Energy Optimization for Platooning through Utilizing the Road Topography

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Abstract

The road haulage industry is a fundamental part of today's society. The companies of haulage stand before a challenge, as the environmental and economic sustainability demands are increasing. The automotive industry tries to meet these demands by developing intelligent systems that will decrease the fuel consumption.

The two systems, predictive controller and platooning, are two intelligent solutions that help to decrease the fuel consumption. A predictive controller uses the knowledge of the future road topography to calculate an optimal velocity profile that utilizes the energy stored in the altitude differences. Platooning describes the concept of driving several vehicles in a close formation. The vehicles are controlled autonomously in the longitudinal direction, which enables a short intermediate distance between the vehicles and a reduction of the decelerating aerodynamic drag force.

In this thesis, a predictive platoon controller has been developed that takes both the topography and the possible reduction of the aerodynamic drag force into account. Two main different platoon control strategies are evaluated. The result shows that the aerodynamic drag has a large influence of the fuel consumption and that a short intermediate distance between the vehicles will often reduce the consumption. However, the road topography has an influence on the driving profile and in some scenarios it would be beneficial to increase the intermediate distance to avoid using the vehicle's brake. The result shows that predictive platoon control enables a fuel-efficient velocity profile, though, more scenarios should be analysed to draw further conclusions about the strategy.

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John Wahnström
Gothenburg, June 2015

Contents

Nomenclature

Acronyms and Abbreviations

ACC	Adaptive Cruise Controller
BLB	Borås-Landvetter-Borås
CACC	Cooperative Adaptive Cruise Controller
CC	Cruise Control
PC	Predictive Controller
PPC	Predictive Platoon Controller
V2V	Vehicle to Vehicle

1

Introduction

The automotive industry is currently focused on development towards automated driving. Today, there are a number of different systems implemented in the vehicles to help the driver to drive in a more environmentally and economically beneficial way, and also increase the safety and comfort for the driver.

In this master thesis, a further development of the control system Adaptive Cruise Control (ACC) is utilized. The ACC system helps the driver to maintain a given speed while keeping a safe distance to the vehicle in front using information from sensors. Cooperative ACC (CACC) is a further development that utilizes the possibility to send data traffic between the vehicles, vehicle to vehicle (V2V)-communication. This exchange of data provides a faster and more accurate information on the vehicles' positions, velocities, accelerations, etc., which opens for opportunities to reduce the intermediate distances between vehicles even further. The CACC technology enables the possibility to link several vehicles together to drive in a convoy (platooning) where the vehicles are autonomously controlled in the longitudinal direction.

The size and shape of a truck gives poor aerodynamics properties and results in a significant decelerating force. By reducing the intermediate distance between the vehicles the aerodynamic drag force for the vehicles in the platoon will be changed. The rear vehicles get a reduced air drag force due to a wind shelter that is created by the lead vehicle, but also the lead vehicle benefits due to that the following vehicle is reducing the drag force that occur at the lead vehicle's rear part. Both vehicles will therefore reduce their fuel consumption by forming a platoon. In addition to forming a platoon, vehicles can also reduce their fuel consumption by considering the future topography and utilize the energy stored in altitude differences. These two systems will in some cases contradict each other and for an optimal fuel minimization it would therefore be of interest to construct a controller that takes both strategies into consideration.

1.1 Background

Haulage transport in the EU-28 states was in 2014 estimated to 3768 billion tonne-kilometres and of these the road freight transport stands for 44.9%. The transport sector in the EU stands for about one third of the total energy consumption [5]. The fuel cost is estimated to be between 25-35% of the total operating costs for a haulage firm [12]. A small reduction of the fuel consumption will have a great impact both on the single vehicle and on the whole transport sector. Previously, focus of improvements has been on the vehicle's engine and the powertrain to increase its efficiency and decrease the fuel consumption. However, today the automotive industry has also added focus on development of different intelligent controllers in order to save fuel.

1.2 Related work

The ACC system is a well-proven system that has been used in the automotive industry for a long period. In the recent years the improved version CACC has been under development and most of the companies in the automotive industry are doing some research in the area. AB Volvo has for example been a part of the European Commission funded project SATRE (Safe Road Trains for the Environment) which has successfully managed to form multiple vehicles in a platoon unit where the vehicles in the rear are autonomously controlled by the first vehicle [11]. In order to utilize the energy stored in the altitude differences, Volvo has developed its own product, I-See, which helps the vehicles to save fuel by utilizing the topographic information [6].

