehicle position with respect to the lane markings. Another common occurrence is that, due to the extensive HDV mass, the vehicle starts accelerating in a downhill if the brakes are not applied. The downhill speed control (DHSC) is a function specially developed for HDVs that prohibits the vehicle to exceed a certain offset when using the cruise control (CC). An extension to the CC is obtained by mounting a radar or a lidar in front of the vehicle. The adaptive cruise control (ACC), described in more detail in Section 2.4, is a technology that enables platooning applications to a certain extent. It is a commercially available product that reacts according to the behavior of a single vehicle ahead. Road topology has a significant effect on the behavior of an HDV. Map and navigation system providers are developing methods to obtain road grade information, providing a three dimensional map.

Key enabling technology for platooning such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) have matured. To enable V2V and V2I (V2X) communication a communication protocol, IEEE 802.11p, has been approved as an amendment to the IEEE 802.11 standard to add wireless access in vehicular environments (WAVE). It is licensed in the 5.9 GHz band (5.85-5.925 GHz) and defines enhancements to the 802.11 standard, required to support data exchange between high-speed vehicles and between the vehicles and the roadside infrastructure. Alternatively, V2X information can be conveyed over the mobile broadband network as presented in the European CoCar project. The wireless communication can provide a rich information range that allows for improvement in the control strategy with



Figure 1.4: The figure depicts some of the available technology to enable HDV platooning. It shows several information attributes. The vehicles obtain local information limited to the vehicle ahead through radar communication. The local information is extended to the immediate environment through V2V communication amongst the vehicles. The information is extended further through V2I communication with road side units in range. The road side units are wireless transmitters, providing the vehicles with relevant road traffic information. Additionally, the infrastructure can provide several services that can be utilized in platooning control applications, such as dynamic road speed, road topology databases, smart lights, traffic congestion reports, shock waves information, and optimal routing.

respect to fuel consumption and emission. In addition, V2X communication can provide the driver or system with local information and global information, such as dynamic behavior of the vehicles within the platoon, optimal traffic routing, safety issues, etc. – enabling strategies based upon events occurring over a large horizon.

Hence, several technologies exist and can be fused to enable and enhance the performance for platooning. However, economical feasibility and safety aspects are still unresolved issues. Thus, implementing new enabling technologies requires careful consideration and design.

1.3 Problem Formulation

The problem that is studied in this thesis is the fuel reduction potential for a platoon of N long haulage HDVs, illustrated in Figure 1.5, traveling on a road with a given initial set speed and relative distance.

Each HDV in the platoon can be modeled based upon the road grade α , the



Figure 1.5: An HDV platoon traveling with a given initial set speed and relative distance. Several external forces such as air drag, road friction and gravity along with internal forces affect a vehicle in motion. (Photo provided courtesy of Scania CV AB)

internal forces produced by the powertrain and the main external forces acting upon the vehicle. A longitudinal dynamics model can be derived for each vehicle in the platoon based upon their individual vehicle properties. The relative distance between the vehicles is modeled as the change in velocity between two vehicles in the platoon. The HDV platoon model is

$$\dot{v}_{1} = f_{1}(v_{1}, d_{1,2}, \alpha, u_{1}),
\dot{v}_{i} = f_{i}(v_{i}, d_{i-1,i}, d_{i,i+1}, \alpha, u_{i}),
\dot{v}_{N} = f_{1}(v_{N}, d_{N-1,N}, \alpha, u_{N}),
\dot{d}_{i-1,i} = g_{i}(v_{i-1}, v_{i}),
\dot{d}_{N-1,N} = g_{N}(v_{N-1}, v_{N}),$$
(1.1)

where v_i denotes the velocity for vehicle i, $d_{i-1,i}$ is the relative distance between i:th vehicle and the preceding vehicle, $d_{i,i+1}$ is the relative distance to the following vehicle, u_i denotes the control input to the vehicle and $i = 2, \ldots, N-1$ denotes the vehicle position index in the platoon. The maps f_i and g_i are the longitudinal and relative distance dynamics respectively.

A coupling is induced by the variation in aerodynamics between HDVs operating at a close distance. This is essential in the analysis of fuel reduction potential for HDV platooning. The aerodynamic drag decreases as the gap between the vehicles are reduced. However, as the relative distance decreases, it becomes more costly to maintain the relative distance due to safety aspects. Moreover, additional constraints are induced due to physical limitation on the control inputs. An HDV can generally produce a maximum engine torque of 2000–3000 Nm depending on the specific diesel engine. The maximum braking torque depends on the vehicle configuration but can be approximated by $60000 \,\mathrm{Nm/axle}$. Hence, the physical constraints for an HDV has an influence on the minimum achievable safe relative distance. Also, fuel optimal control for a single vehicle on a flat road is to maintain a constant velocity, under the presumption that the traveling time is fixed. Any deviations in the form of acceleration and deceleration result in an increased fuel consumption. An HDV platoon control strategy generally receives information regarding the relative velocity and distance to the vehicles in the platoon and thereby maintains the relative distance by adjusting its speed accordingly. The increased control effort that the strategy creates, in the sense of additional transient engine actions and brake events, produces an increased fuel consumption.

Hence, the problem that we consider is finding the fuel reduction potential for an HDV platoon consisting of N vehicles, traveling without any surrounding traffic, subject to the HDV vehicle dynamics, the safety constraints and the physical constraints on the control inputs imposed on the system.

1.4 Main Thesis Contributions

The wind resistance can be reduced significantly by arranging HDVs in a platoon formation. We present a translation from the lowered air drag to the fuel reduction potential in HDV platooning, through simulations and experimental studies. We show that it is beneficial to reduce the intermediate spacing between each vehicle in the platoon and that the conventional control strategy can be improved with respect to fuel consumption. However, by reducing the relative distance safety becomes an issue.

Collision avoidance for cars has been thoroughly investigated. However, in this thesis we propose a novel approach, setting up a relative coordinate framework and thereby computing so called reachable sets to develop safety criteria for HDV platooning. A collision can occur if the unsafe set is entered. Computing safe sets is an efficient method to capture the behavior of entire sets of trajectories simultaneously. By setting up the problem in a game theoretical framework, we determine criteria for which collisions can be avoided in a worst case scenario and thereby establish the minimum possible safe distance to a vehicle ahead. We show that the minimum relative distance depends on the overall braking capabilities of the HDVs within the platoon and that the relative distance between the HDVs can be reduced significantly compared to what is utilized in current ACCs.

As the intermediate spacing is reduced between the vehicles, more costly control effort is required. Wireless information might enlarge the decision space and thereby improve the control strategy with respect to fuel consumption. However, considering the physical constraints in radio range, availability and reliability, a decentralized control strategy is crucial for practical implementation. Hence, the final contribution of this thesis is a decentralized control algorithm, solely based on local model knowledge. It is a linear quadratic regulators (LQR) for chain structured interconnection graphs. The algorithm accounts for the additional coupling induced by the variation in aerodynamics between the vehicles along with the restricted state information involving the immediate preceding vehicle.

1.5 Thesis Outline

The outline of the thesis is as follows. Chapter 2 gives a general description of the framework for vehicle platooning. A brief description is given on what is meant by intelligent transportation systems. Then a short survey on the current technology development in vehicle platooning is given followed by a review of the existing literature on automated vehicle platooning. The ACC has in part served as our first stepping stone to automated platooning. Thus, a description of the ACC functionality is given.

In Chapter 3, several models are presented, which are utilized to address certain aspects of vehicle platooning. First, the longitudinal dynamics are derived for a single vehicle, resulting in a nonlinear model. This model model can naturally be extended to several vehicles. Then a linearized platoon model is presented. For reproducibility and realistic behavior analysis an advanced simulation model is presented, which serves as a basis for evaluation and validation throughout this thesis. Finally, a model for the platoon system architecture is presented.

In Chapter 4, the fuel reduction potential of HDV platooning is evaluated on a measured highway in Sweden. A method is derived to isolate the ACC's influence on the fuel consumption. Several case studies are presented to address the fuel reduction possibilities and to deduce the consequences of provoking the ACC behavior by having two vehicles of different mass. Empirical data obtained through field tests are presented for validation.

Chapter 5 addresses the minimum safety distance between two HDVs traveling on a road. The solution is presented and the derived results are investigated for different HDV configurations. To validate the main results a simulation study is conducted.

Chapter 6 contains a methodology to produce a systematic decentralized LQR control design for HDV platooning. We give a physical interpretation of how to design the weighting parameters and evaluate the performance by giving a frequency analysis and simulation results. Chapter 7 provides concluding remarks and future work.

1.6 Publications

The work described in this thesis has been presented at several conferences, as outlined below.

Chapter 3 is in part based on the work presented in:

A. Alam. Optimally Fuel Efficient Speed Adaptation. Master's thesis, Royal Institute of Technology (2008)

Chapter 4 is an extension of the work presented in:

A. Alam, A. Gattami, and K. H. Johansson. An experimental study on the fuel reduction potential of heavy duty vehicle platooning. In 13th International IEEE Conference on Intelligent Transportation Systems. Madeira, Portugal (2010)

Chapter 5 is an extension of the work presented in:

A. Alam, A. Gattami, K. H. Johansson, and C. J. Tomlin. Establishing safety for heavy duty vehicle platooning: A game theoretical approach. In 18th IFAC World Congress. Milan, Italy (2011b)

Chapter 6 is based on the work presented in:

A. Alam, A. Gattami, and K. H. Johansson. Suboptimal decentralized controller design for chain structures: Applications to vehicle formations. In 50th IEEE Conference on Decision and Control and European Control Conference. Orlando, FL, USA (2011a). To appear

Two master thesis projects have been supervised to evaluate certain aspects of HDV platooning:

H. J. Tehrani. Study of Disturbance Models for Heavy-duty Vehicle Platooning. Master's thesis, Royal Institute of Technology (KTH) (2010)

K. Liang. Linear Quadratic Control for Heavy Duty Vehicle Platooning. Master's thesis, Royal Institue of Technology, Osquldas väg 10, 100 44 Stockholm, Sweden (2011)

The first thesis investigates and evaluates several disturbances that might affect the control performance in a platoon. These disturbances involve delays due to signal processing in the radar, noise, and surrounding traffic behavior. The second thesis have been extended to a conference paper.

K. Liang, A. Alam, and A. Gattami. The impact of heterogeneity and order in heavy duty vehicle platooning networks. In *3rd IEEE Vehicular Networking Conference.* Amsterdam, Netherlands (2011). Submitted

It evaluates the influence of mass variation between the vehicles in a platoon with respect to robustness. A centralized LQR is designed, which accounts for the air drag reduction within the platoon. The issue of merging separate platoons traveling on a highway is also investigated.

Patents

Along with academic publications, three Swedish patents and two international patents have been published.

A. Alam, J. Andersson, and P. Sahlholm. *Metod, system och datorprogram för automatisk hastighetsreglering av ett motorfordon [Method, system and computer program product for automated vehicle speed control]*. Swedish patent SE 531 922 C2 (filed 2008b)

A. Alam, J. Andersson, and P. Sahlholm. *Fastställande av accelerationsbeteende* [Determination of acceleration behavior]. Swedish patent SE 533 144 C2 (filed 2008a)

A. Alam and P. Sahlholm. Metod och system för reglering av ett fordons hastighet i en kurva [Method and system for vehicle curve speed control]. Swedish patent SE 533 044 C2 (filed 2008)

The two international patents are translated versions of the first two Swedish patents.

A. Alam, P. Sahlholm, and J. Andersson. *Method, system and computer program product for automated vehicle speed control.* World patent WO 2009 096882 (filed 2009b)

A. Alam, J. Andersson, and P. Sahlholm. *Determination of acceleration behaviour*. World patent WO 2010 062242 (filed 2009*a*)

Chapter 2

Background

Information technology is paving its path into transportation systems. Many governments spend a countless amount of money on the infrastructure in restoration and expansion of the road network. However, the future improvement lies not in increasingly stringent road taxation policies to change incentives or only in improving aging infrastructure, but also increasing the utilization of information technology and thereby introducing intelligence to road traffic networks.

In this chapter, we first give an overview regarding the possibilities current information technology introduces to transportation systems. Then we present the contemporary technology premise for HDV platooning. Afterward, we give an overview of the related work on vehicle platooning. The literature on control of platoons is quite extensive. Therefore, we have not attempted a thorough review of all the proposed control schemes here, but rather give a review of the general concepts and issues in vehicle platooning that is addressed in the literature. Finally, we give a description of the ACC, since it serves as a first stepping stone to practical implementation of HDV platooning.

2.1 Intelligent Transportation Systems

Transportation systems can be perceived as large mobile networks. By introducing decision making from suitable and accurate information, intelligence is induced in the network. Intelligent transportation systems (ITS), illustrated in Figure 2.1, empower actors in the system with information based actions. The European Road Transport Telematics Implementation Co-ordination Organisation (ERTICO) - ITS Europe is the network of intelligent transport systems and services stakeholders in Europe. It was founded at the initiative of leading members of the European Commission, Ministries of Transport and the European industry. ERTICO's official definition of ITS is the integration of information and communications technology with transport infrastructure, vehicles and users. By sharing vital information, ITS allow people to get more from transport networks, in greater safety and with less impact on the environment (ERTICO, 2011). ITS have received a great deal of



Figure 2.1: An illustration of ITS. ITS include all types of communications in and between vehicles along with communication between vehicles and infrastructure. Note that ITS are not restricted to road transport as they also include the use of information and communication technologies for rail, water and air transport, including navigation systems. (Illustration provided courtesy of (ETSI, 2011))

attention in the transportation community as well as in governments over the last 10 years. The initial efforts were referred to as intelligent vehicle highway systems (IVHS). However, due to the increasingly intermodal focus, the scope was broadened to include modes beyond highways. There are numerous agencies working with ITS throughout the world, such as ITS America and ITS Japan amongst others.

ITS include several applications and can be grouped within five main categories (Ezell, 2010):

- Advanced Public Transportation Systems include systems that for example allow trains, buses, and boats to report their position so passengers can be informed of their real-time arrival status and departure information.
- Advanced Traveler Information Systems provide travelers with real-time navigation routes, traffic lights, weather conditions, traffic construction, delays and congestion. Accident reports can also be provided.

- Advanced Transportation Management Systems include systems that monitors traffic flow and provide decision support based upon traffic control devices, such as traffic signals, variable message signs, and traffic operations centers.
- ITS-Enabled Transportation Pricing Systems provide services such as electronic toll collection and congestion pricing.
- Automated Transportation Systems include supporting and replacing human functions in various driving processes. The focus in this category lies on efforts for developing vehicles with automated components. Here, V2X communication serves as a basis to provide information and enable communication between all the actors.

Through these categories, ITS aim at enhancing safety, operational performance, mobility, environmental benefits, and productivity by expanding economic and employment growth. ITS encompass the full scope of information technologies used in transportation, including control with dynamic feedback, computation and communication, as well as the algorithms, databases, models and human interfaces. The emergence of these technologies as a new pathway for transportation is relatively new. Hence, research that adds to the scientific understanding of the impacts that ITS can have on accessibility, congestion, pollution, safety, and security is an active area.

Several ITS issues commonly arise when vehicles travel closely packed on a congested road. With a limited information range, consisting mainly of sounds and line of sight, the drivers create unnecessary harsh acceleration and braking actions to maintain a short intermediate distance. Due to the transient control actions, pollution in the form of emissions and road particles, congestion and accessibility become a growing issue. As several vehicles drive in a single lane to exploit the road capacity. trying to maintain a suitable intermediate distance, they effectively form a vehicle platoon. Thus, research within intelligent vehicle platooning, in particular HDV platooning, addresses several ITS target issues. Hence, HDV platooning falls under the ITS research items above and embodies the last four summary categories with the strongest emphasis on Automated Transportation Systems. Vehicle platooning includes systems that allow agents within the platoon to report their position and velocity as well as systems that provide navigation routes, information from traffic control devices, road construction and congestion. With the aid of V2X communication devices, a cooperative system is formed for supporting and replacing human functions in various driving processes to enhance operational performance, mobility, environmental benefits, safety, and economic growth.

Congestion can be reduced and throughput can be increased through platooning control strategies that enable vehicles to operate at a much shorter intermediate distance compared to what is possible under manual driving conditions. Hence, in addition to ITS functionalities such as smart traffic lights or traffic flow monitoring, platooning control strategies enables an increase of the total road capacity. Research within the California Partners for Advanced Transportation Technology (PATH) project, established in 1986 (PATH, 2010), has shown that the highway throughput can be increased three times through platooning by utilizing services provided by the automated transportation systems. Another research project, Strategic Platform for Intelligent Traffic Systems (SPITS), shows in addition that potential shock waves arising in traffic congestions can be removed through automated platooning. Furthermore, by effectively creating a smoother traffic flow, greenhouse gas emission can be reduced significantly for highway vehicles (Shladover, 1991). There is also a vast scope for improving safety by replacing human functions through ITS services for vehicle platooning. Accidents commonly occur due to error in human judgment, lack of information, or delays in reaction time. An automated system can rapidly receive information from incidents occurring far beyond the reach of the human senses and produce a nearly instantaneous countermeasure. Findings within the European project, Safe Road Trains for the Environment (SARTRE), project a 20% emission reduction through vehicle platooning, a 10% reduction in fatalities, and a smoother traffic flow with potential increase in traffic flow (Robinson et al., 2010). The findings are based on that a lead vehicle with a professional driver will take responsibility and guide the vehicle platoon. Vehicles will join the platoon and enter an autonomous control mode that will allow the automated system to fully govern the vehicle while the driver can withdraw his attention from the road.

2.2 Technology Premise for HDV Platooning

The demand for enhancing vehicle performance has paved the way for several technological developments. On-board sensors have increased in number and accuracy. This has led to the development of on-board networks to share and convey information between electronic control units (ECUs). Faster and cheaper vehicle computer technology has been developed to process the growing amount of available information. With increasing reliability and computational performance, in parallel with decreasing size and prize, new sensors have been implemented to further enhance the operational performance. However, currently we see a transition, which is not necessarily induced by the vehicle industry. Technology that was initially developed and intended for entirely different markets is now finding its use and presenting a new scope for enhancing vehicle applications and enabling vehicle platooning. Thus, HDV platooning has not been widely implemented until now, but the demand is growing rapidly. In this section, we describe some of the key components that contribute to and enable HDV platooning as shown in Figure 2.2.

Traditionally vehicular research focus has been on improving the vehicle performance. During the last decades on-board sensors have been developed and implemented to facilitate the overall HDV operational efficiency. Initially, sensor technology was introduced to enhance the engine operational performance with respect to fuel efficiency and exhaust gasses. Crank-angle, RPM, and temperature sensors were implemented to enable better engine control. With the passage of time, additional sensors were implemented, for example rotational wheel sensors and gear



Figure 2.2: An overlay of the technological premise for HDV platooning. Each circle represents a specific sensor group with respect to perception range. The inner circle, labeled vehicle, represents on-board sensors and ECUs that provide internal vehicle specific information and control systems. The next circle, labeled local, extends the perception range 50-100 m outside the vehicle through camera and radar sensors. With the introduction of maps, satellites and GPS-technology the perceived range is extended regionally. Wireless area networks, in the final circle labeled global, represents the technology that enables HDV platooning by providing interaction between vehicles and the surrounding infrastructure over a whole country or even a continent.

box sensors, to further increase the operational performance. ECUs process the information and in some cases fused it to create virtual sensors. Today, 30 to 80 ECUs are integrated in an average car, whereas 6 to 17 ECUs are integrated in an HDV. This substantial difference in ECUs is mainly due to that a passenger vehicle and an HDV operate under different premises. An HDV commonly travels under more strenuous conditions. Introducing more ECUs opens up the possibility for more system errors, which is less acceptable in the HDV market. Furthermore, underdeveloped countries demand less ECUs due to manageability. Implementing electronic sensors has become a relatively cheap and efficient way to enable new functionality.

In 1985 Bosch developed the controller area network (CAN) for in vehicle networks. Thereby, dedicated wiring was replaced by a communication bus, which reduced complexity, wiring cost, and weight. This was a revolutionary step, since monitoring and control of the entire electromechanical system could be achieved. Each ECU was now able to communicate internally, enabling more advanced functions such as ABS, ESP, or the airbag, which relied on several sensors. With time, the sensors increased in reliability, accuracy and quality while the size and cost decreased. In parallel, the HDV ECUs memory and processing power have improved significantly. In the 1970s a standard ECU contained 1 kbyte of RAM, 8 kbyte of ROM, and 1 MHz clock speed, whereas today it can contain up to 4 MB ROM, 128 kbyte RAM, and 250 MHz clock speed. Thus, faster and more computational complex functionalities have been developed over time.