There is a wide cooperation between the automotive industry and the academic world. Kemppaninen [7] and Kreuzen [8] are discussing the V2V communication and have chosen to investigate the advantage of using a model predictive controller (MPC) when trying to construct a platooning strategy. However, they have not taken into account the influence from the topography in their problem formulations. Kemppainen briefly discusses two different approaches for platoon strategy control, one centralized approach and one distributed approach. Liang [9] has investigated the coordination of platooning, if a vehicle should split or maintain in the platoon structure, from a fuel saving aspect. Alam [1] and Bühler [3] take into account both the air drag reduction in platooning and the topography and show that fuel reduction is possible by forming a platoon structure for heavy vehicles. However, more drive cycles need to be evaluated in order to confirm their result. Bühler is briefly discussing that an optimal solution for the platoon strategy may be too computationally demanding and that simplifications must be made in order for the strategy to be implementable in the vehicles.

1.3 Problem formulation

The aim of the thesis is to propose a control strategy to handle energy optimization for the CACC with respect to both the topography and the air drag. Different architectures of platoon controllers are evaluated but focus is on a predecessor knowledge control strategy, where information is shared stepwise backwards within the platoon. A comparison between this limited information sharing strategy and a strategy that has full knowledge about the vehicles' dynamics is discussed and evaluated by results from another close collaborative thesis project. In a full knowledge strategy the problem may be too computationally demanding as the size of the platoon increases, it is therefore of interest to evaluate how close to an optimal solution a limited strategy can come.

In the project the assumption is made that the vehicles within the platoon are conventional homogeneous vehicles. The energy optimization can be seen as an upper layer control system that does not need to consider the dynamics that occur at the lower layer dynamics, gearshift etc. The controller is adapted to operate in a typical highway scenario and interference such as surrounding traffic and traffic lights are not taken into account.

1.4 Convex optimization

Convex optimization is a subclass in the mathematical optimization field. In recent years, due to increased computer power and development of algorithms in the field, increased opportunities for solving a convex optimization problem has come up. Convex optimization solves a problem in a reliable and efficient way. The general form of convex optimization is defined as

$$\begin{aligned} &\text{minimize} \;\; f_0(x) \\ &\text{subject to} \; f_i(x) \leq b_i \quad 1 \leq i \leq m \end{aligned}$$

where the functions f_0 ... f_m are convex [2].

The advantage of keeping the problem formulation on a convex form, is that a local minimum also is a global minimum. This makes it possible to create solution methods that solve the problem in numerically efficient ways.

1.5 Outline

A model for a single vehicle in motion is derived in Chapter 2 and some simplifications of the model are discussed. In Chapter 3, how a fuel-efficient velocity profile should be like is discussed. The different choices of the architecture of the platoon system and the necessary information that needs to be shared are addressed. Finally, the choice of platoon cases and drive cycles that are used to evaluate the result is presented. In Chapter 4, the fuel-efficient velocity profile formulation for a single vehicle is implemented and analysed. The implementation of the different platoon strategies is presented in Chapter 5 and the velocity profiles for the vehicles are visualised. In Chapter 6, the energy losses for the different platoon strategies are presented. A deeper study of a two-vehicle platoon using a predecessor knowledge predictive platoon controller is presented in Chapter 7. In the two final chapters, Chapter 8 and Chapter 9, the conclusions of the project are stated and future improvements are discussed.

2

System model

In order to do an energy optimization of a platoon, a model of a single vehicle needs to be described. In the first part of this chapter a description of a simplified powertrain of a vehicle is stated. The second part contains a description of the external forces that affect a vehicle in motion and finally in the last paragraph, a model describing the motion of the vehicle is obtained. The values of the parameters used in this thesis are given in Appendix A.

2.1 Powertrain

The powertrain or the driveline of the vehicle describes how the force from the engine is transported through various components to the vehicle wheels where the final motion of the vehicle is generated, see Figure 2.1. A simplified powertrain is described, the same model is defined and used in [7],[1].