With the development of vehicle internal sensors for improving operational and safety performance, the next step in sensor development reached further to monitor the nearest vicinity. Initially the local environment sensors were costly, large, and therefore not yet suitable for the commercial market. To date, the technology has improved and is becoming fairly inexpensive. Radar or lidar sensors, to detect and monitor objects moving in the neighborhood of the host vehicle, have matured to the extent of being commercially viable. The cost and hardware size have reduced significantly over the years. Low cost monolithic microwave integrated circuit based millimeter-wave front end modules, entailing down to a $1 \,\mathrm{mm}^2$ chip, for automotive radar applications are now available. In-vehicle camera monitoring devices is another local environment sensor technology that has matured. Initially the size of the cameras and the image processing unit were too large to mount in the front window. With the emerging improvement in camera lens technology and signal processing capabilities of microprocessors, most vehicle manufacturers are starting to implement camera based monitoring systems. Commonly, such systems involve lane departure warning or steering. More advanced systems involving traffic sign detection, driver attention, and pedestrian detection are now also being developed and offered by some vehicle manufacturers. Furthermore, fused with radar data, a three dimension environment can be formed for future arising safety and navigation systems. Hence, the small size of the hardware and the computation power to perform advanced calculations within milliseconds, have recently extended the possibilities and range for the on-board vehicle sensors. In addition, the perceived vehicle environment has been extended due to recent advancements in map data technology and in increased accuracy of GPS devices. Map providers, such as NAVTEQ, are developing methods for acquiring road grade information to obtain a three dimensional topology map. In addition, vehicle manufacturers themselves have the possibility to obtain road grade information by using on-board sensors and a global positioning system (GPS), (Sahlholm, 2011). GPS technology can now deliver centimeter accuracy. GPS devices are also becoming increasingly common among all traffic agents. Omnipresent mobile phone devices can deliver positioning, heading and velocity for pedestrians, mopeds, motorcycles and bicycles. Thus, ECUs might now not only be able to monitor and intelligently govern the internal vehicle systems, but also gather external information

regarding the surrounding traffic and topology. Hence, an HDV will be able to react based upon the internal and external environment influences.

For effective and safe platooning additional information is necessary to what is provided by radars and cameras. If vehicles interact through wireless communication, an HDV can adjust the velocity and relative distance based upon events ahead in the platoon. Thus, the safety, fuel efficiency, road capacity and emissions can be improved significantly by enabling a reduced inter-vehicle spacing through preview information. The interaction through V2X communication can improve safety by setting for example a deceleration limit for the HDVs in the platoon or setting a safe distance based upon the vehicle characteristics. Smoother control can also be implemented through prediction based upon information on events occurring upstream. Hence, V2X communication enables cooperative driving and automated platooning systems. The recent wireless communication protocol IEEE 802.11p (802.11p, 2010) has opened up an entire new set of applications for vehicular systems. The purpose of this standard is to provide the minimum set of specifications required to ensure interoperability between wireless devices. It is meant for devices attempting to communicate in rapidly changing communications environments and in situations where transactions must be completed in time frames much shorter than what is set for ad hoc 802.11 networks. Vehicular ad hoc networks (VANETs) impose a new set of requirements on the communication systems. For example, vehicle communication cannot tolerate long delays and the moving vehicles form a dynamic ad hoc communication network. Numerous studies and evaluations have been performed on the standard, for example in (Jiang and Delgrossi, 2008; Ferreira et al., 2008; Barradi et al., 2010). Scalability and safety are challenging issues, since IEEE 802.11 is designed for data communication where reliability is more important than delay (Bilstrup et al., 2010). In dense and high load scenarios the throughput decreases and the delay increases significantly. These issues must be resolved before full implementation of VANETs. Nevertheless, V2V communication enables a wide range of information to the vicinity. Previously most information has been gathered by direct visual observation and in response to sounds. Now, vehicles traveling in a platoon will be able to act faster with interaction, intents and events produced by several vehicles in the surrounding environment. In addition, V2I communication with global information enables reliable automated systems.

Even though there is an apparent strong need for automated HDV platooning systems, they have only recently become a possibility. Each traffic agent will soon be able to serve as an information node through wireless communication; enabling other agents to interact, as opposed to simply react, to internal and external influences. Thereby, vehicles will be able to travel at short intermediate spacings, effectively reducing congestion, relieving driver tension, improving fuel consumption and emissions without compromising safety. There are however many challenges, such as safety, reliability, standards, etc., that must be addressed before HDV platooning can become commercially feasible. With respect to longitudinal control of the vehicles, the question of whether to implement a centralized or decentralized control arises. As depicted in Figure 2.2, there are several technologies and systems involved in the process of HDV platooning. Analyzing the entire system is not manageable due to the system complexity. There are no available tools to handle all the aspects of such a large control system. Thus, an important challenge is to establish a suitable system architecture, which is decomposable into manageable subsystems. In this thesis we present such a system architecture in Chapter 3. Chapter 6 presents a decentralized controller suitable for that architecture.

2.3 Cooperative Vehicle Platooning

Vehicle platooning can be described as a chain of vehicles traveling at a given intermediate distance and velocity. The primary objective for each vehicle with respect to safety is to maintain its distance to the preceding vehicle in the platoon. Even under normal operating conditions there will be deviations from the desired velocities and desired intermediate distances. A vehicle platoon is most commonly modeled in the literature as a set of moving masses

$$\ddot{x}_i + k_i \dot{x}_i = u_i, \quad i = 1, \dots, N \tag{2.1}$$

where x_i represents the position of the *i*:th vehicle, $k_i \geq 0$ denotes a system damping coefficient sometimes referred to as the linearized drag coefficient per unit mass and u_i is the applied control force. Control of vehicular platoons was early studied by (Levine and Athans, 1966) and (Melzer and Kuo, 1971*a*). Their work considered centralized control design for vehicle platoons, indirectly assuming that computational complexity and V2V communication hardware constraints would not be an issue. An LQR control strategy was developed that regulates the position and velocity of every vehicle in a densely packed string of high-speed moving vehicles. The presented control methodology involved full state information of each vehicle in the platoon.

An early hope for high-speed vehicle platoons was that centralized automatic control could encompass very large platoons. Thus, control strategies were derived based upon a countably infinite number of vehicles in order to understand the fundamentals of the problem (Melzer and Kuo, 1971*b*). A new structural analysis was introduced, allowing for a bilateral Z-transform to convert the problem into a family of finite-dimensional systems. It was found that coupling between the vehicles decreases as the platoon index distance between them increases. It has been hypothesized that the controller gain will decrease with increasing index distance, concluding that vehicles far away in a platoon has less controller impact on performance. However, even though infinite platoons capture the essence of large platoons, the LQR problem formulation lacks observability and stabilizability in the infinite case and is therefore ill-posed (Jovanović and Bamieh, 2004).

String stability for vehicle platoons is seen as an important concept (Peppard, 1974; Rogge and Aeyels, 2005; Middleton and Braslavsky, 2010). It is also known as the bullwhip effect in economic theory (Lee et al., 2004). String stability can be described as the ability to suppress a disturbance in position, velocity, or acceleration,

as it propagates along the platoon. As a disturbance is introduced in a vehicle, oscillations might be amplified upstreams in the platoon causing an unstable behavior. In (Swaroop and Hedrick, 1996) a rigorous definition of string stability is presented. Note that a vehicle formation does not need to have the string stability property, as one can quantify and bound the worst case error amplification for each specific formation (Shaw and Hedrick, 2007).

Governing vehicle platoons by an automated control strategy, the overall traffic flow is expected to be improved (Ioannou and Chien, 1993). Through short intermediate distances down to 2 m, the road capacity is significantly increased. It can be increased two to three times compared to roads with manually operated vehicles (De Schutter et al., 1999). Traffic flow has been considered a key performance index in vehicle platooning. In (Varaiya, 1993) it was shown that by forming platoons, the throughput of a highway can be increased from 2000 vehicles per lane per hour to more than 6000 vehicles per lane per hour. The findings were based on an average platoon size of 15 vehicles, with intra-platoon distances of 2 m, inter-platoon distances of 60 m, vehicle length of 5 m, and speed of 20 m/s. However, it was argued that only full automation can achieve significant capacity increases on highways and thereby reduce the occurrences of traffic congestion.

Vehicle platooning might through higher interactivity facilitate an improved safety. Collision avoidance for passenger vehicles has been a vast research area e.g., (Seiler et al., 1998). We propose a novel approach in Chapter 5, through a game theoretical approach for HDV platooning. The approach is an extension of the work presented in (Bayen et al., 2003), where collision avoidance was analyzed with a differential game formulation of an alerting logic for conflicts in high altitude air traffic. V2X communication enables new possibilities and naturally new challenges for safety applications. Safety is increased through automated functions and close coordination. Through interaction each agent in the platoon will be able to take precautionary measures, in the sense of adjusting its speed and intermediate distance, based upon several incidents ahead. However, uncertainties with respect to mixed traffic, communication failure and delays must be resolved.

Communication constraints is an important issue that can dictate the defining feature of the problem (Gupta et al., 2004). It is not realistic to assume that an agent in the platoon would know the state of all the other agents in the formation at any given time and be able to use it to calculate the control input due to physical constraints in the information flow. Hence, it is argued that the problem at hand is a decentralized control problem with arbitrary information flow patterns. In general, this is a much harder to solve than the traditional optimal control problem.

The problem of decentralized control has a long history. Decision team problems were introduced in (Marshak, 1955), where each team member is trying to optimize a common cost function through limited information concerning the global state of nature. In (Mayne, 1979), decentralized control was studied through a sequential manner by closing one loop at a time and in (Bamieh et al., 2002; D'Andrea, 1998) under the assumption of spatial invariance. Control for chain structures in the context of platoons has been studied through various perspectives, for example

in (Bamieh et al., 2008; Varaiya, 1993). It has been shown that control strategies may vary depending on the available information within the platoon. Initially the ACC, not being cooperative in the sense of sharing information with other agents, simply reacted with respect to the behavior of the preceding vehicle. With the introduction of V2X communication, the question arises of what information is relevant, necessary, or critical for platooning applications. Furthermore, it is of interest to determine which agents should serve as the local information sources. A natural extension to the commercially available ACC is to implement a symmetric bidirectional control architecture, where each vehicle bases its control action on the error feedback from its predecessor and follower (Barooah and Hespanha, 2005). In (Sudin and Cook, 2004) a two-vehicle look-ahead information structure is proposed, where each vehicle bases its control strategy only on information regarding relative velocity and relative distance from two vehicles ahead. A more general approach can be found in (Gupta et al., 2004), where the information flow is dictated by the constraints of a pre-specified topology.

Maintaining a suitable relative distance, stability and robustness of the platoon have been identified to be amongst the main criteria to be considered. Control design for platooning applications is still an open problem, despite substantial academic work. In (Levine and Athans, 1966; Stanković et al., 2000; Dunbar and Murray, 2006), optimized procedures were presented to give a systematic approach to the design. However, the vehicle coupling was only introduced through the cost function. To our knowledge, no control algorithm has yet considered decentralized optimal control based upon systems with interconnected dynamics. In HDV platooning applications the coupling is induced by the variation in aerodynamics, which is essential in the analysis of fuel reduction potential. Such a consideration is presented in Chapter 6.

For vehicle platooning it is essential to use realistic models (Sahlholm and Johansson, 2010; Guzzella and Sciarretta, 2007) and not just identical low-order coupled linear models, as has often been the case in the literature. In HDV platooning mass and road slope has a significant effect on the system dynamics. Research into more implementation-relevant aspects is only recently emerging (Naus et al., 2009; Shaw and Hedrick, 2007). The first paper presents a setup for cooperative adaptive cruise control (CACC) for which feasibility of the actual implementation is one of the main objectives. Several practical issues such as constrained communication, heterogeneous traffic and graceful degradation to standard ACC if communication fails, are taken into consideration. In the latter paper heterogeneous vehicle strings under simple decentralized control laws with a constant spacing control policy are analyzed. The considered vehicles do not need to have the same dynamics or the same controllers and can be arranged in any order. It is further argued that centralized formation control is impractical due to the large amount of information that needs to be communicated.



Figure 2.3: Illustration of a finite state machine for the controllers under consideration. The three depicted states can be entered or exited based upon driver actions, as indicated by the arrows.

2.4 ACC in HDV Platooning

The ACC serves as an enabling technology for practical implementation of HDV platooning. Introduced in the late 1990s in luxury passenger vehicles, the ACC has become increasingly common in passenger vehicles and HDVs. The ACC generally acts as an extension to the CC. It can be described as a finite state machine, as illustrated in Figure 2.3. The three states correspond to manual driving, CC and ACC. In manual mode, the driver has full control of the vehicle handling and naturally acts as the controller. If the driver activates the CC, a reference velocity is maintained. The control is deactivated by braking or if the driver manually switches it off. If the driver selects the operating mode for the ACC, the control objective is to maintain a reference speed or a given intermediate distance to a target vehicle. If a target is not detected or the lead vehicle is traveling faster than the set speed of the CC, the ACC will not engage. If a target is located within the same lane and traveling with the same speed or slower, the ACC will adapt the relative distance according to the desired time gap τ . It will not adjust the speed with respect to vehicles in other lanes. When the lead vehicle switches lanes, the ACC will search for a new target accordingly. If a target is not detected, the system returns to CC constant speed mode.

As illustrated in Figure 2.4, the objective of the CC is to maintain a reference velocity by solely governing the throttle, whereas the ACC adapts the reference velocity with respect to the behavior of the immediate preceding vehicle by throttle and braking actions. Information regarding the relative distance and velocity of a preceding vehicle is generally provided through a radar or lidar. The relative distance, d, is determined by letting the driver set a desired time gap $\tau = d/v$, where v is the current velocity of the host vehicle. A short relative distance will require the ACC to perform more stringent control actions.



Figure 2.4: The flowchart shows the main blocks involved in CC and ACC. v_i denotes the velocity, s_i the vehicle position and d_i the relative distance with i = 1, 2. The controller computes a suitable velocity based upon its available inputs. The vehicle-specific controller, consisting of the engine management control and brake management control, ensures tracking of the given control demands.

A commercial ACC is tuned to maintain the desired relative distance in a comfortable manner by sending appropriate requests to the engine and the various brake systems. Safety and fuel-efficiency are also sometimes considered as constraints. However, safety, comfort, and fuel-efficiency constitute conflicting constraints. To implement control actions with respect to safety, quick and harsh behavior is required, which in turn mandates a high acceleration or deceleration. Such behavior is neither comfortable or fuel-efficient. The ACC accounts for switching between different modes, which induces a nonlinear behavior. The switching is generally based on logic rules and specific tuning parameters for each mode (Moon et al., 2009). Finally, the ACC must mimic reasonable human behavior for driver acceptance. The requirement of the ACC to mimic driver behavior for acceptance was investigated to some extent in (Driel et al., 2007).

The ACC has been considered as a means to enable vehicle platooning in (Hedrick et al., 1991; Rajamani and Zhu, 1999). In (Corona and De Schutter, 2008; Naus, 2010) a systematic model predictive control (MPC) approach was presented to account for the constraints of safety and comfort. Studies have shown that the ACC is most commonly utilized in highway situations. Hence, the impact of the speed controller on the traffic flow is of interest (Wang and Rajamani, 2004). To further understand practical implementation issues and constraints, we consider the ACC in Chapter 4 and thereby investigate the fuel reduction potential of HDV platooning, with respect to a commercial control strategy.

2.5 Summary

A brief introduction has been given on ITS. ITS aim at enhancing safety, operational performance, mobility, environmental benefits, and productivity by expanding economic and employment growth. It covers a broad range of services and focuses on topics that adds understanding of accessibility, congestion, pollution, safety and security in transportation. We have discussed the technology premise for HDV platooning. On-board sensor technology and ECU functionality have improved and become increasingly present during the last decades. Sensors and ECUs have increased in numbers. ECUs have developed in memory and processing speed. Radar and camera technology have developed to extend the information range to a local environment. GPS technology can provide up to centimeter accuracy and map providers are focusing on delivering three-dimensional road topology. With the introduction of wireless communication to vehicle networks, which is the final key technology that enables HDV platooning by providing interaction between vehicles and the surrounding infrastructure, a cooperative control system could be produced to improve fuel efficiency, safety and congestion. A brief overview of the related work within platooning have been presented. String stability, collision avoidance and several control approaches have been mentioned. Despite the substantial academic work, control design for platooning is still an open problem. Furthermore, research into more implementation relevant aspects is only recently emerging. Finally, a system description of the ACC was given and its application within HDV platooning.
Chapter 3

Modeling

In this chapter we present models that serve as a basis for the analysis and control design presented in the following chapters. First a general description of the internal and external forces affecting a vehicle in motion is given, resulting in an analytical model. Then a more detailed simulation model is presented. Finally a proposal of a layered hierarchical platooning architecture is given to facilitate control applications for HDV platooning. A summary of the presented models and the benefits of the proposed architecture concludes this chapter.

3.1 Vehicle Model

3.1.1 Nonlinear Vehicle Model

The main propelling parts of an HDV consist of engine, clutch, transmission shafts and wheels. A combination of all these parts forms the powertrain (driveline). The powertrain can be modeled in various ways depending on the specific purpose and use. The main interest in this section is to create a continuous-time model of the powertrain, based upon the simple model depicted in Figure 3.1.

Powertrain

General powertrain modeling can be found in (Kiencke and Nielsen, 2003). Our main objective is to model the power transfer from the engine to the road surface. Each part of interest is described briefly and then combined at the end to provide the complete powertrain model for each HDV. Note that we skip the index i to indicate the individual vehicle i in the platoon.

Engine: The engine we consider produces a torque through combustion of diesel mixed with a surplus of air in a very high pressurized chamber. The highly explosive combustion drives the crank shafts, which in turn are connected to the clutch, producing the desired torque. Internal dynamics characterized by the torque resulting from the combustion, the internal friction from the chamber walls, temperature



Figure 3.1: A basic model of the powertrain. (The picture of the engine and the gearbox is provided through the courtesy of Scania CV AB.)

variations, etc. is neglected in this model due to its highly nonlinear and engine specific properties. Thus given the engine inertia, Newton's second law gives

$$J_e \dot{\omega}_e = T_e(\omega_e, \gamma) - T_c. \tag{3.1}$$

where $T_e(\omega_e, \gamma)$ is the net engine torque generated after the internal losses and the external load from the clutch (T_c) , J_e is the moment of inertia of the engine including the flywheel, ω_e is the angular velocity of the crank shaft and γ denotes the injected fuel amount.

A standard HDV diesel engine operates at 500 - 2500 RPM with an optimal operating range 950 - 1500 RPM. The net engine torque can be obtained empirically through a Torque-RPM-Fuel graphical model for each specific engine.

Clutch: The clutch involves two frictional discs, which are pressed together and connects the flywheel of the engine with the gearbox's input shaft. Such clutches are commonly found in vehicles equipped with manual gearbox. The purpose of the clutch is to decouple the engine from the drivetrain to enable gear shifts. When the clutch is engaged, negligible losses arise at the connection point. Thus, the connection between the gearbox and the clutch is considered to be stiff. Hence, it can be modeled as

$$\begin{aligned} T_t &= T_c, \\ \omega_t &= \omega_c, \end{aligned} \tag{3.2}$$

where T_t denotes the torque output from the gearbox, ω_t the output angular speed from the gearbox, T_c the torque output from the clutch and ω_c the output angular speed from the clutch.

Gearbox: The gearbox is the connection between the clutch and the propeller shaft. It consists of a set of cogwheels (gears) which are connected such that the output torque from the clutch is transformed depending on which gear is engaged. The transformation is modeled in this case as a conversion ratio i_t , which varies according to the specific gearbox transmission characteristics. The gearbox is modeled without distinguishing between idling and neutral position and the gear shifts are assumed to be instantaneous, maintaining the RPM within operating range.

Typically a slight drop in power transfer occurs in the gear box due to frictional losses. This characteristic of the gear box is modeled as an efficiency η_t . Hence, assuming an immediate change of conversion ratio and efficiency, the connection between the transmission and propeller shaft is given as

$$T_p = i_t \eta_t T_t,$$

$$i_t \omega_p = \omega_t,$$
(3.3)

where T_p denotes the torque output and ω_t the output angular speed from the propeller shaft.