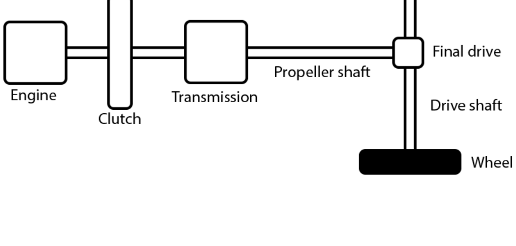


Figure 2.1: Simplified model of the powertrain

Engine The powertrain begins with the engine, where the torque is produced through fuel combustion. Newton's second law gives the motion

$$J_e\dot{\omega}_e = T_e - T_c \tag{2.1}$$

where J_e is the inertia of the engine, ω_e is the angular velocity of the engine, T_c is the torque from the clutch and T_e is the driving torque from the engine. The driving torque depends both on the angular velocity of the engine and on the amount of fuel input

$$T_e(\omega,\gamma) = a\gamma + b\omega_e + c \tag{2.2}$$

where γ is the fuel input and a, b and c are constants.

The fuel injection depends mainly on the torque and, hence, the angular velocity's influence can be neglected [3]. With this simplification, equation (2.2) is modified and an expression for the fuel consumption can be obtained

$$\gamma = c_1 T_e + c_2 \tag{2.3}$$

where c_1 and c_2 are constants. The constants c_1 and c_2 are empirically calculated with the assumption that that angular velocity is 1200rpm. A comparison with other surrounding angular velocities shows quite close values of c_1 and c_2.

Clutch The clutch consists of two discs that connect the produced engine force with the transmission. Its purpose is to decouple the engine from the powertrain to enable gearshifts in the transmission part. In this thesis a simplified engine model with no gearshifts is considered. The connection is assumed to be stiff and the input torque, T_e and the angular velocity, ω_e remain unchanged when going forward to the transmission.

Transmission The transmission consists of a set of gears that converts the torque. The conversion will depend on the gear's conversion ratio, i_c, and its efficiency constant, η_c. In this work, the gearshifts dynamics have not been modelled. It is therefore assumed that the gears have the same conversion ratio and no losses occur. The transmission part can be described as

$$T_t = i_c\eta_c T_e \tag{2.4}$$

$$i_c\omega_t = \omega_e \tag{2.5}$$

Propeller Shaft The propeller shaft is assumed to be stiff and therefore the torque from the transmission, T_t and the angular velocity, ω_t remain unchanged in this part.

Final Drive The final drive is similar to the transmission and is described with a conversion ratio, i_f, and an efficiency constant, η_f. It is expressed as

$$T_d = i_f \eta_f T_t \tag{2.6}$$
$$i_f \omega_d = \omega_t \tag{2.7}$$

where T_d is the torque output from the final drive and ω_d is the angular velocity.

Drive Shafts The drive shafts connect the final drive with the wheels. They are assumed to be stiff and the torque and angular velocity remain the same

$$T_w = T_d \tag{2.8}$$
$$\omega_w = \omega_d \tag{2.9}$$

where T_w is the torque of the wheels and ω_d the angular velocity of the wheels.

Wheels The final part of the powertrain is the wheels and under the assumption that no slip occurs, the equation of motion can be described as

$$J_w \dot{\omega}_w = T_w - r_w F_w \tag{2.10}$$
$$v = r_w \omega_w = \frac{r_w \omega_e}{i_t i_f} \tag{2.11}$$

where J_w is the inertia of the wheels, r_w is the radius of the wheel, v is velocity of the vehicle and F_w is the resulting force in the tire-road contact.

From Equations (2.1)-(2.11) a final expression of the force from the powertrain can described as

$$F_w = \frac{i_f i_c \eta_f \eta_c}{r_w} T_e - \frac{J_w + i_f^2 i_c^2 \eta_f \eta_c J_c}{r_w^2} \dot{v} = F_{\text{engine}} - F_{\text{inertia}} \tag{2.12}$$

where F_{engine} is the produced force and F_{inertia} is the inertia in the system.

2.2 External forces

The external forces that influence a vehicle in motion can be divided into three main forces; aerodynamic force, rolling resistance force and gravitational force. The forces can be seen in Figure 2.2 and are explained below.