Propeller Shaft: The propeller shaft connects the gearbox to the final drive. The frictional losses are negligible and the connection is considered to be stiff. Hence, it can be modeled as

$$T_p = T_f,$$

$$\omega_n = \omega_f.$$
(3.4)

where T_f denotes the torque output and ω_f the output angular speed from the final drive.

Final Drive: Like the gearbox, the final drive is characterised by a conversion ratio i_f and an efficiency η_f . The value for the ratio and the efficiency depend on the final drive design. Neglecting inertia, the following relation can be established between the propeller shaft and the final drive torque and angular velocity:

$$T_d = i_f \eta_f T_f,$$

$$i_f \omega_d = \omega_f.$$
(3.5)

where T_d denotes the torque output and ω_d the output angular speed from the drive shafts.

Drive Shafts: The drive shafts connects the final drive to the wheels. In this simplified model it is assumed that the wheel speed is the same for both wheels.

In reality, the wheel speed differs when the vehicle enters a curve. However, it is negligible compared to other simplifications within the model. The connection between the wheels and the drive shafts is considered to be stiff and can therefore be modeled as

$$\begin{aligned} T_w &= T_d, \\ \omega_w &= \omega_d. \end{aligned} \tag{3.6}$$

where T_w denotes the torque output and ω_w the output angular speed at the wheels.

Wheels: The connection between the road and the wheels is assumed to have no slip, hence

$$J_w \dot{\omega}_w = T_w - T_b - r_w F_w,$$

$$v = r_w \omega_w = \frac{r_w \omega_e}{i_t i_f}.$$
(3.7)

where r_w denotes the wheel radius. The braking torque T_b is often difficult to model, since the characteristics varies significantly with respect to vehicle configuration and brake control logic.

To conclude the first part of the nonlinear vehicle model, combining (3.1)-(3.7) the longitudinal driving force produced in the powertrain is given as

$$F_{\text{powertrain}} = \frac{i_t i_f \eta_t \eta_f}{r_w} T_e(\omega_e, \gamma) - \frac{J_w + i_t^2 i_f^2 \eta_t \eta_f J_e}{r_w^2} \dot{v} - T_b, \qquad (3.8)$$

where the first term denotes the vehicle propulsion force produced by the engine and the second term is the internal inertial force.

External Longitudinal Forces

Several external forces are also imposed on the vehicle in motion. The main external forces are depicted in Figure 3.2 with the arrows indicating the corresponding sign convention, where α denotes the road grade, F_{brake} denotes the negative longitudinal force obtained if the brakes are applied and $F_{\text{powertrain}}$ denotes the positive longitudinal driving force produced by the engine. However, during coasting the engine exerts a constant braking force as it is driven by the accumulated kinetic energy or potential energy and not by fuel. In our model this effect is accounted for in the braking force. Therefore, the sign convention indicated by Figure 3.2 is maintained. Each external force of interest is described briefly and then combined at the end with the powertrain model to provide the complete vehicle dynamics model.

Air Drag: The aerodynamic drag has a strong impact on an HDV and can amount up to 50% of the total resistive forces at full speed. Studies have shown that



Figure 3.2: The longitudinal forces inflicted upon an HDV in motion.



Figure 3.3: An HDV experiences an increased pressure at the front, when traveling on the road. The pressure is also lowered at the back. The combination of these to occurrences is what is referred to as the air drag. If two HDVs travel at a close intermediate distance, the pressure at the back of the lead vehicle is increased and the pressure at the front of the follower vehicle is reduced, which will create an overall reduced air drag.

the wind resistance can be reduced significantly by arranging trucks in a platoon formation as depicted in Figure 3.3 . It is partly due to the drag produced behind the lead vehicle, which will be reduced when a follower vehicle lies close behind. The follower vehicle experiences a significant reduction of air drag due to a relatively large reduced pressure at the front. Hence, the total air drag is reduced, which in turn lowers the fuel consumption. The reduction in the air drag coefficient is modeled by an empirical model, as the one presented in Figure 3.4. The aerodynamic drag is given by

$$F_{\text{airdrag}} = \frac{1}{2} c_D(d) A_a \rho_a v^2, \qquad (3.9)$$

where $c_D(d)$ denotes the airdrag coefficient, d the relative distance between vehicles, A_a the maximum cross-sectional area of the vehicle and ρ_a the air density.

Rolling Resistance: The rolling resistance occurs due to the resistive frictional force that occurs between the road surface and the wheels. It is given by



Figure 3.4: The empirical air drag coefficient c_D and distance, d, between the vehicles. Adapted from (Wolf-Heinrich and Ahmed, 1998). Similar findings have been confirmed by the fluid dynamics department at Scania CV AB and in (Bonnet and Fritz, 2000).

$$F_{\rm roll} = c_r mg \cos(\alpha), \tag{3.10}$$

where c_r denotes the roll resistance coefficient, g the gravitational constant, and m the vehicle mass.

Gravitational Force: As an HDV travels along an incline, the gravitational force has a strong influence. In contrast with a passenger vehicle, an HDV is typically not able to produce a sufficient driving torque to maintain the velocity when traveling along an uphill with a slope greater than 3.5 % at 90 km/h. Similarly, when facing a downhill the vehicle will typically experience a speed increase if the slope is less than -1.4 %. Hence, the induced gravitational force can act as a positive or negative longitudinal force depending on the incline of the road. It is given by

$$F_{\text{gravity}} = mg\sin(\alpha). \tag{3.11}$$

Vehicle Model

Applying Newton's second law of motion along with all the external forces described above, a non-linear continuous mathematical vehicle model is derived as

$$m_t \dot{v} = F_{\text{engine}} - F_{\text{brake}} - F_{\text{airdrag}}(v) - F_{\text{roll}}(\alpha) - F_{\text{gravity}}(\alpha)$$
$$= \frac{i_t i_f \eta_t \eta_f}{r_w} T(\omega_e, \gamma) - F_{\text{brake}} - \frac{1}{2} c_D A_a \rho_a v^2 - c_r mg \cos(\alpha) - mg \sin(\alpha) \quad (3.12)$$
$$= k_e T(\omega_e, \gamma) - k_b F_{\text{brake}} - k_d v^2 - k_{fr} \cos \alpha - k_g \sin \alpha$$

where

$$m_t = \frac{J_w}{r_w^2} + m + \frac{i_t^2 i_f^2 \eta_t \eta_f J_e}{r_w^2}$$
(3.13)

is the total inertial mass.

Model Uncertainties

The vehicle model is based upon perfect knowledge of the vehicle parameters. In practice, only the gearbox ratio and the final gear ratio is known to be static. The inertias and efficiencies vary based upon the temperature and quality of the corresponding lubricating oil. The wheel radius also varies based upon the current air pressure and the friction between the road surface and tire is not static. The rolling resistance varies nonlinearly with tire temperature and velocity. However, the dominant uncertainty in (3.12) is the vehicle mass. During a freight transport assignment the cargo is often unloaded at several points, since it generally encompasses different contractors. Each time part of the cargo is unloaded there is seldom a measuring device to obtain new accurate mass measurements. The mass is generally several magnitudes larger than the other parameters. We adopt the common approach that all the parameter uncertainties can be aggregated as an uncertainty in mass.

An accurate model of the powertrain would mandate flexible shafts, where energy is stored when the shafts are twisted. However, the effects of such dynamics come into play when there are quickly varying changes in the engine torque. The platooning scenarios we consider does not involve such behavior, since the objective is fuel efficiency, which requires only smooth control actions.

3.1.2 Linearized Vehicle Model

When studying the behavior of vehicles within a platoon, the velocities are controlled and should not deviate significantly from the lead vehicles velocity trajectory. Thus, a linearized model might describe satisfactory vehicle behavior. The non-linear model (3.12) can be linearized with respect to a set reference velocity, an engine torque which maintains the velocity, a fixed time gap between the vehicles and a constant slope. The equilibria are denoted

$$v_{0} = v^{ref}$$

$$\alpha_{0} = \alpha^{ref}$$

$$d_{0} = v_{0}\tau^{ref}$$

$$T_{0} = \frac{c_{d}(d_{0})v_{0}^{2} + c_{fr}\cos(\alpha_{i_{0}}) + c_{g}\sin(\alpha_{i_{0}})}{c_{e}}$$

$$(3.14)$$

where

$$c_{e} = \frac{r_{w}i_{t}i_{f}\eta_{t}\eta_{f}}{J_{w} + mr_{w}^{2} + i_{t}^{2}i_{f}^{2}\eta_{t}\eta_{f}J_{e}} \qquad c_{d} = \frac{\frac{1}{2}r_{w}^{2}A_{a}\rho_{a}}{J_{w} + mr_{w}^{2} + i_{t}^{2}i_{f}^{2}\eta_{t}\eta_{f}J_{e}}c_{D}(d)$$

$$c_{fr} = c_{r}\frac{r_{w}^{2}mg}{J_{w} + mr_{w}^{2} + i_{t}^{2}i_{f}^{2}\eta_{t}\eta_{f}J_{e}} \qquad c_{g} = \frac{r_{w}^{2}mg}{J_{w} + mr_{w}^{2} + i_{t}^{2}i_{f}^{2}\eta_{t}\eta_{f}J_{e}} \qquad (3.15)$$

To account for the aerodynamics, the air drag function can be described as

$$c_D(d) = c_D^0 (1 - \frac{\Phi(d)}{100})$$

where c_D^0 is the nominal air drag coefficient for a single HDV and $\Phi(d) = a_{lsq}d + b_{lsq}$ is a least squares approximation within a relevant operating range.

Applying a first order Taylor approximation to (3.12) around the equilibrium points v_0 , T_0 , α_0 , d_0 , the linearized model for a single vehicle is given by

$$\frac{dv}{dt} \approx g(v_0, T_0, \alpha_0, d_0) + \frac{\partial}{\partial v} g(v_0, \mathcal{T}_0, \alpha_0, d_0) \Delta v
+ \frac{\partial}{\partial d} g(v_0, T_0, \alpha_0, d_0) \Delta d + \frac{\partial}{\partial T} g(v_0, T_0, \alpha_0, d_0) \Delta T$$
(3.16)

$$= c_e \Delta T - 2c_d v_0 \Delta v - \frac{a_{lsq}}{100} \frac{\frac{1}{2} r_w^2 A_a \rho_a}{J_w + m r_w^2 + i_t^2 i_f^2 \eta_t \eta_f J_e} v_0^2 \Delta d,$$

where c_e and c_d is given in (3.15). Approximately we have

$$\dot{v} = c_e T + \Theta v + \delta d, \tag{3.17}$$

where, with abuse of notation, T, v denote the deviation in control input and the vehicle velocity from the equilibrium point, $\delta = -\frac{a_{lsq}}{100} \frac{\frac{1}{2}r_w^2 A_a \rho_a}{J_w + mr_w^2 + i_t^2 i_f^2 \eta_t \eta_f J_e} v_0^2$ and $\Theta = -2c_d v_0$. Note that for the lead vehicle we get

$$\dot{v} = c_e T - 2c_D^0 v_0 v,$$

since the air drag reduction obtained due to a following vehicle is minor and therefore not considered.

3.2 Simulation Model

The model was constructed in Dymola (Dynasim, 2007). Dymola is an acausal modeling environment and enables bidirectional data flow, which in turn makes it possible to model and simulate acceleration as well as coasting. In the process of acceleration, the force produced by the engine flows towards the road surface, whereas it is reversed during coasting. A CAN system is also modeled to describe the interaction between the ECUs, actuators and physical properties of the HDV.

An analytical model can serve as a basis for controller design. However, in practice the vehicle and its interaction with the environment is highly complex. The analytical model describes the dynamic behavior of vehicles in the platoon, however the presented model does not directly account for fuel consumption and is not sufficiently detailed for real life evaluation. In reality, for example dynamics such as internal engine friction, powertrain oscillations, and internal brake friction have an impact on the behavior and fuel consumption. An HDV, as opposed to a passenger vehicle, has additional braking systems in parallel with the service brakes (wheel brakes). Due to the extensive mass of an HDV, there is lots of wear on the service brakes and the brake power can fade if they overheat. Therefore, an exhaust brake is implemented. In addition, there is a retarder brake, which effectively is a hydraulic brake system. Furthermore, the engine does not only drive the vehicle forward, but also propels auxiliary systems such as the alternator, servo steering, the air condition, etc., which have an impact on the fuel consumption. Energy losses in the hardware bearings also influence the fuel consumption. An analytical model does not capture the behavior of the embedded systems that come into play. Thus, a more complex simulation model is necessary to evaluate the fuel reduction potential of the implemented control strategy and platoon behavior. A validated simulation model that mimics real life behavior also serves as a necessary precaution measure before evaluating safety critical operations in practice. In addition, a simulation model facilitates reproducible data. In experimental HDV studies it is very difficult to obtain repeatable surrounding conditions during field experiments because the ambient variables temperature, wind, humidity and traffic conditions are constantly changing.

To create a simulation model, which produces reliable results and mirrors real-life behavior, an advanced model for coupled HDVs traveling in a platoon is developed as an extension to the acausal nonlinear model for a single vehicle created in (Sandberg, 2001). Figure 3.5 illustrates the individual parts in the powertrain, such as engine, gearbox, clutch, auxiliary systems, bearing losses, etc., which are modeled in detail. The model consists of 3313 variables, 1058 equations, and 626 states for a single HDV. The HDV model incorporates the full braking system, including the nonlinear behavior and a complex model for rolling resistance. The gearbox model and hydraulic retarder brake are controlled by software utilized in real life HDVs. The model also includes the dynamic behavior of the tires and relates rolling resistance to tire temperature and vehicle speed, which along with the rolling radius is significant for accurate fuel consumption simulations.



Figure 3.5: Schematic overlay of the simulation model. The ambient settings contains user input parameters, which consists of road topology, engine, gearbox, set speed and distance. The acausal HDV model created in Dymola communicates with the controller logic through the CAN system. The controller logic consists of production DHSC-, ACC- and CC-logic to govern the trucks. The complete model is extended to several HDVs that can utilize wireless communication and/or receive radar information.

The single HDV model in (Sandberg, 2001) is modified to handle additional control inputs consisting of external speed request and external brake request. It is modified to handle more advanced controller logic and extended to several vehicles by integrating the Dymola model with Simulink (Matlab). DHSC-, ACC- and CC-logic to govern the trucks is implemented by utilizing the current software implemented in Scania CV AB's trucks in production. The ECU software is modeled in Simulink and communicates with the HDV model through the internal CAN system. Exchangeable data sets are utilized to allow for the whole production range of gearboxes, engine types and recorded road profiles throughout Europe. The overall behavior of the entire simulation model is tested and verified to mimic real-life behavior. It serves as a basis for the evaluation of fuel reduction possibilities in HDV platooning that we consider in Chapter 4. In Chapter 5 safety regions with respect to collision avoidance for HDV platooning is derived. The simulation model then serves as a precautionary validation tool before the practical evaluation.

3.3 Systems Architecture

In this section, we present an architecture for how the vast control problem of cooperative platooning can be approached. The need for a proper architecture has been studied, for example in (Varaiya, 1993). The control systems rely on the underlying information and their structure will vary with a varying range of inputs, which must be considered. Thus, an understanding of both the control architecture and the underlying sensor and communication architecture is important.

3.3.1 Control System Architecture

We propose the three-layer hierarchical control system architecture, depicted in Figure 3.6. It is mainly designed with respect to control applications within platooning. The proposed architecture enables a hierarchical control by decomposing the control problem into manageable subsystems. The overall control objectives are similar in each layer, namely fuel efficiency, robustness, and safety. Each layer, with increasing index, presents additional control challenges with elevated system complexity. In the event of a layer failing the entire system can be prone to fail. We believe that the proposed platooning architecture is robust to such events, which is crucial in controller performance and especially in safety applications.

Starting from the bottom, layer I includes control challenges that can only incorporate information measured from the immediate surrounding environment. Each vehicle controller in this layer simply tries to maintain a suitable relative distance and velocity based upon a time gap setting. The set of controllers that we are referring to in this layer is for example the conventional ACC. The layer is an egocentric system, since no interaction is present and the vehicles operate independently. Therefore, the controller objective is to maintain a suitable intermediate distance to the following and preceding vehicle, since the cost function cannot include the interests of the surrounding vehicles. Fuel efficient control decisions can be performed in this layer to a certain extent by incorporating smooth control actions. In case of system failure, the driver is warned and is instructed to take full control of the vehicle.

In layer II, interaction is introduced in the platoon. The control challenge in this layer is to form a CACC that makes optimal decentralized decisions with respect to fuel consumption based on vehicles within spatial range of its wireless tranceiver. In this layer the cost function can include the behavior of the surrounding vehicles, hence control actions are based on self-interest as well as the interests of all other agents in the platoon. For example, the effect of a change in speed of the host HDV on all other vehicles in the platoon is considered. Thus, the controller objective is now to maintain a suitable intermediate distance to the following and preceding vehicles by accounting for fuel efficiency, robustness and safety of HDVs within radio range. By displaying a synchronous behavior the intermediate distance can be reduced, lowering the fuel consumption. Safety is improved by forming control actions based on preview information. If platooning constraints are imposed with



Figure 3.6: Control System Architecture: The boxes indicate decision-making and the arrows information flow. Processing is made in all layers but actuation is limited to each vehicle.

respect to maximum acceleration and deceleration, controller actions might be implemented to further improve safety, comfort and fuel optimality. Furthermore, strategies for local road attributes such as road speed changes, traffic lights road topology, etc., provided by road side units are also formed in this layer. If a system failure occurs in this layer, the control actions are degraded to the lower layer.

Lastly, layer III consists of a central controller unit, a supervisor, which can communicate with all vehicles within operation range. The control challenge in this layer is extended to a higher level, where a global perspective is undertaken. A centralized control design could be implemented in this layer. However, centralized control in HDV platooning applications generally produces a vast cost in computation and communication. Also, delays in tranceiving information from the central unit must be taken into consideration. Additional control tasks in this layer is for example dynamic optimal route planning for the entire platoon, path and route assigning, lane maneuvers, which are based upon the platoon properties and global traffic information. Coordinating, ordering and merging several platoons to enhance the operational performance is also performed in this layer. Strategies can be formed to adjust the speed for upcoming traffic lights, traffic events, or to improve the traffic flow. The controller will be able to make strategic decisions based on future and global events.

As we move up in the architecture layers, the driver burden is alleviated. Fuel optimal and robust control, in parallel with increasing safety applications, is enabled. Implementing a wide span of information in each layer enables a range of control strategies.

3.3.2 Sensor and Communication Architecture

The controller form relies and changes based upon the available information from the vehicles in the platoon. Thus, it is equally important to develop an information system architecture to gain further insight and understanding of the underlying inputs to the controller architecture. Hence, a four-layer information system architecture is presented in Figure 3.7, to serve as a supporting foundation to the control system architecture.

Layer I represents the vehicle specific system. Communication only occurs between the ECUs and sensors. This layer conveys all vehicle specific parameters, obtained through the on-board sensors and ECUs to the appropriate information layers. The sensor system can monitor and provide current velocity, acceleration, braking and acceleration capacity, driver inputs, etc. Vehicle constraints such as engine power, mass, tire pressure, and so on, are also monitored.

Layer II provides information regarding the local environment. It adds GPS, radar or lidar and camera information. Feedback information regarding the relative distance and velocity of the vehicle ahead is thereby obtained through the radar or lidar sensor. The camera provides road sign detection information. No external communication is present in this layer. Thus, only the behavior of the preceding and follower vehicle in the immediate environment can be measured or detected. The information task within this layer is not only to provide the control strategy in layer I, Figure 3.6, with inputs, but also to convey sensor specific information to the next layer above. Data for GPS accuracy verification is also provided to the next layer.

Layer III, expands the information range through V2V communication with the introduction of wireless nodes. Suitable vehicle and local information provided by the lower layers is broadcast to all vehicles within radio range. The task in this layer is to provide layer II in Figure 3.6 with regional information regarding the intents and behavior of the local agents within HDV the platoon. The GPS-information from vehicles in the immediate environment can be fused with the relative distance and velocity information provided by the radar or lidar in layer II. Wireless information is obtained regarding the dynamics of the surrounding vehicles, for example in the form of vehicle specific parameters. Specified or standardized platoon relevant information is provided to the next layer.