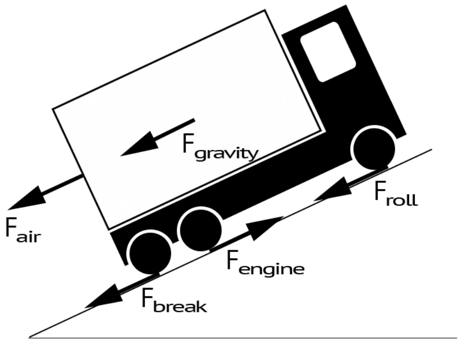


Figure 2.2: The forces that affect a vehicle in motion

Aerodynamic Force

The air pressure in the front of the vehicle creates an air drag force. By keeping a close distance to the predecessor vehicle the aerodynamic force can be reduced for both vehicles. By assuming that the velocity of the wind is negligible compared to velocities of the vehicles, the aerodynamics force can be described as in Formula (2.13).

$$F_{\text{air}}(v,d) = \frac{1}{2}c_D(d_b,d_p)A\rho v^2 \tag{2.13}$$

where A is the front area of truck, ρ is the air density, v is the velocity of the vehicle and $c_D(d_b,d_p)$ is an air drag coefficient that depends on the intermediate distance to both the predecessor vehicle, d_p and to the vehicle behind, d_b, see Equation (2.14). The reduction of the air drag also depends on the number of vehicles in the platoon and the order. The air drag coefficient has been empirical measured at Scania [7] and a first order approximation of this empirical data is shown in Equation (2.16). The function $g(d_b)$ describes the reduced aerodynamic drag created by the vehicle behind and $f_i(d_p)$ describes the reduced aerodynamic drag created by the predecessors' vehicles. The index, i, indicates the vehicle's position in the platoon.

$$c_D(d_b,d_p) = c_d(1 - \frac{g(d_b)}{100} - \frac{f_i(d_p)}{100}) \tag{2.14}$$

$$\begin{aligned} g(d_b) &= -0.94d_b + 13 & 0 \le d_b \le 14 \\ f_2(d_p) &= -0.45d_p + 43 & 0 \le d_p \le 95 \\ f_3(d_p) &= -0.48d_p + 52 & 0 \le d_p \le 110 \\ f_i(d_p) &= f_3(d_p) & i \ge 4 \end{aligned} \tag{2.16}$$

Rolling Resistance Force

The force generated from the friction between the wheels and the road can be estimated as

$$F_{\text{roll}}(\alpha) = c_r mg\cos(\alpha) \tag{2.17}$$

where c_r is the roll coefficient, α is the angle of the slope and g is the gravity constant.

Gravitational Force

The gravitational force is given by

$$F_{\text{gravity}}(\alpha) = mg\sin(\alpha) \tag{2.18}$$

where m denotes the mass of the vehicle, g is the gravity constant and α is the angle of the slope.

2.3 Equations of motion

Newton's second law of motion, together with the Equations (2.12),(2.13), (2.17) and (2.18) give the total motion of the vehicle.

$$m_a\frac{dv}{dt} = F_{\text{engine}} - F_{\text{brake}} - F_{\text{air}}(v, d_b, d_p) - F_{\text{roll}}(\alpha) - F_{\text{gravity}}(\alpha) \tag{2.19}$$

where m_a is the total mass of acceleration defined as

$$m_a = m + \frac{J_w + i_f^2 i_c^2 \eta_f \eta_c J_c}{r_w^2} \tag{2.20}$$

Spatial domain

Equation (2.19) is in the time domain. The topography information will be given in the spatial domain and it would therefore be interesting to discretize the vehicle movement in distance. With the help of the mathematical relationship in Equation (2.21) and the expression for the kinetic energy (2.22), an expression of the kinetic energy of the vehicle, E_{kin}, in the spatial domain can be derived, see Equation (2.23)

$$\frac{dv}{dt} = \frac{ds}{dt}\frac{dv}{ds} = v(s)\frac{dv}{ds} = \frac{1}{2}\frac{d}{ds}v^2 \tag{2.21}$$

$$E_{\text{kin}} = \frac{m_a v^2}{2} \tag{2.22}$$

$$\frac{d}{ds}E_{\text{kin}} = F_{\text{engine}} - F_{\text{brake}} - F_{\text{air}}(v, d_b, d_p) - F_{\text{roll}}(\alpha) - F_{\text{gravity}}(\alpha) \tag{2.23}$$

The time, t_s, it takes to travel each sample distance can be expressed as a function of the kinetic energy, see Equation (2.24).