Lastly, layer IV extends the information range through V2I communication. In



Figure 3.7: Information System Architecture: The figure depicts four layers with the vehicle nodes in the platoon indicated by the boxes. The arrows indicating the direction of information flow obtained from the communication system. Wider arrows in layer III indicates the conveyance of a richer information span between the vehicles.

this layer information from several infrastructure sensors such as inductive loop detectors, piezoelectric sensors, pneumatic road tubes, ultrasonic sensors, active and passive infrared sensors, microwave sensors, magnetometers, video cameras, weather sensors, etc., is provided. The information consists of, for example lane occupancy, traffic densities, global average and instantaneous vehicle velocities, congestion reports, length and duration of traffic jams, accident reports, rush hour data, road condition, platoon formation, route topology, and so on. Global information is provided in this layer over a whole country or even a continent to the central control unit in layer III, Figure 3.6. The task of this layer is also to provide information from several possible ITS services such as smart lights, road information, traffic events and the position of other HDV platoons, mentioned in Chapter 2. As an example, consider a platoon traveling in the vicinity toward the same destination. The host platoon, could then be informed about its position, heading, and velocity in this layer and a suitable merging point.

Naturally, several information layers can be active at the same time. In our view, the layers embody the core of the information technology services for HDV platooning. The proposed architecture can also easily be adapted to future technology. A future technology could add to a layer's information span or possibly form a new layer and inserted accordingly. As the information span increases, predictability increases, enabling more effective control strategies.

There are many ways to compose a platoon architecture. An entirely centralized architecture generally imposes computation and communication issues. Such an architecture is very sensitive to network failure, which can result in severe consequences. Also, a fully autonomous system requires a lot of intelligence in particular with respect to safe maneuvering. Hence, it heavily relies on expensive technology, which makes it sensitive to uncertainties and sensor failure. We believe that the proposed architectures naturally combines a centralized and decentralized approach by distributing functionalities and services between the local, regional and global information network. Forming a layered architecture with control strategies that are hierarchical in nature, allows for a distributed and partially centralized system that is robust to system failures. If the information span decreases, a layer fails, the spacing policy can be adjusted accordingly with respect to safety and stability, hence enabling a graceful degradation. Naturally, system security in the sense of external attacks must be implemented. However, that is a vast area and not the focus of this thesis.

3.4 Summary

Several models for the analysis and synthesis of HDV platoons have been derived. A nonlinear model, obtained by modeling the powertrain along with the external forces affecting an HDV, serves as the basis for the qualitative dynamic behavior of the vehicles in the platoon. Additionally, the nonlinear air drag occurring between neighboring vehicles is modeled, which is essential in the fuel reduction analysis of HDV platooning. A linearized model have been presented that captures the normal operating mode behavior to a certain extent. Even though the analytical models serve as a basis for control design, the controller performance must be evaluated and verified on a more advanced model before practical implementation. Thus, an advanced simulation model have been presented to serve as a evaluation platform. To confirm the validity of the advanced simulation model, empirical results were presented. The results showed that the simulation model mimics real life behavior.

Finally, we presented a three-layer hierarchical control system architecture and a sensor and communication architecture control system architecture that naturally combines a centralized and fully autonomous approach by distributing functionalities and services between the local, regional and global information network. The technology needed to implement the three last layers in Figure 3.7 is already available but not yet implemented. Certain issues, for example standardization, must be evaluated before commercialization is feasible.

Chapter 4

Fuel Reduction Potential of Platooning

Where the environmental benefits and safety issues but it is of equal importance to also investigate the economical prospective and feasibility of platooning for commercial purposes. Yet conclusive results with respect to the fuel reduction possibilities of platooning remain unclear. Recall that the road transport industry is very fuel price sensitive, since fuel cost constitutes approximately one third of the total operational cost in European long haulage HDVs. The focus in this chapter is the fuel reduction that HDV platooning enables and the analysis with respect to the influence of a commercial ACC on the fuel consumption. We consider a platoon consisting of N HDVs. The main forces affecting a vehicle in motion is given by

$$\begin{split} m_t \frac{dv}{dt} = & F_{engine} - F_{brake} - F_{airdrag}(v) - F_{roll}(\alpha) - F_{gravity}(\alpha) \\ = & \frac{i_t i_f \eta_t \eta_f}{r_w} \mathcal{T}(\omega_e, \delta) - F_{brake} - \frac{1}{2} c_D A_a \rho_a v^2 - c_r mg \cos \alpha - mg \sin \alpha, \end{split}$$

where α denotes the slope of the road, c_D and c_r are characteristic coefficients, g denotes the gravitational force, ρ_a the air density, r_w the wheel radius, and i_t , i_f , η_t , η_f are transmission and gear specific constants. The accelerated mass of the truck $m_t(m, J_w, J_e, i_t, i_f, \eta_t, \eta_f)$ depends on the gross mass m, wheel inertia J_w , engine inertia J_e , gearbox ratio and efficiency i_t, η_t as the final drive ratio and efficiency i_f, η_f .

The aim of this study is to determine the fuel reduction possibilities for a platoon of N HDVs traveling on a road with a given set speed and relative distance. We want to separate the fuel reduction obtained through the reduction in air drag and the fuel consumption produced by the commercial ACC effort. The reduction in the air drag coefficient is modeled by the empirical model presented in Section 3.2.

It is difficult to make an accurate deduction merely based on empirical results due to the varying external disturbances. For example, weather conditions might vary and traffic conditions might change, producing incomparable and inconclusive empirical results with respect to the fuel consumption. Note also that the behavior



Figure 4.1: The air drag is reduced for all the vehicles in the platoon due to a lowered overall pressure experienced by each HDV.

of an HDV differs significantly from a light vehicle. Physical constraints have a larger impact on the vehicle dynamics due to the higher mass and inertia.

4.1 Fuel Consumption for Identical HDVs

It is known (Wolf-Heinrich and Ahmed, 1998; Bonnet and Fritz, 2000) that the wind resistance can be reduced significantly by arranging trucks in a platoon formation, as depicted in Figure 4.1 . The reduction occurs partly due to the drag produced behind the lead vehicle will be lowered when allowing a follower vehicle to lie close behind. The follower vehicle will experience a significant reduction of air drag due to a relatively large reduced pressure at the front. Hence, the total air drag is reduced, which in turn lowers the fuel consumption. In this section the advanced simulation model presented in Section 3.2 is evaluated on a 300 km road along with experimental results for validation to determine the fuel reduction possibilities for HDV platooning under practical circumstances. It is interesting to evaluate the implication a varying topology and air drag reduction have on the fuel consumption. Furthermore, the fuel consumption for the follower vehicle is unclear when maintaining the intermediate spacing through additional transient control actions.

The main contribution of this section is to investigate the fuel reduction potential of heavy duty vehicle platooning, solely with respect to a commercial control strategy. The aim is not to investigate the specifics of the control strategy but rather establish the contemporary fuel consumption. Fuel optimal control for a single vehicle on a flat road is to maintain a constant velocity, under the presumption that the traveling time is fixed (Hellström et al., 2008). Any deviations in the form of acceleration and deceleration result in an increased fuel consumption. The ACC generally receives information regarding the relative velocity and distance to the vehicle ahead and thereby maintains the relative distance by adjusting its speed accordingly. The increased control effort that the ACC creates, in the sense of additional transient engine actions and brake events, produces an overall increased fuel consumption. Thus to the best of our knowledge, it is still unclear whether the increased control effort produced by the ACC possibly cancels the reduction in fuel consumption achieved by decreasing the air drag. Hence, the aim is to determine the fuel reduction possibilities for a platoon of HDVs traveling on a road with varying topology, a given set speed and relative distance.

Results in this chapter were obtained empirically and by simulating a truck with



Figure 4.2: Topology for the road Södertälje - Jönköping, Sweden

a 620 hp engine and a 12 speed gear box on a measured road with a given set speed as an input. The vehicle configuration was 6×2 and the gross mass of the truck was chosen to be 40000 kg, which is the estimated standard average weight of the European long haulage trucks. Both vehicles start at an initial velocity of 20 km/h, an initial relative distance of 20 m, and then accelerates to the set reference velocity. ACC- and CC-logic to govern the trucks was implemented by utilizing the current software implemented in Scania CV AB's HDVs in production.

To obtain results based upon conditions that represent real-life scenarios, a fairly hilly road was selected as a simulation basis. The Swedish road between Södertälje and Jönköping, depicted in Figure 4.2, is considered to characterize a varied range of road conditions. Moreover, trucks have a speed restriction by law upon many roads; hence 70 km/h was considered to be a reasonable set speed for the lead vehicle's CC, as depicted in Figure 4.3. The calibration parameters are unaffected by the change in set speed since the fuel reduction is measured relative to the lead vehicle. The set speed for the follower truck with ACC was set at 80 km/h to inhibit a possible loss of the leading vehicle due to factors in the topology. Hence, the results from simulating two identical trucks on the afore mentioned road are stated in Table 4.1 for various time gaps.

The results clearly show that a reduction of 4.7–7.7% in fuel consumption is attainable with an ACC compared to a truck with a conventional CC. Furthermore,



Figure 4.3: Simulation scenario.

	Fuel	Average
	consumption $[\%]$	Velocity $[\rm km/h]$
Lead Truck	100	69.89
Time Gap 1	92.3	69.90
Time Gap 3	93.6	69.90
Time Gap 5	95.3	69.89

 Table 4.1: Normalised results from simulation with identical trucks

the fuel reduction is obtained without reducing the average velocity. Therefore, the traveling time is unaffected, which is considered to be a crucial factor for many HDV fleet operators as they are commonly commissioned based on delivery time and punctuality. The transport assignments are often very time sensitive, since a delay can in many cases result in a significant increase in cost as they might in turn lose their slot for unloading the goods.

4.2 Isolating the Influence from the ACC

We have shown that an overall fuel reduction can be obtained when driving two trucks in a platoon. Hence, it has become evident that the general control effort produced by the ACC to maintain the relative distance between the vehicles does not cancel the total fuel reduction possibilities obtained through the reduced air drag. However, it is unclear whether the ACC effort produces an increase or decrease of fuel consumption and if it can be improved further.

To separate and determine the effect of the control effort on the fuel consumption, all other factors must be kept constant. Hence, the truck parameters, i.e. engine, gear box, weight, rolling resistance, etc., are set equal for both vehicles—eliminating any possibilities for the fuel consumption to differ due to different physical properties between the trucks. Furthermore, to facilitate a correct deduction, the ambient variables, i.e. ambient temperature, humidity, traffic conditions, etc., and the *air drag*, are also set equal for both vehicles, effectively isolating the effect of the control strategy on the fuel consumption within the simulation model presented in Chapter 3.2.

The simulation results for different time gaps presented in Table 4.2, show that the overall control effort actually reduces the fuel consumption. Maximum

	Fuel	Average
	consumption $[\%]$	Velocity $[\rm km/h]$
Lead Truck	100	69.89
Time Gap 1	98.8	69.90
Time Gap 3	98.9	69.89
Time Gap 5 $$	99.1	69.89

 Table 4.2: Normalised results from simulation with identical air drag and trucks

reduction in fuel consumption solely with respect to the control strategy is obtained on time gap 1. There is a slight but insignificant change in fuel consumption for time gap 5. A possible explanation for this discovery is derived by studying a segment of the road depicted in Figure 4.4, which shows the vehicle behavior for both of the trucks controlled with CC and ACC. The top plot shows the actual vehicle velocity trajectory of the two trucks, with implied speed requests. When traveling along a downhill, the ACC-logic allows the subject vehicle to increase its speed and thereby decrease the relative distance. When exiting the downhill the ACC deters the preservation of the set speed, thus effectively increasing the relative distance. The lead vehicle on the other hand, at the 6040m marker, exceeds its maximum set speed limit threshold of $75 \,\mathrm{km/h}$ in this case and therefore the DHSC is activated. Hence, stored energy is lost through the braking action whereas it is maintained for the follower vehicle. Thus, it becomes evident by studying the instantaneous fuel consumption (Figure 4.4: second plot from the top) at the 6040m marker that such a control strategy reduces the fuel consumption, since the overall braking action is reduced through preview information from the lead vehicle. The area between the curves at the aforementioned markers represent the saved fuel. Studies in economical cruise control (ECC) strategy (Hellström et al., 2006), have also proven that utilizing the gravitational force obtained in a downhill to increase the velocity and utilizing the provided energy to deter control actions until mandated, reduces fuel consumption. Therefore the observed behavior can be characterized as enabling classical ECC behavior through preview information of the road characteristics ahead from the lead vehicle, which undoubtedly reduces the fuel consumption.

The noted result could also have been a consequence of finding a more fuelefficient Fuel–Torque–RPM point for the specific engine due to a small difference in actual speed between the two trucks. However, an identical simulation with a different 620 hp engine resulted in equivalent results concluded from Table 4.2.



Figure 4.4: Simulation results: Top plot: Velocity trajectory for the first truck controlled by CC, sub indexed T1, (solid line) and the second truck governed by ACC, sub indexed T2 (dashed line). Second plot from the top: Instantaneous fuel consumption for T1 (solid line) and T2 (dashed line). Third plot from the top: Relative distance between the vehicles (solid line). Bottom plot: Topology for T1 (solid line) and T2 (dashed line).

4.3 Mass Variations

Owing to the aforementioned results, they indicate that platooning with two identical trucks reduces the fuel consumption due to both air drag reduction and control strategy. However, two trucks with different masses could induce a different ACC behavior. In some cases when following a lighter truck in an uphill, the lead vehicle will be able to maintain its velocity, while the follower vehicle will decline in speed due to its extensive mass. Similarly when following a heavier lead vehicle, the follower vehicle will have to accelerate while traveling along a steep downhill to maintain the relative distance. Hence, a difference in mass between the two trucks will inflict constraints on the ACC, hence altering the controller behavior in comparison with the case of two identical trucks. Thus it is of interest to study the effects of provoking the ACC strategy in such a manner.



Figure 4.5: The figure illustrates the results of simulating platooing with two trucks of different mass and identical mass.

Two scenarios were investigated. In the first scenario, the mass of the lead vehicle is set to $m_1 = 30$ t, whereas the truck governed by ACC is maintained at $m_2 = 40$ t, see Figure 4.3. In the second scenario, the leading vehicle's mass is set to $m_1 = 50$ t. All other conditions are identical and the simulation is carried out on the same road as before.

The results displayed in Figure 4.5 were derived by comparing the fuel consumption of the follower vehicle, with the fuel consumption of a lead vehicle with the same mass to avoid ambiguity. Figure 4.5 reveals a fuel reduction of 3.8–7.4%, while following a lighter lead vehicle and a reduction in fuel consumption of 4.3–6.9%, when following a heavier lead vehicle. The results show that a significant fuel reduction can still be obtained with various time gaps. However a noticeable difference in fuel consumption is detected due to the physically induced change in control. For time gap 1, a 0.5% higher fuel reduction can be obtained with a lighter lead vehicle in comparison with a heavier lead vehicle. It is probably due to the fact that the vehicle governed by ACC acts as a low pass filter when it is heavier, making it insensitive to small fluctuations in the lead vehicle's velocity. Thus less variance in control effort is implemented on the vehicle, resulting in lower fuel consumption. However, on time gap 5 a lighter lead vehicle produces an increase of 0.5% in fuel consumption compared to the results from a heavier lead vehicle. A lighter lead vehicle will be able to maintain its speed with less effort in an uphill. Thus, the heavier truck governed by the ACC will need more effort to maintain the relative distance. Hence, more fuel is injected to the system to reduce the relative distance.

4.4 Experiments

The main difficulty lies in producing an environment where reproducible results can be obtained. In this section we present a method to obtain data empirically for N = 2 HDVs, to be utilized as a basis for verification of the simulation model presented in Section 3.2.

4.4.1 Setup

Experiments were conducted upon a Swedish highway with two identical trucks as illustrated in Figure 4.6. The masses of the heavy duty vehicles was measured to be 39.3 t and 39.2 t. Both of them were equipped with a Scania 620 hp engine. The fuel consumption was measured and recorded through each vehicles CAN-devices. It can be measured for two trucks traveling on the road, but to facilitate a correct deduction, the ambient variables, e.g., wind, ambient temperature, humidity, etc., must be equal during every measurement instance (test-run) to create reproducible results. Small variations in these disturbances can produce a significant difference in measured fuel consumption. An additional reference truck was therefore used as a calibration device to reduce the error due to the varying environment factors. All the vehicles were traveling with a set speed of 90 km/h. Several runs were conducted for which the accumulated results are presented in Section 4.4.2.

4.4.2 Results

The results are presented in Table 4.3, where the accumulated fuel consumption data is provided for several test-runs with varying time gap settings 1, 3, 5. Simulated fuel consumption is given together with experimental fuel consumption. The lead truck was governed by a CC and used as a reference.

The results in Table 4.3 verify that a significant fuel reduction can be obtained through platooning and the simulated values correspond very well to the empirical results. The findings presented in Figure 3.4 were however derived from experiments conducted on buses in a wind tunnel. Hence no effects from additional aerodynamics, e.g., lateral winds, were taken into consideration. Convoy driving does not reduce the resistance from such winds. Thus, only 80% of the suggested values was utilized and assumed to give a good estimate of reasonable air drag reduction within platooning applications. The slightly lower values in fuel reduction are most likely a result of the aforementioned assumption. Therefore it can be deduced that the results produced



Figure 4.6: Two heavy duty vehicles traveling at close intermediate distance on a measured Swedish highway. The picture is provided at the courtesy of Scania CV AB.

	Simul. Fuel	Exper. Fuel
	consump. $[\%]$	consump. $[\%]$
Lead Truck	100	100
Time Gap 1	93.2	92.9
Time Gap 3	94.9	-
Time Gap 5	98.8	98.7

 Table 4.3: Fuel reduction for a two vehicle platoon.

by the simulation are most certainly reliable and mirrors real truck behavior quite accurately.

4.5 Summary

A maximum fuel reduction of 4.7-7.7% depending on the time gap, at set speed equal to 70 km/h, can be obtained with two identical trucks. If the lead vehicle is 10 t lighter a corresponding 3.8-7.4% fuel reduction can be obtained depending on the time gap setting. Similarly if the lead vehicle is 10 t heavier a 4.3-6.9% fuel reduction can be obtained. This indicates that HDVs in a platoon should be ordered based on mass and the time gap setting for fuel efficiency. The fuel consumption in a N > 2 HDV platoon can most likely be lowered further due to an additional reduction in air drag for additional vehicles. All results indicate that a maximum fuel reduction will be achieved with time gap 1, due to both reduction in air drag and the control strategy.

The ACC-strategy does not increase the fuel consumption according to the results obtained in this study. By naturally mirroring ECC behavior through preview information from the vehicle ahead, the current ACC becomes a fuel efficient control strategy by reducing the overall braking actions for a hilly topology, which produces approximately 1% fuel reduction solely based upon the ACC actions. Surprisingly, the more stringent control effort implemented on time gap 1 does not increase the overall fuel consumption. The results clearly show that no significant difference in fuel reduction occurs between time gaps with respect to control effort. However, a vast reduction of air drag can be obtained by reducing the time gap. Hence, it is favorable to minimize the relative distance between the vehicles to achieve a maximum reduction in air drag. However issues such as feedback delay and communication delay for safety and driver comfort arises. Thus a need for further investigation within the subject matter arises.

The analysis conducted in this study shows that improvements can be made to the ACC-logic by designing it based upon fuel optimal criteria. Owing to the fact that the ACC-strategy produces different fuel reduction results when following a truck of different mass and to the fact that isolated strategies within this chapter have shown fuel reduction possibilities, there is a vast scope of designing a fuel optimal controller for commercial purposes without compromising comfort and safety issues.

Chapter 5

Safety Constraints

It is fuel efficient to minimize the relative distance between the vehicles to achieve a maximum reduction in air drag. As traffic intensity is growing, the complexity of the coupled traffic dynamics is increasing. The actions of one vehicle may in turn affect all vehicles in a linked chain. Thus, through rapidly increasing technology in sensors, wireless communication, GPS-devices, and digital maps, advanced driver assistance systems are being developed to aid the driver. However, these information sources impose constraints in terms of accuracy, reliability and delays amongst others. Therefore, safety constraints with respect to how close we might drive to a vehicle ahead without risking collision scenarios becomes a challenge. A question arises of how close the automated vehicles might operate without endangering a collision.

As an example, consider a collision avoidance scenario for a vehicle in a platoon equipped with an ACC-system. The signal from the radar must first generally be received and filtered through the corresponding ECU. It is then processed by calculating the relative distance and velocity to the vehicle ahead. The ACC receives the information as an input and determines the proper control action. If the control action is braking, a slight delay arises from sending the brake request to producing the actual brake torque at the wheels. Alternatively, wireless communication may be utilized. However, delays are still imposed due to package drops, retransmission time, etc. Thus, the impact of the vehicle control on the safety criterion must be established and verified. Rigorous guarantees cannot be obtained through extensive simulations, but mathematical tools need to be developed.

In this chapter, we consider an HDV platooning scenario where each vehicle only receives information regarding the relative position, velocity and characteristics of the immediate vehicle ahead. The objective is to determine the minimum relative distance between a lead vehicle and a follower vehicle that can be maintained without endangering a collision. It can be obtained by finding the largest set of initial states, irrespective of how the lead vehicle behaves, for which there exists a controller that manages to keep all executions inside a prespecified set of states; a subset in which the system is defined to be safe inside the boundary. The main contribution of this chapter is to primarily establish safe sets, which can serve as a reference for HDV platooning in collision avoidance. We propose a novel approach by computing so called reachable sets to develop safety criteria for HDV platooning. A differential game formulation of the problem enables such a set derivation by capturing the event when the lead vehicle blunders in the worst possible manner. We model the game as the follower vehicle (player u_2) is trying its best to avoid a collision and the lead vehicle (player u_1) is trying its best to create a collision. We determine criteria for which collisions can be avoided in a worst case scenario and thereby establish the minimum possible safe distance to a vehicle ahead. A numerical study is performed to derive safe sets for a two-vehicle platoon. We show that the minimum relative distance with respect to safety depends on the overall braking capabilities of the HDVs within the platoon.

5.1 Preliminaries

To obtain a better understanding of the work presented in this chapter, fundamental concepts must be kept in mind. Therefore, we present the three main concepts that serve as a foundation for the presented theory in this section. Fundamental concepts for the problem formulation, such as game theory and reachability, are hence briefly presented for completeness.

A pursuit-evasion game, (Basar and Olsder, 1995) p.423, is a family of problems in which one group of members try to capture another group in a given setting. The system dynamics is given by

$$\dot{x} = f(t, x, u_1, u_2), \quad x(0) = x_0, \quad x(t) \in \mathbb{R}^n,$$

where f(t, x, u) is globally Lipschitz in x and continuous in u. Generally u_1 is the strategy of the player referred to as the *pursuer* and u_2 is the strategy of the player referred to as the *evader*. The problem can be described, through the principle of optimality, as a game where the players are trying to minimize respectively maximize a cost function. The game can then generally be formulated as

$$\max_{u_2 \in \mathcal{U}} \min_{u_1 \in \mathcal{D}} H(x, p, u) \tag{5.1}$$

where $H(x, p, u) = p^T f(x, u_1, u_2)$ is the Hamiltonian and p denotes the costates, which must satisfy $\dot{p} = -\frac{\partial H^T}{\partial x}$. Additional necessary conditions for optimality that must be satisfied are summarized in Table 5.1.

For reachability, the classical notion could be described as the ability to reach one state from another. Hence, given a compact set of controller actions $u_1 \in \mathcal{U}$ and $u_2 \in \mathcal{D}$, the ability to reach a defined unsafe set from a set of feasible initial states x(0) is of interest for establishing safety criterion. In (Mitchell et al., 2002), it was proved that the unsafe set $\mathcal{G}(\tau)$ in which the pursuer in a two-person dynamic game, (Isaacs, 1999 (1965)), can create a collision in the next τ time units despite the best effort from the evader, is given by $\mathcal{G}(\tau) = \{x \in \mathbb{R}^3 | \Phi(x, -\tau) \leq 0\}$, where

Description	Equation
State Equation	$\dot{x} = \frac{\partial H^T}{\partial p} = f(x, u^*)$
Costate equation	$\dot{p} = -\frac{\partial H^T}{\partial x} = -\frac{\partial f^T p}{\partial x} + \frac{\partial L^T}{\partial x}$
Input stationarity	$\frac{\partial H}{\partial u} = \frac{\partial f^T p}{\partial u} + \frac{\partial L^T}{\partial u} = 0$
Transversality conditions	$\frac{\partial \Phi}{\partial x(t_f)} - p^T = -\frac{\partial \varphi^T}{\partial x(t_f)} \lambda$
	$H(t_f) = 0$

Table 5.1: Table of necessary conditions for optimality for time invariant systems.

 $\Phi(\cdot, \cdot)$ is the viscosity solution of the following modified Hamilton-Jacobi-Isaacs partial differential equation (HJI PDE)

$$\frac{\partial \Phi(x,t)}{\partial t} + \min(0, H(x, p, u^*)) = 0, \quad t \in \mathbb{R}^-,$$
(5.2)

with terminal conditions $\Phi(x, 0) = \Phi_0(x)$.

The procedure for solving the HJI PDE can intuitively be described as starting at any point on the boundary of the unsafe set $\partial \mathcal{G}$. The usable part is then defined as:

$$\chi = \{ x \in \partial \mathcal{G} \mid p^T(0) f(x, u^*) < 0 \},$$
(5.3)

which denotes all the state trajectories heading in towards the unsafe set. Thus, the reachable set is calculated by starting on $\partial \mathcal{G}$ and under optimality constraints simultaneously solving the ODE:s, \dot{x} and \dot{p} , backwards by calculating terminal conditions of $x(t_f)$ for when $p^T(t_f)x(t_f) \geq 0$. Hence, all the trajectories are calculated on the boundary of the usable part, for which it is possible to move away from the unsafe set and thus the surface sets which partitions the safe and unsafe regions are derived.

5.2 System Model

Using the notation of Chapter 3.1.1, the state equation of each HDV can be formulated as

$$\frac{ds_i}{dt} = v_i$$

$$m_t \frac{dv_i}{dt} = F_{engine} - F_{brake} - F_{airdrag}(v_i) - F_{roll}(\alpha_i) - F_{gravity}(\alpha_i)$$

$$= k_i^e T(\omega_e, \delta) - k_i^b F_{brake} - k_i^d v_i^2 - k_i^{fr} \cos \alpha - k_i^g \sin \alpha$$
(5.4)

where m_t denotes the accelerated mass and i = 1, 2 denote the vehicle index. $k_i^e, k_i^b, k_i^d, k_i^{fr}$, and k_i^g denote the characteristic vehicle and environment coefficients



Figure 5.1: Two trucks traveling on a flat road where vehicle 1 is referred to as the lead vehicle (the pursuer) and vehicle 2 is the follower vehicle (the evader).

for the engine, brake, air drag, road friction, and gravitation respectively. The presented model is accurate for high velocities. At low velocities the internal dynamics of the vehicle has a larger impact on the longitudinal dynamics.

For simplicity of this study, the road is assumed to be flat and the control input is $u = F_{brake}$. The system can be simplified to three dimensions as partially relative variables with respect to the follower vehicle:

$$\dot{x} = f(x, u_1, u_2) = \begin{cases} v_1 - v_2 = -v_r \\ \dot{v}_2 - \dot{v}_1 = c_2^u u_2 - c_1^u u_1 - c_2^w (d) v_2^2 + c_1^d (v_2 - v_r)^2 - c_2^{fr} + c_1^{fr}, \\ c_2^u u_2 - c_2^w (d) v_2^2 - c_2^{fr} \end{cases}$$
(5.5)

where $x = [d v_r v_2]^T$, $c_i^z = \frac{k_i^z}{m_t}$ and z = (b, d, fr, g). The state variable d denotes the relative distance between the vehicles, v_r is the relative velocity between the vehicles, and v_2 is the velocity of the follower vehicle (Figure 5.1). The variable

$$c_2^w(d) = c_2^d \left(1 - \frac{-0.414d + 41.3}{100} \right)$$
(5.6)

denotes the linearized air drag reduction, which is a result of driving close to a vehicle ahead.

Both vehicles are only allowed to move in a forward longitudinal direction. The collision scenarios we are mainly focused on in this chapter is when vehicles are traveling closely spaced with a given initial velocity and relative distance. Thus, there is a inherent constraint in (5.5):

$$v_1 = v_2 - v_r \ge 0.$$

5.3 Safety Sets

The problem at hand can be set up as a two-vehicle dynamic pursuer-evader game as described in Section 5.1:

$$\max_{u_2 \in \mathcal{U}} \min_{u_1 \in \mathcal{D}} p^T f(x, u_1, u_2) = H(x, p, u^*),$$
(5.7)

where $f(x, u_1, u_2)$ is the system (5.5) and u_1^*, u_2^* are the optimal strategies. The derived unsafe set $\mathcal{G}(\tau)$ under this condition then becomes conservative, which is preferable to ensure safety. Thus, the unsafe set $\mathcal{G}(\tau)$ can be computed for which it is guaranteed that given all the control inputs of the leader and follower vehicle, there is a possibility that a collision occurs despite the best effort from the follower vehicle.

The analytical Hamiltonian can be derived from (5.5) and (5.7) as:

$$H^{*}(x,p) := H(x,p,u^{*}) = \max_{u_{2} \in \mathcal{U}} \min_{u_{1} \in \mathcal{D}} p^{T} f(x,u_{1},u_{2})$$

$$= \begin{bmatrix} p_{1} & p_{2} & p_{3} \end{bmatrix} \begin{bmatrix} \dot{d} \\ \dot{v}_{r} \\ \dot{v}_{2} \end{bmatrix}$$

$$= -p_{1}v_{r} - p_{2}c_{1}^{u}u_{1}^{*} + (p_{2} + p_{3})c_{2}^{u}u_{2}^{*} - (p_{2} + p_{3})c_{2}^{w}(d)v_{2}^{2} + p_{2}c_{1}^{d}(v_{2} - v_{r})^{2}$$

$$- (p_{2} + p_{3})c_{2}^{fr} + p_{2}c_{1}^{fr}.$$
(5.8)

The lead vehicle in (5.8) is given the advantage of determining its optimal control strategy based upon information regarding the following vehicles strategy. This is generally not the case. However, we wish to find a set which guarantees that a collision can be avoided despite the best effort of the pursuer with respect to a compact set of controller actions, $u_1 \in \mathcal{D}$ and $u_2 \in \mathcal{U}$.

The costates can be derived as

$$\dot{p} = \frac{\partial H^*}{\partial x} = \begin{cases} -(p_2 + p_3)c_2^d \frac{0.414}{100}v_2^2 \\ -p_1 - 2p_2c_1^d(v_2 - v_r) \\ -2(p_2 + p_3)c_2^w(d)v_2 + 2p_2c_1^d(v_2 - v_r) \end{cases}$$
(5.9)

Due to the linear dependency of the optimal control inputs in (5.8), they can easily be computed as:

$$u_1^* = \frac{\bar{T}_1 + \underline{T}_1}{2} + \operatorname{sgn}(s_1) \frac{\bar{T}_1 - \underline{T}_1}{2}, u_2^* = \frac{\bar{T}_2 + \underline{T}_2}{2} + \operatorname{sgn}(s_2) \frac{\bar{T}_2 - \underline{T}_2}{2},$$
(5.10)

where $T_i \in [\underline{T}_i, \overline{T}_i], i = 1, 2$, is the brake torque available to vehicle i and $s_1 = p_1 c_1^u$, $s_2 = (p_1 + p_2)c_2^u$. Since the sign function is undefined for $s_1 = s_2 = 0$, the sign of \dot{s}_1 and \dot{s}_2 is checked to determine the value in those situations. The control input for each vehicle can switch instantaneously between \underline{T} and \overline{T} in (5.10). In practical applications this would imply that the brake- or acceleration request can be computed and implemented without any delay. However, the scenarios for when

delay is present in the system is not excluded by this assumption, which is discussed further in Section 5.3.3.

We define the unsafe set \mathcal{G}_0 , as a region when the two vehicles are within \tilde{d} units from each other:

$$\mathcal{G}_0 = \{ x \in \mathbb{R}^3 | d - \tilde{d} < 0 \}.$$
(5.11)

The HDVs modeled here are described as traveling in a longitudinal direction and a collision has therefore occurred if $d \leq \tilde{d} = 0$. The maximum braking torque in an HDV depends on the vehicle configuration but can be approximated as ~ 60000 Nm/axle. A maximum deceleration on a flat and dry road have been measured up to 6.5 m/s^2 . Commercial HDVs generally have a speed restriction of 90 km/h. Therefore, the unsafe set is calculated backwards for $\tau = -t = -4$ s, which implies that a vehicle is able to reduce its velocity by 93.6 km/h. Hence, the chosen simulation time enables the vehicles to come to a full stop within the calculated safety sets. It is considered as safe if the vehicles have stopped and no collision has occurred.

To compute the unsafe set from the solution of (5.2), a state-of-the-art toolbox of Level Sets Methods, (Mitchell, 2007), is utilized. Computing safe sets is an efficient method to capture the behavior of entire trajectories simultaneously.

5.3.1 Identical HDVs

The collision avoidance scenario is first investigated for two identical HDVs. Both vehicles have identical vehicle parameters in Eq. (5.4) and a 4×2 vehicle configuration. The gross mass of each HDV was chosen to be 40000 kg, which is considered to be a standard weight for European Long-haulage HDVs.

Figure 5.2 shows the boundary $\partial \mathcal{G}(\tau)$, of the unsafe set contained between the plotted level surface and \mathcal{G}_0 . As $v_r = v_2 - v_1$ increases, the relative distance $d = s_1 - s_2$ must also increase. The fold in the boundary surface area is due to the physical constraint $v_1 \geq 0$. Any trajectory heading behind that surface area would imply that the lead vehicle has reversed to create a collision. If the follower vehicle is within the safe set, it will always be able to avoid a collision regardless of the best effort of the lead vehicle (pursuer) with respect to a compact set of controller actions. Thus a least restrictive controller could be implemented outside the unsafe set without endangering a collision. However, if it is within the unsafe set a collision might occur given that the pursuer acts in the worst possible manner.

In platooning applications the vehicles generally travel in what we here refer to as a normal mode, where each vehicle is traveling at a constant fixed velocity, $v_r = 0$, and a desired relative distance is set by the driver. Figure 5.2 reveals that a collision can be avoided for two identical HDVs if the lead vehicle is traveling at a higher velocity than the follower vehicle. However, if the vehicles are operating in normal mode and has a relative distance $d \leq \gamma$, where $\gamma = \partial \mathcal{G}(\tau)|_{v,v_r=0}$, a collision could occur. The lead vehicle experiences a greater air drag and is therefore able



Figure 5.2: The backward reachable set obtained under the assumption that no delay is present in the system.

to obtain a slightly higher braking force. Thus, if the vehicles are both traveling at a velocity, $v \leq 2.5$ m/s, a collision could occur for $\gamma = 0.2$ m. As both vehicles' velocities increase, the air drag and inherently the obtainable brake force becomes higher for the lead vehicle. Thus, a larger relative distance of $d > \gamma = 1.1$ m must be maintained at v = 25 m/s to stay out of the unsafe region. Hence, the minimum relative distance that can be obtained for two identical vehicles depends on their current velocity. Assuming that no delay is present in the system and the vehicles are traveling in normal mode, the vehicles could maintain a relative distance of 1.2 m without endangering safety.

5.3.2 Varying Vehicle Parameters

Here we investigate the unsafe set for a lower or higher mass of the follower vehicle compared to the lead vehicle, keeping all other parameters constant. A difference in mass affects the deceleration stretch compared to when both the vehicles are identical.

The unsafe set in Figure 5.3a is derived for the case where the follower vehicle is 10 t lighter than the lead vehicle. A similar unsafe set is formed when the available brake force is solely increased for the follower vehicle. The follower vehicle being lighter implies that it has a lower mass to decelerate. Therefore, the deceleration stretch becomes shorter compared to the lead vehicle. The shape of the reachable set seems unchanged. However, a shift has occurred in the level surface in the positive v_r -direction, hence the follower vehicle will be able to lie closer without endangering a collision. The minimum safe relative distance is therefore shorter compared to the case of two identical vehicles. If no delay is present in the system the vehicles would in theory be able to lie attached to each other and the lead vehicle could have a slightly lower velocity at the time when a the lead vehicle strives to collide and no collision would occur. The minimum relative distance of d > 1.1 m is no longer valid since the higher overall braking force induced by a lower mass for the follower vehicle is greater than the larger air drag for the lead vehicle.

However, in Figure 5.3b the follower vehicle is 10 t heavier than the lead vehicle. Hence, the lead vehicle has a greater braking capability and thus a perturbation arises in the level surface at $v_r \approx 0$. In this case a minimum distance of d = 13 m must be maintained to remain outside the reachable set at normal mode. Thus, the relative distance must be increased significantly if the lead vehicle has a stronger braking capability.

5.3.3 Delay and Model Uncertainties

The results presented so far have been derived by assuming that there is no delay present in the system. However, in real life this is rarely the case. In this section we describe how delays can be translated to the previously derived results.

Delays commonly occur due to transmission, computation, and producing the control command. Consider the case where a delay of τ_1 [s] occurs due to transmission delay, e.g. receiving information regarding the relative distance and velocity through a radar or wireless communication. An additional delay of τ_2 [s] occurs in detection and confirmation that a vehicle in front is braking rapidly. The actuation delay is measured to be τ_3 [s]. Thus, the total delay can be $\tau = \sum_{i=1}^{3} \tau_i$ in a worst case scenario. Hence, the lead vehicle will be able to act before the follower vehicle is able to react. This implies that the lead vehicle will be able to reduce the relative velocity and distance, which can easily be computed in the worst case scenario.

A delay can be translated into a shift of the reachable in Figure 5.2 and 5.3 by Δd units in the positive direction along the *d*-axis and by Δv_r units in the negative direction along the v_r -axis. However, no change occurs in the follower







(b) Follower vehicle has a 10t higher mass.

Figure 5.3: The backward reachable set obtained under the assumption that no delay is present in the system and the vehicles have different configuration.
vehicles velocity, v_2 , since it does not react. Depending on the radar and the collision detection algorithm, the worst case delay can be approximated to be $\tau_1 + \tau_2 \approx 500$ ms. Hence, the lead vehicle will be able to reduce the relative velocity by 3.25 m/s and the relative distance by 0.8 m if it is driving 25 m/s at normal mode. Thus if the follower vehicle maintains $d \geq 2 \text{ m}$, a collision can always be avoided for two identical vehicles according to Figure 5.2.

5.4 Validation

To investigate the validity of the derived safety regions in Figure 5.2, a simulation study is conducted within this section for a finite number of scenarios.

Two identical vehicles were simulated in the simulation model presented in Chapter 3.2, consisting of 3313 variables, 1058 equations, and 626 states for each vehicle. The model is verified to mimic real life behavior. Hence, two different simulation scenarios are presented in Figure 5.4. The velocity trajectory for the lead vehicle is displayed in the top plot and the velocity trajectory for the follower vehicle is displayed in the middle plot. The bottom plot shows the relative distance between the vehicles.

The first scenario was chosen as a point on the level surface in Figure 5.2. It can be described as an HDV traveling on a highway and another HDV appears in front, e.g. from a shoulder at a lower velocity. Upon entering, the vehicles suddenly brake due to an incident ahead on the road. The follower vehicle has a velocity of 20.23 m/s and approaches the lead vehicle entering with a 13 m/s lower velocity. When a relative distance of 45.14 m is reached, both vehicles implement the optimal control input derived in (5.10). We can see that a collision is avoided since both vehicles have come to rest at d = 5.32 m. Hence, collision could be avoided for a higher relative velocity or a lower relative distance, which is a point below the level surface. This is due to the problem formulation, which produces a preferred overapproximated level surface in safety applications.

In the second scenario a point below the level surface in Figure 5.2 was chosen by lowering the relative distance and increasing the relative velocity by 9.7%. The follower vehicle has a velocity of 20.23 m/s and approaches the lead vehicle with a 14.3 m/s higher velocity. Both vehicles initiates an emergency braking action at a relative distance of 40.76 m. The lead vehicle has come to a rest while $v_2 > 0$ in Figure 5.4 and the relative distance is zero. Thus a collision has occurred.

Several scenarios were investigated for different points on the level surface in Figure 5.2 and within the reachable set. The results are summarized in table 5.2, where the initial conditions for each collision scenario is given in the middle columns and the final relative distance is given in the fourth column.