$$t_s = \frac{\Delta s}{\sqrt{2E_{\text{kin}}/m_a}} \tag{2.24}$$

Discretization

The discretization of Equation (2.23) in distance sample, Δs, (assuming α and T_e are constant during each sample) is seen in Equation (2.26). Note that the part from the aerodynamic force is expressed in terms of kinetic energy.

$$E_{\text{kin}}(k+1) = E_{\text{kin}}(k) + \\ [\frac{i_f i_c \eta_f \eta_c}{r_w} T_e(k) - F_{\text{brake}} - \frac{c_D(d_b, d_p) A \rho E_{\text{kin}}(k)}{m_a} - mgc_r \cos(\alpha(k)) - mg \sin(\alpha(k))]\Delta s \tag{2.26}$$

In the same way a discretization of Equation (2.24) sampled in distance is seen in Equation (2.27).

$$t_{\text{s}}(k) = \frac{\Delta s}{\sqrt{2E_{\text{kin}}(k)/m_a}} \tag{2.27}$$

3

Architecture model

In order to build up a control strategy for the system, it needs to be discussed how to address the problem and what different possible control strategies that exist. Initially in this chapter an intuitive discussion over which variables that can be controlled and what a suitable velocity profile should look like is done. The chapter also addresses what kind of information that needs to be shared between the vehicles and the two main approaches to control the behaviour of a platoon are presented. The two last sections discuss the different platoon cases of interest and what drive cycles that are used to evaluate the controllers.

3.1 Intuitive reasoning

A fuel-efficient velocity profile can be obtained by minimizing the energy losses in the system. The equation of motion, shown in Equation (2.19), shows that the retarding forces on a vehicle in motion are F_{brake}, $F_{\text{air}}(v,d)$, $F_{\text{roll}}(\alpha)$ and $F_{\text{gravity}}(\alpha)$. The rolling resistance force and the gravitational force are both influenced by external conditions and are therefore not possible to control. The two remaining forces, the aerodynamic drag force and the brake force, are possible to control and for a fuel-efficient velocity profile a minimization of energy losses from these two forces should be made.

The aerodynamic drag force, Equation (2.13), is proportional to the square of velocity and depends also on the distance to the surrounding vehicles. To minimize the energy loss from the aerodynamic part, the velocity should be maintained constant and the intermediate distance between the vehicles should be kept as small as possible. The usage of the brake can be seen as a direct energy loss and should be avoided. In a flat road profile, it is possible to follow these constraints. However, trucks are heavy vehicles and a typical road profile will contains road sections where the slopes make it impossible for a truck's engine to provide enough power to maintain a constant velocity and this will change the conditions for an optimal solution.

By today's technology, a vehicle has access to both its own position and information about the upcoming topography. A controller should therefore be able to construct a fuel efficient velocity profile that allows the vehicle to increase its speed before an uphill road segment and the vice versa before a downhill road segment. If a vehicle also has knowledge about its predecessor's future velocity profile, a fuel optimal solution that considers both the potential aerodynamic reduction and the brake usage can be obtained.

3.2 Shared information

The development of ACC technology has improved fuel-efficient driving by helping the drivers to drive in close distance to its predecessor and keep an even velocity. On a flat road, the ACC technology acts as a platooning controller and allows the drivers to drive in a fuel-efficient way as mentioned in previous sections. A typical road profile consists of hills and in this part the ACC technology is not enough for fuel-efficient drive. A heavy truck will not be able to maintain its speed during a steep uphill, which leads to that the trucks in the rear platoon start to decelerate even before the uphill in order to keep the intermediate distance. In a steep downhill, the vehicles in the rear platoon need to use the brakes to avoid driving to close.

The CACC technology opens up opportunities to share more information between the vehicles in the platoon. This technique is essential for the development of potential platoon strategies. The possibility to link several vehicles together, share information about future velocities and control the vehicles simultaneously open up opportunities. The intermediate distance can be decrease but also increase depending on what is most fuel-efficient.

What kind of information and the level of accuracy of the information that needs to be shared, differ depending on which possible platoon strategy that is used. However, at least some information about the vehicles future velocity profiles needs to be shared in order to calculate an optimal velocity trajectory with limited use of the brakes.

3.3 A full knowledge control strategy

In a full knowledge control strategy, it is assumed that all information about the participants' vehicles is shared between the vehicles. Based on the vehicles' limitations in the powertrain, the vehicle's mass etc. an optimal solution can be obtained. The algorithm could be implemented in a distributed way such as each vehicle has access to same problem formulation and receive its velocity trajectory by solving the optimization problem. It could also be assumed that a holistic platoon coordinator exists that solves the optimization for all vehicles and returns velocity trajectories for each vehicle to follow. In this thesis, the later alternative is implemented, see Figure 3.1.