As can be deduced from Table 5.2 and Figure 5.4, the safe set ensures that collision is avoided. The level surface is more accurate for simulations no.4-6, where the HDVs are operating close to normal mode. Both the HDVs have come to a total halt at an $d \leq 0.3$ m. For the scenarios when the relative velocities differ



Figure 5.4: Simulated emergency brake scenario. Solid line illustrates the scenario with initial conditions selected on the level surface for two identical vehicles and the dashed line illustrates initial conditions behind the level surface. The \times :s in the bottom plot indicates the point where both vehicles initiates their optimal control inputs.

more, simulations no. 1-3, the vehicles come to rest at a larger relative distance. A collision occurs if the initial conditions for (d, v_r) are shifted 11% below the level surface. Thus, a larger overapproximation is observed in these cases, which is due the increased model uncertainty at lower velocities. Hence, even though Eq. (5.4) is a fairly simple model of an HDV, it seems to be a sufficient for this application.

5.5 Experiments

Experiments were conducted to evaluate the safety sets and simulation results. Two Scania tractors were driven on a flat road. When the vehicles reached a given reference speed, relative velocity, and intermediate distance, the optimal control inputs were implemented in both vehicles. The experiments presented in this section are obtained for platooning vehicles traveling under normal operating conditions with initial $v_r \approx 0$. To obtain a reproducible scenario, the experiments procedure is automated.

Simulation no.:	$v_r(t_0)$	$d(t_0)$	$v_2(t_0)$	$d(t_f)$
1)	18.3	71.9	25.1	10.9
2)	11.7	45.7	20.2	10.3
3)	3.6	13.7	10.4	6.7
4)	0.24	1.14	10.4	0.3
5)	0.2	1.14	15.3	0.5
6)	0.5	2.3	25.1	0.05

Table 5.2: Table of several initial conditions for collision scenarios.

5.5.1 Setup

Two standard Scania tractors are utilized with additional control and communication hardware. Both tractors have a 4×2 vehicle configuration and the masses were measured to be 13.10 t for the lead vehicle and 12.37 t for the follower vehicle. They are equipped with standard radars, which sends the relative distance with a 40 ms interval to the central coordinator ECU and gated every 100 ms. An external supplier provides the radar with an internal filter of undisclosed characteristics. The lead vehicle is equiped with a semi-automatic gearbox and the follower has a fully-automatic gearbox. Standard ECUs, utilized in Scania HDVs, are modified to add the automated optimal control logic. As illustrated in Figure 5.5, a wireless sensor unit (WSU) carrying the standard wireless communication protocol 802.11p is mounted in each vehicle. The WSU is directly connected to the tractors internal CAN system and messages are broadcast on demand. Thereby, the internal CAN signals such as velocity, acceleration and control inputs are available to both vehicles. Velocity reading is obtained through the internal tachometer and both vehicles' acceleration is obtained by differentiating the front axle velocity signal. The data is logged in the lead vehicle.

To evaluate the safety sets and simulation model under normal operating conditions, the vehicle's CC and internal brake request functionality is utilized. The control action is implemented at an intermediate distance of 30 m due to safety precautions. Additional precautionary measures are undertaken by installing an emergency button or by pushing the brake pedal to deactivate the entire system if the drivers deem it necessary. The brake system is calibrated as an attempt to eliminate any braking discrepancies in the tractors, making them behave as identical vehicles. A constant pressure is induced at the brake discs when a brake deceleration is requested. It is desirable to obtain the same deceleration as requested. However, in real life HDVs the braking dynamics is nonlinear and varies slightly with time. Finally, to minimize delays that can occur in the system, all control signals are first sent to the WSU. The WSU then transmits the signal while echoing the same information back through the internal CAN system. Thereby, both vehicles will be able to initiate their control actions nearly simultaneously.



Figure 5.5: A schematic overlay of the experimental hardware setup. The top picture shows the tractors utilized in this experiment. The yellow tractor is the lead and the black is the follower. The WSU, ECU and PC communicate through CAN. As soon as new information is obtained through the ECU or the vehicle, it is broadcast through the WSU.

5.5.2 Results

The results for two test-runs at $60 \,\mathrm{km/h}$ are given in Figure 5.6. As shown, the experiments are initiated by starting the vehicles at a given intermediate distance. Both vehicles accelerate to a given reference speed and then maintains it. The lead vehicle initially maintains a 5 km/h lower speed compared to the follower vehicle. As the follower vehicle approaches and an intermediate distance of less than $50 \,\mathrm{m}$ is reached, the lead vehicle changes its speed to match a relative distance of $30 \,\mathrm{m} \pm 0.1 \,\mathrm{m}$. When it is reached, both vehicles initiate their optimal control inputs with a maximum braking capacity of $-3 \,\mathrm{m/s^2}$. The first collision test is presented between the 60-70 s time marker. The top plot shows that the vehicles nearly have an identical velocity trajectory. As the vehicles decelerate, their gearboxes automatically changes to lower gears. At lower speed, the difference in gearbox has a stronger effect. Furthermore, the clutch must be pressed before coming to a halt in the lead vehicle since it has a semi-automatic gear box. Hence, the dynamic behavior of the vehicles are different during deceleration at lower velocities. The follower vehicle obtains a slightly stronger braking capacity before coming to stop and thereby increases the relative distance in the end, as can be seen in the middle plot. The same behavior is displayed by the relative distance trajectory obtained from the simulation model. The bottom plot shows the deceleration trajectories for both vehicles along with



Figure 5.6: Collision experiments conducted at a reference speed of 60 km/h, at d = 30 m and an initial $v_r = 0$. The lead vehicle's trajectories are denoted by T_1 and the followers by T_2 . The top plot shows the velocity trajectories for the lead vehicle (solid blue line), follower vehicle (dashed red line) obtained from the experiments. Simulated trajectories are also given for the lead vehicle (dotted magenta line) and the follower vehicle (dashed-dotted green line). The middle plot shows the relative distance trajectory obtained through the radar (solid blue line) and simulation (dashed red line). The bottom plot shows the acceleration trajectories for each vehicle with the same line description as in the top plot. Note that the radar information can occasionally be lost as seen between the 80-90 s time marker.

simulated deceleration trajectories between the 60-70 s time marker. The simulated and empirically obtained trajectories are similar. Hence, the simulation model mimics a real life harsh braking behavior rather accurately. As can be seen between the 105-115 s time marker, the second collision experiment did not produce the requested deceleration. The follower vehicle, being newer, obtained a higher deceleration with the same brake request as before and thereby the relative distance was increased. Furthermore, a slight variation can be seen in the deceleration trajectories. Thus, a slight offset can occur based on the state and condition of the brake system.

Several collision experiments were conducted at various reference velocities to evaluate different points on the safety set, as illustrated by the trajectories in Figure 5.7 and Figure 5.8. The initial points of all the trajectories are shifted to the minimum safe relative distance given by the safety set, based on the relative velocity and follower vehicle velocity at initial time of implementing the optimal control inputs. A delay of 200-300 ms has occasionally occurred and hence the minimum safety distance have been adjusted accordingly. Figure 5.7 shows the empirically obtained deceleration trajectories in comparison with the safety set for vehicles with identical braking power. None of the trajectories intersect the safety set above $v_2 \geq 5 \text{ m/s}$. Figure 5.8 shows a two-dimensional projection of the deceleration trajectories, omitting the minor variation in relative velocity. The top plot shows the collision tests for varying initial velocities and similar vehicle braking capacity. It can be seen that the intermediate spacing remains fairly constant throughout the collision tests. However, below a velocity of 5 m/s the vehicles starts changing gears, which has a clear impact on the vehicle dynamics. The model for deriving the safety sets does not take gear change logic into consideration. Nevertheless, the safety sets are conservative and a collision is hence still avoided. The middle plot. in Figure 5.8, shows the deceleration trajectories for when the follower vehicle has a 30-40 % lower braking capacity. It can be seen that the intermediate spacing is constantly reducing. Most of the trajectories end with both vehicles at rest and still a few meters to spare. Finally, the bottom plot shows the deceleration trajectories for when the follower vehicle has a 20-30 % higher braking capacity. It can be seen that the intermediate spacing remains the same or increases, which is congruent with the results obtained from the corresponding safety set. Hence, if the follower vehicle has a higher braking capacity, an intermediate spacing within decimeters could have been maintained with the presented system and still no collision would have occurred.

Even though the model and procedure utilized for deriving the safety sets do not encompass all nonlinear features of a HDV in motion, the sets serve as a reliable reference to ensure that a collision can be avoided. Both theoretical and empiric results show that it is suitable to order HDVs according to increasing braking capacity further down the platoon. Thereby, the intermediate spacing can be reduced significantly without compromising safety. Naturally, it only holds under the assumption that V2V communication is available.



Figure 5.7: Three-dimensional plot of the empirical deceleration trajectories for varying initial velocities. The \times denotes the starting point for each trajectory. The starting point of the trajectories is shifted to the minimum safe relative distance in the safety set based on the relative velocity and current follower vehicle velocity at the time of initiating the optimal control input.



Figure 5.8: Two-dimensional plot of the empirical braking trajectories for varying initial velocities, where the \times denotes the starting point for each trajectory. The trajectories are presented in the (d, v_2) -plane, omitting the slight variation in the relative velocity. Each color indicates a set of experiments obtained for a given initial follower vehicle velocity at time of emergency braking. The starting point of the trajectories is shifted to the minimum safe relative distance in the safety set with respect to initial relative velocity and current follower vehicle velocity.

5.6 Summary

It is full efficient to drive vehicles closely spaced to each other due to the inherent minimized air drag reduction. A minimum distance for two HDVs can be deduced with respect to a compact set of controller actions without endangering a collision despite the worst possible action by the vehicle ahead. Thus, if the minimum distance is determined for each vehicle pair, a collision can be avoided throughout the platoon. The level set toolbox utilized in this chapter provides a the means to visualize the reference frame and boundary of the safety set. During normal mode operation a minimum distance of $1.2 \,\mathrm{m}$ should be maintained to ensure that a collision can be avoided for two identical vehicles and no delay is present in the system. Delays can be measured and implemented in the reachable set formulation through a simple translation. The derived minimum possible relative distance with a measured worst case delay of 500 ms in this chapter for identical vehicles is $2 \,\mathrm{m}$, which is lower compared to what is utilized in commercial applications today without endangering safety. The experimental results presented in this chapter indicates that the derived safety sets are reliable for platoons traveling under normal operational mode. The presented method forms a conservative safety set. Therefore, uncertainties from unmodeled dynamics do not cause a collision, as was seen in the experimental results. Hence, V2V communication enables HDVs to operate at very short intermediate spacing.

Chapter 6

Suboptimal Decentralized LQR Control for HDV Platooning

hrough commercially available systems, for example radar and wireless communication, each vehicle in a platoon is able to measure or receive the relative distance, relative velocity and additional relevant information concerning the preceding vehicle. The objective is to maintain a predefined headway to the vehicle ahead. By traveling at a close intermediate distance to an HDV, the air drag is reduced. Hence, the effort needed to maintain the desired relative velocity varies with the relative distance. This creates a coupling of the dynamics between vehicles throughout the platoon. Furthermore, with the aid of V2V communication, vehicle characteristics and events such as emergency braking, can be transmitted within radio range. Therefore, a minimum distance, far less than what is utilized in todays commercial systems, between two HDVs can be deduced with respect to a compact set of controller actions without endangering a collision despite the worst possible scenario displayed by the vehicle ahead. However, the control becomes increasingly stringent with shorter intermediate distance. Due to the additional control effort produced by the existing control systems for maintaining the relative distance, the fuel consumption increases. Hence, it is of vast interest for the industry to produce a new fuel optimal control. The question of whether to implement a centralized, decentralized, or some combination of the control strategies then naturally arises.

Considering large platoons, the computational complexity with respect to a centralized control strategy might become an issue. Even though the ECU computation power and memory has increased for commercial HDV ECUs, it is far less dramatic than modern PC:s that can handle up to quadrillion calculations per second and embodies several terabytes of memory. Therefore, there are significant limitations in the computation power and speed of an HDV ECU compared to a modern PC, making relatively simple mathematical operations an issue. Another implementation issue arises due to the fact that platoons will not generally consist of vehicles from the same manufacturer. Thus, vehicles in the platoon will most likely utilize the available information but not allow another vehicle from a different manufacturer to dictate a centralized control strategy. However, if standardization is enforced, this issue can be resolved and a centralized control might be implemented.

The key defining feature of the problem is set by the proposed technology and system structure. In the considered practical problem of HDV platooning, the physical or communication constraints often impose a specific interconnection structure. A key issue for centralized control is that it mandates a full state information. In real-life scenarios, agents in the platoon will occasionally fail to transmit or receive information due to physical radio limitations, inducing a time varying delay in the system. It cannot be assumed that state information from other agents will be available at every single point in time, producing a varying state availability (Gupta et al., 2004). Hence, a significant feature of the problem is while the cost function can embody all the individual agents in the formation, physical limitations in the radio range and transmission delays impose constraints on the form of the control law by limiting information to various agents at any time. Therefore, a decentralized longitudinal control is practical, to ensure scalability and robustness. However, other control applications such as route assigning, coordinating, ordering and merging several platoons are not time and information critical operations and thus suitable as centralized control strategies.

In this chapter, we are primarily concerned with the case of forming a decentralized longitudinal control, solely based on local model knowledge. We consider linear quadratic regulator (LQR) design. We propose a systematic method to derive suboptimal stabilizing decentralized controllers, which imposes a lower block-diagonal structure on the feedback gain matrix. We also show that the controller gives a stable and robust closed-loop system.

The main contribution of this chapter is to design and investigate the performance of the proposed controllers, under normal operating conditions, with respect to physical constraints that are imposed in a practical set-up. An LQR-based method is given for deriving a suboptimal decentralized feedback that takes dynamic coupling into consideration and does not rely on the wireless information being available at every point in time. We give physical insight of how to derive the weighting factors for the problem at hand. The structure of the controller feedback matrix can be tailored with respect to the locally available state information.

6.1 Structured LQR

In this section, we present the system under consideration and provide the procedure for solving the suboptimal stabilizing decentralized controllers for an interconnected HDV platoon.

The objective is to design suboptimal stabilizing decentralized controllers, solely based on local model knowledge, for an N-HDV system when there is interconnection between different subsystem dynamics, without compromising system performance. The vehicles can only receive information from the interconnected preceding vehicle,



Figure 6.1: The figure shows a platoon of N heavy duty vehicles, where each is only able to communicate with the preceding vehicle.

which is generally the case for commercially available systems. However, the local information can naturally be extended to a larger subset.

Consider a system consisting of N HDVs as depicted in Figure 6.1, where each vehicle is interconnected with the preceding vehicle. The system structure under consideration, presented in Chapter 3, is given as

$$\dot{x} = \begin{bmatrix} A_{11} & 0 & 0 & \dots & 0 \\ A_{21} & A_{22} & 0 & \dots & 0 \\ 0 & A_{32} & A_{33} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & A_{NN} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_N \end{bmatrix} + \begin{bmatrix} B_1 & 0 & 0 & \dots & 0 \\ 0 & B_2 & 0 & \dots & 0 \\ 0 & 0 & B_3 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & B_N \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ \vdots \\ u_N \end{bmatrix}, \quad (6.1)$$

where A_{ij} , $i \neq j$, denotes the interconnection between the system dynamics. An optimal LQR state-feedback controller can be derived by minimizing the quadratic cost function given by

$$J(u) = x(t_f)^T S x(t_f) + \int_{t_0}^{t_f} x(t)^T Q x(t) + u(t)^T R u(t) dt,$$
(6.2)

where S and Q are positive semidefinite and R is positive definite. The known control input that minimizes (6.2) is given by

$$\dot{P} = PBR^{-1}B^{T}P - A^{T}P - PA - Q$$

$$L = R^{-1}B^{T}P$$

$$u_{cen}^{*} = -Lx,$$
(6.3)

where the optimal control solution, u_{cen}^* , implies a communication topology that provides each vehicle with full state information. However, such an assumption is not realistic, since the available information is limited in practice.

6.1.1 Structural Decomposition

Due to the constraints set upon the information topology and the interconnection between the subsystems, as illustrated in Fig. 6.1, the global system (6.1) can be

divided into sub-blocks. Thereby, the first vehicle (subsystem 1) can optimize its control input by setting its weighting parameters Q_1 and R_1 with respect to the desired performance criterion. By conveying the information, each interconnected follower vehicle (subsystem *i*) can subsequently derive locally optimal stabilizing controllers based on the local model. The local optimization is performed separately for each vehicle and the weighting parameters Q_i and R_i in the respective optimization steps are set with respect to each vehicle's performance criteria. Therefore, they need only be known to the individual vehicle and the dimension can vary based upon the available state information. The matrix Q_i will in particular have a specific form, which will contribute to the desired coupling behavior of the interconnected vehicle. As a result of subsequently deriving controllers based upon local model information and interconnection, a global suboptimal decentralized feedback matrix with a lower block diagonal form is produced with respect to (6.1), which can be given as

$$L = \begin{bmatrix} L_{11} & 0 & 0 & \dots & 0 \\ L_{21} & L_{22} & 0 & \dots & 0 \\ 0 & L_{31} & L_{33} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & L_{NN} \end{bmatrix}.$$
 (6.4)

Thus, a systematic decentralized LQR-optimization can be performed for each subsystem, as described in Algorithm 1.

Theorem 6.1.1. Consider a chain of N interconnected subsystems with dynamics given by (6.1). Algorithm 1 provides a locally optimal state-feedback controller u = -Lx with L as in (6.4) that results in a globally asymptotically stable closed-loop system.

Proof. Consider subsystems $(\bar{A}_{ii}, \bar{B}_i)$, i = 1, ..., N, as introduced in Algorithm 1. It is easy to see that with the specified state-feedback control law u = -Lx the resulting closed-loop system has eigenvalues given as the solutions to

$$\prod_{i=1}^{N} \det \left[\lambda I - (A_{ii} - B_i L_{ii}) \right] = 0.$$

Thus, Algorithm 1 produces a globally asymptotic stable system, since

$$\operatorname{Re}\left[\lambda_i \left(A_{ii} - B_i L_{ii}\right)\right] < 0, \ \forall i.$$

Algorithm 1:

- 0) Set the weight matrices Q_i , R_i , i = 1, ..., N, positive definite and in accordance with the desired performance criteria.
- 1) Derive the locally optimal feedback controller, u_1^* , for subsystem 1 (the lead vehicle) by solving

$$\min_{u_1} \int_{t_0}^{t_f} x_1^T Q_1 x_1 + u_1^T R_1 u_1 dt$$

s. t. $\dot{x}_1 = A_{11} x_1 + B_1 u_1.$

$$\dot{P}_1 = P_1 B_1 R_1^{-1} B_1^T P_1 - A_{11}^T P_1 - P_1 A_{11} - Q_1,$$

$$L_{11} = R_1^{-1} B_1^T P_1$$

$$u_1^* = -L_{11} x_1.$$

2) Each preceding vehicle's dynamics is known to the follower vehicle. Therefore, utilize this information of subsystem i-1 in the control design of subsystem i (the follower vehicle) and subsequently compute for i = 2, ..., N,

$$\min_{u_i} \int_{t_0}^{t_f} \begin{bmatrix} x_{i-1} \\ x_i \end{bmatrix}^T Q_i \begin{bmatrix} x_{i-1} \\ x_i \end{bmatrix} + u_i^T R_i u_i dt$$

s. t.
$$\begin{bmatrix} \dot{x}_{i-1} \\ \dot{x}_i \end{bmatrix} = \underbrace{\begin{bmatrix} A_{(i-1)(i-1)} - B_{i-1}L_{i-1} & 0 \\ A_{i(i-1)} & A_{ii} \end{bmatrix}}_{\bar{A}_{ii}} \begin{bmatrix} x_{i-1} \\ x_i \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \\ B_i \end{bmatrix}}_{\bar{B}_i} u_i,$$

Obtain locally optimal, u_i^* , feedback by solving

$$\begin{split} \dot{P}_i &= P_i \bar{B}_i R_i^{-1} \bar{B}_i^T P_i - \bar{A}_{ii}^T P_i - P_i \bar{A}_{ii} - Q_i, \\ \tilde{L}_i &= R_i^{-1} \bar{B}_i^T P_i, \\ u_i^* &= -\tilde{L}_i \begin{bmatrix} x_{i-1} \\ x_i \end{bmatrix}, \\ \end{split}$$
where $\tilde{L}_i &= \begin{bmatrix} L_{i(i-1)} & L_{ii} \end{bmatrix}.$

6.2 System Model

In this section, we consider the HDV platooning control problem. The general system structure is presented, using the same notation as presented in Chapter 3.1.2, and we give physical insight of how to derive the weighting factors for the LQR control problem. We also investigate the performance with respect to system requirements and stability.

The state equation of a single HDV is

$$s_{i} = v_{i}$$

$$m_{t_{i}}\dot{v}_{i} = F_{\text{engine}} - F_{\text{brake}} - F_{\text{airdrag}}(v_{i}) - F_{\text{roll}}(\alpha_{i}) - F_{\text{gravity}}(\alpha_{i}) \qquad (6.5)$$

$$= k_{i}^{e}T_{i}(\omega_{e}, \delta) - k_{i}^{b}F_{brake} - k_{i}^{d}v_{i}^{2} - k_{i}^{fr}\cos\alpha_{i} - k_{i}^{g}\sin\alpha_{i}$$

where v_i is the vehicle velocity, m_{t_i} denotes the accelerated mass, i = 1, ..., N the vehicle platoon index and $T_i \in \mathbb{R}$ denotes the net engine torque. $k_i^e, k_i^b, k_i^d, k_i^{fr}$, and k_i^g denote the characteristic vehicle and environment coefficients for the engine, brake, air drag, road friction, and gravitation respectively.

The non-linear model, (6.5), can be linearized with respect to a set reference velocity, an engine torque which maintains the velocity, a fixed time gap between the vehicles, and a constant slope.

When traveling in a platoon, the air drag have a significant impact on the overall resistive forces, which is one of the key factors in fuel reduction possibilities and must therefore be taken into account. To account for the aerodynamics the air drag characteristic coefficient in (6.5) can be modeled as

$$\tilde{k}_d = k_d (1 - \frac{\Phi(d)}{100}),$$

where $\Phi(d) = -0.414d + 41.29$ and $0 \le d \le 99$ is the longitudinal relative distance between two vehicles. The linearized model is hence given by

$$\begin{bmatrix} \dot{v}_{1} \\ \dot{d}_{12} \\ \dot{v}_{2} \\ \dot{d}_{23} \\ \dot{v}_{3} \\ \vdots \\ \dot{v}_{N-1} \\ \dot{d}_{(N-1)N} \\ \dot{v}_{N} \end{bmatrix} = \begin{pmatrix} \Theta_{1} & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 & \cdots & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 & \cdots & 0 & 0 & 0 \\ 0 & 0 & 0 & \delta_{3} & \Theta_{3} & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & \Theta_{N-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \delta_{N} & \Theta_{N} \end{bmatrix} \begin{bmatrix} v_{1} \\ d_{12} \\ v_{2} \\ d_{23} \\ v_{3} \\ \vdots \\ v_{N-1} \\ d_{(N-1)N} \\ v_{N} \end{bmatrix} \\ + \underbrace{\begin{bmatrix} c_{1}^{e} & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \delta_{N} & \Theta_{N} \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & c_{2}^{e} & 0 & \cdots & 0 \\ 0 & 0 & c_{3}^{e} & \cdots & 0 \\ 0 & 0 & c_{3}^{e} & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ B \end{bmatrix} \begin{bmatrix} T_{1} \\ T_{2} \\ T_{3} \\ \vdots \\ T_{N} \end{bmatrix},$$

$$(6.6)$$

where $\Theta_1 = -2c_i^d v_{i_0}$, $\Theta_i = -2\tilde{c}_i^d v_{i_0}$, $\delta_i = -0.0414\kappa v_{i_0}^2$, $\kappa = \frac{\frac{1}{2}r_w^2 A_a \rho_a}{J_w + mr_w^2 + i_t^2 i_f^2 \eta_t \eta_f J_e}$, $i = 2, \ldots, N, c_i^z = \frac{k_i^z}{m_t}$ and z = (b, w, fr, g). Hence, the HDV platooning system has a block treediagonal structure, as in (6.1), on which the proposed controller design method can be implemented.

6.2.1 Cost function

For general LQR-design the weighting factors need to be specified and adjusted based upon the results of the specified design goals. In the proposed decentralized control algorithm the weighting factors can be set separately for each subsystem. The lead vehicle's objective is to follow a given reference velocity and minimize the control input with respect to fuel optimality. However, the follower vehicles in the platoon have an additional objective of maintaining the set intermediate distance. The desired relative distance generally varies depending on the vehicle velocity. It is determined by setting a timegap τ s, which gives the desired headway as $d_{ij} = \tau v_j$. Thus, considering the platoon objectives, the cost function can be set up as

$$J(T_{e_{i}}^{*}) = \min_{T_{e_{i}}} \int_{t_{0}}^{t_{f}} w_{i}^{\tau} (d_{(i-1)i} - \tau v_{i})^{2} + w_{i}^{\Delta v} (v_{i-1} - v_{i})^{2} + w_{i}^{d} d_{(i-1)i}^{2} + w_{i}^{v} v_{i}^{2} + w_{i}^{T_{e_{i}}} T_{e_{i}}^{2} dt$$
$$= \min_{T_{e_{i}}} \int_{t_{0}}^{t_{f}} \begin{bmatrix} v_{i-1} \\ d_{(i-1)i} \\ v_{i} \end{bmatrix}^{T} Q_{i} \begin{bmatrix} v_{i-1} \\ d_{(i-1)i} \\ v_{i} \end{bmatrix} + R_{i} T_{e_{i}}^{2} dt,$$
(6.7)

where

$$Q_{i} = \begin{bmatrix} w_{i}^{\Delta v} & 0 & -w_{i}^{\Delta v} \\ 0 & w_{i}^{d} + w_{i}^{\tau} & -\tau w_{i}^{\tau} \\ -w_{i}^{\Delta v} & -\tau w_{i}^{\tau} & \tau^{2} w_{i}^{\tau} + w_{i}^{\Delta v} + w_{i}^{v} \end{bmatrix}, \quad R_{i} = w_{i}^{T_{e_{i}}}.$$
 (6.8)

In accordance with the objective for a vehicle traveling in a platoon, w_i^{τ} in (6.7) determines the importance of not deviating from the desired time gap and $w_i^{\Delta v}$ creates a cost for deviating from the velocity of the preceding vehicle. The following terms, $w_i^d, w_i^v, w_i^{T_i}$, put a cost on the deviation from the linearized states and the control input. Since the main objective is to maintain a set intermediate distance, w_i^{τ} and $w_i^{\Delta v}$ must be set larger than the remaining weights.

6.3 Robustness Evaluation

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In this section, we state a definition of string stability and give the performance by analyzing if the proposed controller produces a string stable system. An analytic expression is derived for the system under consideration and numerical results are given to show that the system is string stable.

Relative distance and velocity tracking are key factors in measuring the performance of the system. However, a concern regarding the robustness is frequently raised in vehicle platooning applications. In (Swaroop and Hedrick, 1996) a definition of string stability is presented. String stability can loosely be described as the ability to suppress a disturbance along the platoon. We will use a less rigorous approach similar to that presented in (Sheikholeslam and Desoer, 1993) and (Yamamura and Seto, 2006). Assuming that the *i*:th vehicle (Fig. 6.1) controls the headway distance by using only information from the immediate preceding vehicle, the transfer function from the lead vehicle's velocity v_1 to the tail-end vehicle's velocity v_n can be expressed as

$$V_n(s) = G_1^v(s)G_2^v(s)\cdots G_{n-1}^v(s)V_1(s),$$
(6.9)

where

$$V_i(s) = G_i^v(s)V_{i-1}(s), \quad i = 2, \dots, n.$$
(6.10)

and $V(s) := \mathcal{L}(v(t))$ is the Laplace transform of the time domain velocity. We define that a string of n vehicles in a platoon is string stable if for all i = 2, ..., n

$$||G_i^v||_{\infty} \le 1,\tag{6.11}$$

where $|| \cdot ||_{\infty}$ denotes the maximum peak of the frequency response. The definition states that a deviation in the lead vehicles velocity from its steady-state value should not be amplified downstream. The plant model (6.6) together with state-feedback

$$u_i = -(L_i^1 v_{i-1} + L_i^2 d_{(i-1)i} + L_i^3 v_i)$$

gives the transfer function relation

$$V_i(s) = \frac{(\delta_i - c_{e_i} L_i^2)}{s - (\Theta_i - c_{e_i} L_i^3)} D_{(i-1)i}(s) - \frac{c_{e_i} L_i^1}{s - (\Theta_i - c_{e_i} L_i^3)} V_{i-1}(s).$$
(6.12)

The transfer function for the relative distance is given by

$$D_{(i-1)i}(s) = (V_{i-1}(s) - V_i(s))/s.$$
(6.13)

By combining (6.12) and (6.13) it is straight forward to derive the transfer functions

$$V_i(s) = G_i^v(s)V_{i-1}(s), (6.14)$$

where

$$G_i^v(s) = \frac{-c_{e_i}L_i^1 s + \delta_i - c_{e_i}L_i^2}{s^2 - (\Theta_i - c_{e_i}L_i^3)s + \delta_i - c_{e_i}L_i^2}.$$
(6.15)

As presented in Section 6.4, we have considered a platoon consisting of N = 6 identical vehicles and utilized equal LQR-weights for each follower vehicle. Thus, the transfer functions $G_i^v(s)$ are identical for each vehicle pair with $\Theta_1 = -3.6 \times 10^{-3}$, $\Theta_i = -2.2 \times 10^{-3}$, $\delta_i = -1.44 \times 10^{-4}$, $c_{e_i} = 0.148 \times 10^{-3}$, $\forall i$. Hence, the maximum peak response for each transfer function can easily be calculated, (6.16), by inserting the subsystem LQR feedback gains $[L_e \ L_{11}] = 10^3 \times [-0.32 \ 2.06]$, $L_2 = 10^4 \times [-2.7, -5773.5, 1446.1]$, $L_i = 10^4 \times [-1.3, -5773.5, 1446.1]$, using Algorithm 1, into (6.15).

$$||G_i^v||_{\infty} = 1.00, i = 2, \dots, 6.$$
(6.16)

The results show that the robustness condition in (6.11) is satisfied. If additional HDVs are added to the platoon with identical weighting parameters Q_i and R_i , the transfer function, (6.15), and inherently the maximum peak response, (6.16), will not change. Thus, the proposed decentralized controller design produces a string stable control regardless of how many vehicles of identical configuration that are added to the platoon.

6.4 Simulations

In this section, we evaluate the proposed controller algorithm on the system model for an HDV platoon consisting of six vehicles. The performance is evaluated through simulation results and we also investigate the feasibility and fuel efficiency of the derived controller.

When studying the behavior of vehicles within a finite platoon, the velocity does not deviate significantly from the lead vehicles velocity trajectory. The control strategy is simply to provide an input that maintains the platoon velocity at a set relative distance. However, concern arises when a disturbance is introduced to the system. The disturbance can be modeled as a deviation in the lead vehicles velocity.

The controller for each vehicle is designed with respect to the proposed Algorithm 1. The optimal feedback gain, L_{11} , for subsystem 1 is derived through (6.17) with $A_{11} = \begin{bmatrix} 0 & -1 \\ 0 & \Theta_1 \end{bmatrix}$, $B_1 = \begin{bmatrix} 0 \\ c_{e_1} \end{bmatrix}$, $Q_1 = \begin{bmatrix} w_e & 0 \\ 0 & w_1^v \end{bmatrix}$, and $R_1 = w_1^{T_{e_1}}$. $\min_{u_1} \int_{t_0}^{\infty} \begin{bmatrix} e \\ v_1 \end{bmatrix}^T Q_1 \begin{bmatrix} e \\ v_1 \end{bmatrix} + w_1^{T_{e_1}} T_1^2 dt$ (6.17)
s. t. $\begin{bmatrix} \dot{e} \\ \dot{v}_1 \end{bmatrix} = A_{11} \begin{bmatrix} e \\ v_1 \end{bmatrix} + B_1 T_1 + \begin{bmatrix} 1 \\ 0 \end{bmatrix} w$,

The the locally optimal feedback is given by $u_1^* = -L_{11}v_1 - L_e e$, where L_e is the static feedback gain, e is the integrated error and w is the imposed disturbance. The controller for the rest of the subsystems in this case are derived iteratively in

$$(6.18) \text{ with } A_{(i-1)(i-1)} = \begin{bmatrix} \Theta_{i-1} & 0 \end{bmatrix}, A_{i(i-1)} = \begin{bmatrix} 1 & 0 \\ 0 & \delta_i \end{bmatrix}, A_{ii} = \begin{bmatrix} -1 \\ \Theta_i \end{bmatrix}, B_{i-1} = c_{e_{i-1}}$$
$$B_i = \begin{bmatrix} 0 \\ c_{e_i} \end{bmatrix}, L_{i-1} = L_{i-1}^3, \text{ and } Q_i, R_i \text{ given in } (6.8).$$
$$\min_{u_i} \int_{t_0}^{\infty} \begin{bmatrix} v_{i-1} \\ d_{(i-1)i} \\ v_i \end{bmatrix}^T Q_i \begin{bmatrix} v_{i-1} \\ d_{(i-1)i} \\ v_i \end{bmatrix} + R_i T_i^2 dt$$
s.t. (6.18)
$$\begin{bmatrix} \dot{v}_{i-1} \\ \dot{d}_{(i-1)i} \\ \dot{v}_i \end{bmatrix} = \begin{bmatrix} \Theta_{i-1} - c_{e_{i-1}} L_{i-1}^3 & 0 & 0 \\ 1 & 0 & -1 \\ 0 & \delta_i & \Theta_i \end{bmatrix} \begin{bmatrix} v_{i-1} \\ d_{(i-1)i} \\ v_i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ c_{e_i} \end{bmatrix} T_i,$$

By utilizing L_{i-1}^3 in (6.18), which is the gain corresponding to the available state of the preceding vehicle's velocity, the controller becomes independent of all other

Table 6.1: Table of the required control input (Torque) to handle the disturbances in Figure 6.2b.

i =	1	2	3	4	5	6
$ T_i _2$ [kNm]	45.72	45.49	45.43	45.37	45.32	45.26
T_i^{max} [kNm]	1.86	1.85	1.84	1.84	1.84	1.83
T_i^{min} [kNm]	-3.66	-3.66	-3.65	-3.64	-3.64	-3.63

indirectly preceding vehicles. The optimal feedback gain is obtained by solving the Riccati-equations for each subsystem as described in Algorithm 1. Hence the optimal control input is given as

$$u_i^* = -\begin{bmatrix} L_i^1 & L_i^2 & L_i^3 \end{bmatrix} \begin{bmatrix} v_{i-1} \\ d_{(i-1)i} \\ v_i \end{bmatrix}, \ i = 2, \dots, 6.$$

The modeled HDVs are described as traveling in a longitudinal direction on a flat road. The maximum engine and braking torque for a commercial HDV varies based upon vehicle configuration but can be approximated to be 2500 Nm and 60000 Nm/Axle respectively. The time gap is set to $\tau = 0.25$ s and the mass of the vehicles are set to m = 40000 kg, which is generally considered to be the standard weight of a long haulage heavy duty vehicle. All the vehicles are assumed to be travelling in the steady state velocity $v_0 = 19.44$ m/s (70 km/h) and relative distance $d_0 = \tau v_0$.

Based upon these physical constraints, we investigate the controller performance when several disturbances are imposed on a N = 6 vehicle platoon (Figure 6.2). The disturbances can be explained by the following scenario. The lead vehicle is first forced to accelerate through a step input from 70 km/h to 80 km/h due to a new road speed point. When reaching 80 km/h it suddenly has to decelerate to a lower speed of 60 km/h, because an obstruction in the form of a slower vehicle has entered the lane that has not yet reached the road speed. The obstructing vehicle increases its speed to 70 km/h and then switches lanes, enabling the platoon to resume the road speed again.

The control design handles the disturbance well and demonstrates a good tracking performance. It can be seen in Figure 6.2a that there is no overshoot in the velocity or relative distance tracking. The control input required (Figure 6.2b) to produce the tracking performance is also well within the boundaries of what is known to be physically obtainable. However, an engine cannot produce an instantaneous input torque. Therefore, a ramp input more suitable in these applications.

Table 6.1 shows the maximum, minimum, and accumulated torque energy that was required to account for the disturbances. The results show that the required control effort energy, which corresponds to the fuel consumption, decreases along the chain of vehicles. Hence, the designed controller is fuel efficient. In comparison



(a) The figure displays the velocity trajectories in the top plot and the relative distance between each HDV in the bottom plot.



(b) The figure shows the corresponding input torque for the platoon of 6 HDVs. Figure 6.2: The figure shows a platoon of 6 HDVs, where a disturbance in velocity of the lead vehicle is imposed.

with a centralized controller for an identical scenario, assuming that all states are available at all time instances, the control effort energy is up to 29 % higher for the decentralized controller. However, the decentralized control system have a 41 % lower rise time because the follower vehicle dynamics are not taken into consideration. In freight transportation the delivery time is equally important. Hence, even though a more energy efficient control can be obtained through a centralized approach, there is a trade off with the overall system performance in the considered system.

6.5 Summary

We have proposed a systematic method in this chapter to derive globally suboptimal stabilizing decentralized controllers. The proposed decentralized controller satisfies topology induced communication constraints and handles dynamically interconnected systems. It can easily be extended to more advanced communication topologies such as receiving state information from additional preceding or follower vehicles. The proposed methodology produces a simple and energy efficient suboptimal decentralized controller with good tracking performance, stability, and robustness properties. It is simple in its nature, since the optimal control input is calculated sequentially for each vehicle and is only based on information from the preceding vehicle that can be obtained at one instance in time. Thus, it is also scalable, since adding a vehicle to the end of the chain will not mandate a change in decentralized controllers within the platoon. Yet it maintains the overall system performance. A centralized control strategy might produce a lower LQR-cost, however it is not realistic to assume that an agent in the platoon would know the state of all the other agents in the formation at any given time and be able to use it to calculate the control input due to physical constraints in the information flow. There is also a trade of in performance, since the system becomes slower when considering the dynamics of follower vehicles. Furthermore, a centralized control is not suitable with respect to scalability, since the entire control must be recomputed if an additional vehicle joins the platoon. Hence, the control design methodology is practically feasible and can be implemented in real life applications.

Chapter 7

Conclusions and Future Work

DV platooning is a promising means to reduce the fuel consumption, improve safety, reduce congestion, decrease the emission of harmful exhaust gasses and aid the driver in complex driving situations. In this thesis, a system for dividing the complex problem into manageable subsystems for optimal control has been presented. Nonlinear and linear HDV platooning models have been derived. We have investigated the current fuel reduction potential of HDV platooning for a commercial ACC. It has been shown through experimental and analytical results that it is favorable with respect to the fuel consumption to operate the vehicles at a much shorter intermediate spacing than what is currently utilized by commercially available systems, without compromising safety. We have also argued why a decentralized control strategy is favorable and presented an algorithm that produces a simple and energy efficient suboptimal decentralized controller with good tracking performance, stability, scalability and robustness properties. This chapter concludes the thesis by detailing the conclusions that can be drawn from the obtained results and outlines directions for possible future work in this area.

7.1 Conclusions

The recent emergence of several platooning related projects indicate that platooning is becoming increasingly important. Even though platooning offers many benefits in traffic networks, it mostly offers comfort functionality to the passenger vehicle industry. The ground transportation industry on the other hand has a strong incentive to utilize platooning applications due to its prize sensitive market and long freight transport assignments. Hence, platooning will most likely find an initial market entry in the transportation industry due to the high demand and strong business case.

The results in Chapter 4 show that a fuel reduction of 4.7-7.7% in HDV platooning for identical vehicles can be obtained depending on the time gap setting with respect to a commercial ACC. If the lead vehicle is 10 t lighter a corresponding 3.8-7.4% fuel reduction can be obtained depending on the time gap. Similarly if the

lead vehicle is 10 t heavier a 4.3-6.9% fuel reduction can be obtained. Hence, HDV heterogeneity and order has a significant impact on the fuel reduction possibilities. Furthermore, reducing the inter spacing distance between the HDVs traveling in a platoon yields the highest fuel reduction potential. Thus, it seems most beneficial to minimize the intermediate spacing between HDVs traveling in a platoon.

The results presented in Chapter 5 show that the relative distance can be reduced significantly lower compared to what is utilized in the current commercial systems. During normal mode operation a minimum distance of 1-2m can be maintained without endangering a collision despite the worst possible behavior displayed by the preceding vehicle. The safe intermediate distance varies with braking capability and delays within the system. A stronger overall braking capability in the follower vehicle creates the possibility of reducing the relative distance further. Thus, in platooning applications the results suggest that vehicles with stronger braking capabilities should always be placed last to enable the shortest possible relative distance without endangering a collision. This could easily be achieved with wireless communication if the braking capabilities and mass are transmitted between each vehicle in the platoon. However, rearranging the HDVs on for example a highway is not always practically feasible. Hence, another approach to ensure safety and obtain a minimum relative distance is to set maximum braking constraints through wireless communication within the platoon. Wireless communication could further improve the system by enabling a reduction of the relative distance between each vehicle from the 2:nd to the N:th vehicle. Producing the maximum brake torque through the internal brake system after a request could take up to 0.4s depending on the vehicle configuration, which will be propagated downstream. However, if the first vehicle transmits that it is emergency braking to all the following vehicles within the platoon, they will be able to commence the control action almost simultaneously and thereby cancel a propagation in actuation delay.

In Chapter 6 we presented a method to derive an LQR-based suboptimal decentralized controller for HDV platooning. An interesting observation from the results can be made with respect to the system behavior due to the time varying nature of the desired intermediate distance. As a disturbance is introduced to the system in the sense of changing the velocity of the lead vehicle, the intermediate distance will initially change between the first two vehicles in the platoon. However, as the velocity increases or decreases for the lead vehicle, so will the desired intermediate spacing reference. Hence, if for example the lead vehicle accelerates, the follower vehicles will deter their control actions accordingly until the relative distance is increased and produce a smoother control input to change their own speed. Thus, a lower control effort will be mandated from the follower vehicle. Furthermore, the proposed controller can easily be extended to more advanced communication topologies such as receiving state information from additional preceding vehicles. The controller form varies based upon the available state information. Hence, a gain scheduling scheme can be acquired for each information system structure.

With the results obtained in this thesis, it is clear that a vast fuel reduction potential exists for HDV platooning. All results indicate that a maximum fuel reduction can be achieved at a short relative distance due to the air drag reduction and that a relatively short spacing can be obtained without compromising safety. The results also show that a cooperative control strategy, where the HDVs interact and consider the dynamics of their local neighbors, produces a lowered energy consumption downstream. However, safety is an issue as V2X communication cannot be guaranteed at all time instances for the currently available systems. If V2X communication is available, the intermediate spacing can be relatively close without compromising safety. However, if communication is lost the spacing should be increased. Thus, the available information structure dictates the intermediate spacing indirectly, creating a need for a graceful degradation scheme in the architecture presented in Chapter 3.

7.2 Future Work

The experimental and simulation results presented in this thesis have been conducted based upon two HDVs traveling at a close intermediate distance. Studies on the air drag reductions show that the wind reduction is reduced additionally for vehicles traveling further down the chain. Thus, aligned with one of the main objectives of this Ph.D. project, further experiments conducted with respect to the fuel reduction for several HDVs in a platoon is crucial to get a better understanding of the full real-life fuel reduction potential of HDV platooning.

The safety analysis presented in this thesis has been performed through certain simplifications. In real life scenarios the vehicles commonly travel along a varying topology. Due to the extensive mass of an HDV, the gravitational force has a significant impact on the overall braking power. Hence, the impact of a varying road incline serves as a natural direction to establish minimum intermediate safety distances for HDV platooning. Additional factors may shape the safety boundary, which is not captured by the presented model. One of the vehicles might be traveling on a wet patch or the tires might be in a worse condition, reducing the frictional force from the road. Also, nonlinearities might arise in the applied brake force due to temperature variation. Investigating these factors would require a more advanced vehicle model and is therefore a possible avenue for future work before practical evaluation.

In Chapter 6 it was shown that each HDV in the platoon could compute a LQR-based control strategy and transmit its computed gain to the follower vehicle. Robustness, in the sense of string stability, is only guaranteed for identical HDVs traveling in the platoon. Partial studies in this Ph.D. project, in (Liang et al., 2011), and the results in Chapter 5 indicate that the robustness should be maintained if the platoon is ordered with respect to a decreasing order in mass. However, more careful analytical studies could be performed to determine necessary and sufficient conditions for heterogeneous platoons such that robustness in a finite N-vehicle HDV platoon is always guaranteed.

The presented control design methodology is based on a linearized model. In

real life applications, there are many nonlinearities. The braking power becomes nonlinear due to a temperature variation in the braking hardware and the produced engine torque transferred to the wheels is a nonlinear function of the current gear. Also the air drag reduction is nonlinear with respect to the relative distance. Thus, the proposed controller should be evaluated in practice to determine the actual performance and feasibility of the controller. If the nonlinear factors are taken into account, a more fuel efficient control strategy could possibly be produced. Also, delays or losses within the communication is a common occurrence in real applications. Hence, accounting for these issues follows as a natural extension and future work within this subject.

The main drawback of the proposed controller is that it does not directly account for the physical constraints that are present in the systems. The LQR-weighting factors must be adjusted in an ad hoc manner until the constraints criteria are met and robustness must be checked. Hence, a more systematic optimal control procedure that can directly consider the system constraints when deriving a fuel optimal controller is preferable.

Nomenclature

Acronyms and Abbreviations

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
CAN	Controller Area Network
CACC	Cooperative Adaptive Cruise control
CC	Cruise Control
DHSC	Down Hill Speed Control
ECC	Economical Cruise Control
ERTICO	European Road Transport
	Telematics Implementation Co-ordination Organisation
GPS	Global Positioning System
HDV	Heavy Duty Vehicle
ITS	Intelligent Transportation Systems
\mathbf{ITF}	The International Transport Forum
OECD	Organisation for Economic Co-operation and Development
PATH	Partners for Advanced Transportation TecHnology
SARTRE	SAfe Road TRains for the Environment: EU project
UMTS	Universal Mobile Telecommunications System
VANET	Vehicular Ad hoc NETwork
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure
V2X	Vehicle to Vehicle and/or Infrastructure
WSU	Wireless Sensor Unit

Bibliography

- 802.11p. Status of project IEEE 802.11, Task Group p, Wireless Access in Vehicular Environments (WAVE) (2010). URL http://www.ieee802.org/11/Reports/ tgp_update.htm. Accessed: May 30, 2011.
- A. Alam. Optimally Fuel Efficient Speed Adaptation. Master's thesis, Royal Institute of Technology (2008).
- A. Alam, J. Andersson, and P. Sahlholm. Fastställande av accelerationsbeteende [Determination of acceleration behavior]. Swedish patent SE 533 144 C2 (filed 2008a).
- A. Alam, J. Andersson, and P. Sahlholm. Metod, system och datorprogram för automatisk hastighetsreglering av ett motorfordon [Method, system and computer program product for automated vehicle speed control]. Swedish patent SE 531 922 C2 (filed 2008b).
- A. Alam, J. Andersson, and P. Sahlholm. Determination of acceleration behaviour. World patent WO 2010 062242 (filed 2009a).
- A. Alam, A. Gattami, and K. H. Johansson. An experimental study on the fuel reduction potential of heavy duty vehicle platooning. In 13th International IEEE Conference on Intelligent Transportation Systems. Madeira, Portugal (2010).
- A. Alam, A. Gattami, and K. H. Johansson. Suboptimal decentralized controller design for chain structures: Applications to vehicle formations. In 50th IEEE Conference on Decision and Control and European Control Conference. Orlando, FL, USA (2011a). To appear.
- A. Alam, A. Gattami, K. H. Johansson, and C. J. Tomlin. Establishing safety for heavy duty vehicle platooning: A game theoretical approach. In 18th IFAC World Congress. Milan, Italy (2011b).
- A. Alam and P. Sahlholm. Metod och system för reglering av ett fordons hastighet i en kurva [Method and system for vehicle curve speed control]. Swedish patent SE 533 044 C2 (filed 2008).

- A. Alam, P. Sahlholm, and J. Andersson. Method, system and computer program product for automated vehicle speed control. World patent WO 2009 096882 (filed 2009b).
- B. Bamieh, M. R. Jovanović, P. Mitra, and S. Patterson. Effect of topological dimension on rigidity of vehicle formations: Fundamental limitations of local feedback. In 47th IEEE Conference on Decision and Control, 369 –374. Cancun, Mexico (2008).
- B. Bamieh, F. Paganini, and M. A. Dahleh. Distributed control of spatially invariant systems. *IEEE Transactions on Automatic Control*, 47(7) (2002).
- P. Barooah and J. P. Hespanha. Error amplification and disturbance propagation in vehicle strings with decentralized linear control. In 44th IEEE Conference on Decision and Control and the European Control Conference, 1350 – 1354. Seville, Spain (2005).
- M. Barradi, A. Hafid, and J. Gallardo. Establishing strict priorities in ieee 802.11p wave vehicular networks. In *IEEE Global Telecommunications Conference*, 1–6. Miami, FL, USA (2010).
- T. Basar and G. J. Olsder. Dynamic Noncooperative Game Theory. Academic Press, New York, 2nd edition (1995). ISBN: 978-0-89871-429-6.
- A. M. Bayen, S. Shanthanam, I. Mitchell, and C. J. Tomlin. A differential game formulation of alert levels in etms data for high altitude traffic. In *GNC Conference*, volume AIAA, 2003-5341. Austin, Texas (2003).
- K. Bilstrup, E. Uhlemann, and E. Strom. Scalability issues of the mac methods stdma and csma of ieee 802.11p when used in vanets. In *IEEE International Conference on Communications Workshops (ICC)*, 2010, 1–5. Capetown, South Africa (2010).
- 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*. Costa Mesa, CA, USA (2000). SAE paper 2000 01 3056.
- D. Corona and B. De Schutter. Adaptive cruise control for a smart car: A comparison benchmark for mpc-pwa control methods. *IEEE Transactions on Control Systems Technology*, 16(2): 365–372 (2008).
- R. D'Andrea. A linear matrix inequality approach to decentralized control of distributed parameter systems. In *Proceedings of the American Control Conference*, volume 3, 1350 – 1354. Philadelphia, PA, USA (1998).
- B. De Schutter, T. Bellemans, S. Logghe, J. Stada, B. De Moor, and B. Immers. Advanced traffic control on highways. *Journal A*, 40(4): 42–51 (1999).

- C. V. Driel, M. Hoedemaeker, and B. V. Arem. Impacts of a congestion assistant on driving behaviour and acceptance using a driving simulator. *Transportation Research Part F Traffic Psychology and Behaviour*, 10(2): 139–152 (2007).
- W. B. Dunbar and R. M. Murray. Receding horizon control of multi-vehicle formations: a distributed implementation. Automatica, 42: 549 – 558 (2006).
- Dynasim. User Manual Dymola 6 Additions. Dynasim AB, Research Park Ideon, SE-223 70 Lund, Sweden (2007).
- ERTICO. ITS can help improve our daily lives (2011). URL http://www.ertico. com/about-ertico-its/index.html. Accessed: May 30, 2011.
- ETSI. Intelligent Transportation Systems (2011). URL http://www.etsi.org/ website/Technologies/IntelligentTransportSystems.aspx. Accessed: August 24, 2011 - ©European Telecommunications Standards Institute 2008. Further use, modification, redistribution is strictly prohibited. ETSI standards are available form http://pda.etsi.org/pda/.
- European Commission. Communication from the Commission to the Council and the European Parliament - Keep Europe moving - Sustainable mobility for our continent (2006). URL http://ec.europa.eu/transport/transport_policy_ review/doc/2006_transport_policy_review_en.pdf. Mid-term review of the European Commission's 2001 Transport White Paper {SEC (2006) 768}.
- S. Ezell. Intelligent Transportation Systems. The Information Technology & Innovation Foundation (2010). URL http://www.itif.org/files/2010-1-27-ITS_ Leadership.pdf.
- N. Ferreira, J. Fonseca, and J. Gomes. On the adequacy of 802.11p mac protocols to support safety services in its. In *IEEE International Conference on Emerging Technologies and Factory Automation*, ETFA, 1189–1192 (2008).
- V. Gupta, B. Hassibi, and R. Murray. On the synthesis of control laws for a network of autonomous agents. In *Proceedings of the American Control Conference*, volume 6, 4927 –4932. Boston, MA, USA (2004).
- L. Guzzella and A. Sciarretta. Vehicle Propulsion Systems. Springer Berlin Heidelberg New York, 2nd edition (2007). ISBN: 978-3-540-74691-1.
- J. K. Hedrick, D. McMahon, V. Narendran, and D. Swaroop. Longitudinal vehicle controller design for ivhs systems. In *Proceedings of American Control Conference*, 3107 –3112 (1991).
- E. Hellström, J. Åslund, and L. Nielsen. Design of a well-behaved algorithm for on-board look-ahead control. In *IFAC World Congress*. Seoul, Korea (2008).

- E. Hellström, A. Fröberg, and L. Nielsen. A real-time fuel-optimal cruise controller for heavy trucks using road topography information. In SAE 2006 World Congress. Detroit, MI, USA (2006). SAE paper 2006-01-0008.
- P. Ioannou and C. Chien. Autonomous intelligent cruise control. *IEEE Transactions* on Vehicular Technology, 42(4): 657 –672 (1993).
- R. Isaacs. Differential Games. Dover Publications, Inc. (John Wiley) (1999 (1965)).
- ITF. Reducing transport greenhouse gas emissions. OECD (2010). URL www.int ernationaltransportfoum.org.
- ITF. Combating road deaths moves up on global policy agenda (2011). URL http://www.internationaltransportforum.org/Press/PDFs/2011-05-26Sa fety.pdf. Press release.
- D. Jiang and L. Delgrossi. Ieee 802.11p: Towards an international standard for wireless access in vehicular environments. In *IEEE Vehicular Technology Conference*, *VTC 2008*, 2036 –2040 (2008).
- M. R. Jovanović and B. Bamieh. On the ill-posedness of certain vehicular platoon control problems. In 43rd IEEE Conference on Decision and Control. Atlantis, Paradise Island, Bahamas (2004).
- U. Kiencke and L. Nielsen. *Automotive Control Systems*. Springer Verlag, Berlin (2003).
- H. L. Lee, V. Padmanabhan, and S. Whang. Information distortion in a supply chain: The bullwhip effect. *Management Science*, 50(12): 1875 1886 (2004).
- W. Levine and M. Athans. On the optimal error regulation of a string of moving vehicles. *IEEE Transactions on Automatic Control*, 11(3): 355 361 (1966).
- K. Liang. Linear Quadratic Control for Heavy Duty Vehicle Platooning. Master's thesis, Royal Institue of Technology, Osquldas väg 10, 100 44 Stockholm, Sweden (2011).
- K. Liang, A. Alam, and A. Gattami. The impact of heterogeneity and order in heavy duty vehicle platooning networks. In 3rd IEEE Vehicular Networking Conference. Amsterdam, Netherlands (2011). Submitted.
- J. Marshak. Elements for a theory of teams. Management Science, 1:127–137 (1955).
- D. Q. Mayne. Sequential design of linear multivariable systems. Proceedings of the Institution of Electrical Engineers, 126(6): 568 –572 (1979).
- S. Melzer and B. Kuo. A closed-form solution for the optimal error regulation of a string of moving vehicles. *IEEE Transactions on Automatic Control*, 16(1): 50 52 (1971a).

- S. M. Melzer and B. C. Kuo. Optimal regulation of systems described by a countably infinite number of objects. *Automatica*, 7: 359–366 (1971b).
- R. Middleton and J. Braslavsky. String instability in classes of linear time invariant formation control with limited communication range. *IEEE Transactions on Automatic Control*, 55(7): 1519 –1530 (2010).
- I. Mitchell. A toolbox of level set methods (version 1.1). Vancouver, BC, Canada (2007). Tech. Rep. TR-2007-11, [Online]. Available: http://www.cs.ubc.ca/mitchell/ToolboxLS/toolboxLS.pdf.
- I. Mitchell, A. M. Bayen, and C. J. Tomlin. Computing reachable sets for continuous dynamic games using level set methods. *IEEE Transactions on Automatic Control* (2002).
- S. Moon, I. Moon, and K. Yi. Design, tuning, and evaluation of a full-range adaptive cruise control system with collision avoidance. *Control Engineering Practice*, 17(4): 442 – 455 (2009).
- G. Naus, R. Vugts, J. Ploeg, R. van de Molengraft, and M. Steinbuch. Towards on-the-road implementation of cooperative adaptive cruise control. In 16th World Congress on Intelligent Transport Systems and Services, Stockholm, Sweden (2009).
- G. J. L. Naus. *Model-based control for automotive applications*. Ph.D. thesis, Eindhoven University of Technology, Eindhoven, Netherlands (2010).
- PATH. About California PATH (2010). URL http://www.path.berkeley.edu/ About/Default.htm. Accessed: June 3, 2011.
- L. Peppard. String stability of relative-motion pid vehicle control systems. IEEE Transactions on Automatic Control, 19(5): 579 – 581 (1974).
- R. Rajamani and C. Zhu. Semi-autonomous adaptive cruise control systems. In Proceedings of the American Control Conference, volume 2, 1491–1495. San Diego, CA, USA (1999).
- T. Robinson, E. Chan, and E. Coelingh. Operating platoons on public motorways: An introduction to the sartre platooning programme. In 17th World Congress on Intelligent Transport Systems. Busan, Korea (2010).
- J. Rogge and D. Aeyels. Decentralized control of vehicle platoons with interconnection possessing ring topology. 44th IEEE Conference on Decision and Control and the European Control Conference, 1491–1496 (2005).
- P. Sahlholm. Distributed Road Grade Estimation for Heavy Duty Vehicles. Ph.D. thesis, Royal Institute of Technology (KTH) (2011).

- P. Sahlholm and K. H. Johansson. Road grade estimation for look-ahead vehicle control using multiple measurement runs. *Control Engineering Practice*, 18(11): 1328 – 1341 (2010).
- T. Sandberg. Heavy Truck Modeling for Fuel Consumption, Simulations, and Measurements. Licentiate thesis LiU-TEK-LIC-2001:61, Linköpings universitet, S-581 83 Linköping, Sweden (2001).

Scania CV AB. Annual Report. Scania CV AB (2010).

- M. Schittler. State-of-the-art and emerging truck engine technologies for optimized performance, emissions and life cycle costs. In 9th Diesel Emissions Reduction Conference. Rhode Island, USA (2003).
- P. Seiler, B. Song, and J. Hedrick. Development of a collision avoidance system. In SAE 1998 World Congress. Detroit, MI, USA (1998). SAE paper 980853.
- E. Shaw and J. Hedrick. String stability analysis for heterogeneous vehicle strings. In American Control Conference, 3118 –3125. New York, USA (2007).
- S. Sheikholeslam and C. A. Desoer. Longitudinal control of a platoon of vehicles with no communication of lead vehicle information: A system level study. *IEEE Transactions on Vehicular Technology*, 42(4) (1993).
- S. E. Shladover. Potential contributions of intelligent vehicle/highway systems (ivhs) to reducing transportation's greenhouse gas production. Report TECH MEMO-91-04 (1991).
- S. S. Stanković, M. J. Stanojević, and D. D. Šiljak. Decentralized overlapping control of a platoon of vehicles. *IEEE Transactions on Control Systems Technology In Control Systems Technology*, 8(5): 816 – 832 (2000).
- S. Sudin and P. A. Cook. Two-vehicle look-ahead convoy control systems. In 59th IEEE Vehicular Technology Conference, VTC. Milan, Italy (2004).
- D. Swaroop and J. K. Hedrick. String stability of interconnected systems. *IEEE Transactions on Automatic Control*, 41(3) (1996).
- H. J. Tehrani. Study of Disturbance Models for Heavy-duty Vehicle Platooning. Master's thesis, Royal Institute of Technology (KTH) (2010).
- United Nations Population Division. World Population Prospects: The 2010 Revision. http://esa.un.org/unpd/wpp/Excel-Data/population.htm (2010). Department of Economic and Social Affairs.
- P. Varaiya. Smart cars on smart roads: Problem of control. *IEEE Transactions on Automatic Control*, 38(2) (1993).

- J. Wang and R. Rajamani. The impact of adaptive cruise control systems on highway safety and traffic flow. *Proceedings of the Institution of Mechanical Engineers* Part D: Journal of Automobile Engineering, 218, no. 2: 111–130 (2004).
- H. Wolf-Heinrich and S. R. Ahmed. Aerodynamics of Road Vehicles. Society of Automotive Engineers, Inc, Warrendale (1998).
- Y. Yamamura and Y. Seto. A study of string-stable acc using vehicle-to-vehicle communication. In SAE 2006 World Congress. Detroit, Michigan, USA (2006). SAE paper 2006-01-0348.

"It's almost as if a demon might have passed from one host to another." John Forbes Nash, Jr.
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