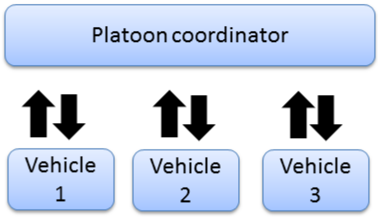


Figure 3.1: A schematic view of the full knowledge strategy

A strategy with full knowledge will be able to construct a fuel-efficient solution that is optimal for the whole platoon. The method will be able to take into account heterogeneous vehicles with different drivabilities. There are some drawbacks with this method. First, the computational complexity might become a problem, due to that the amount of shared information increases as the size of the platoon increases. The solution must be implementable and solvable in the trucks' own computer systems. Second, a platoon will consist of trucks from different manufacturers and there might be a limit on the information that the manufacturers are willing to share between themselves.

3.4 A predecessor knowledge control strategy

The rise of the computational complexity in the full knowledge strategy might become a problem. It would therefore be of interest to evaluate a control strategy that might not give the optimal solution but still a very fuel-efficient solution. In this predecessor knowledge strategy it is assumed that all vehicles only have knowledge about their own dynamics and access to its predecessor's velocity profile. The schematic view of the strategy is shown in Figure 3.2.

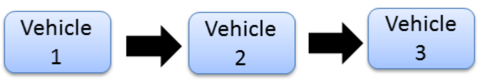


Figure 3.2: A schematic view of the predecessor knowledge strategy

The first vehicle in the platoon will base its velocity profile on the topography information and the following vehicles will optimize their velocity profiles based on the topography information and on its predecessor's future velocity profile. Each vehicle solves an optimization problem that minimizes its fuel consumption. This solution method will not consider what is optimal for the whole platoon, which might be a drawback. On the other hand, the computational complexity of the problem will not rise as the size of the platoon increases. It would therefore be of interest, to see how close a limited information sharing strategy would come to the optimal solution.

3.5 Platoon cases

In this work, a platoon containing four vehicles has been chosen. Three different predictive platoon controllers (PPC) have been implemented and a comparison between them has been done to evaluate advantages and disadvantages. The three different platoon cases that have been implemented are

A simple knowledge PPC The first vehicle solves an optimization problem to minimize the fuel consumption based on the information in the future topography. The following three vehicles have knowledge about their predecessors' future velocity profiles and calculate a velocity profile that keeps the constant predetermined intermediate distance.

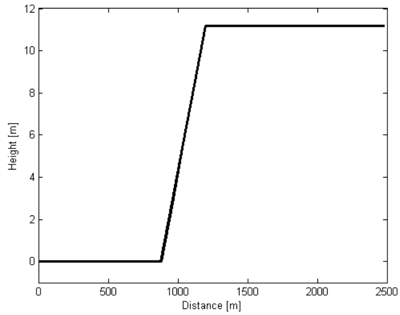
A predecessor knowledge PPC All vehicles have access to their own dynamics, the future topography and its predecessor velocity profile. From this information an optimal velocity profile for the ego vehicle is derived to minimize the fuel consumption. The predetermined intermediate distance can be varied in order to construct a more fuel-efficient drive.

A full knowledge PPC A holistic platoon coordinator that is assumed to have knowledge about all the participating vehicles and their limitations. With this information and the knowledge about the upcoming topography, optimal velocity profiles are constructed and given to all vehicles to follow. The predetermined intermediate distance can be varied in order to construct a more fuel-efficient drive.

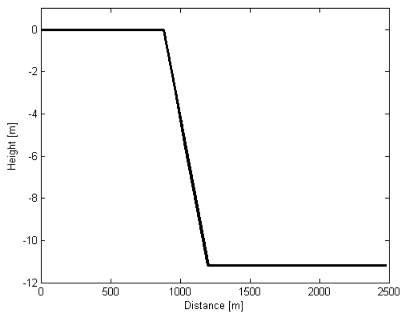
In additional to these three platoon cases with four vehicles, a deeper focus will be on evaluation of the predecessor knowledge PPC on a two-vehicle platoon.

3.6 Road profile

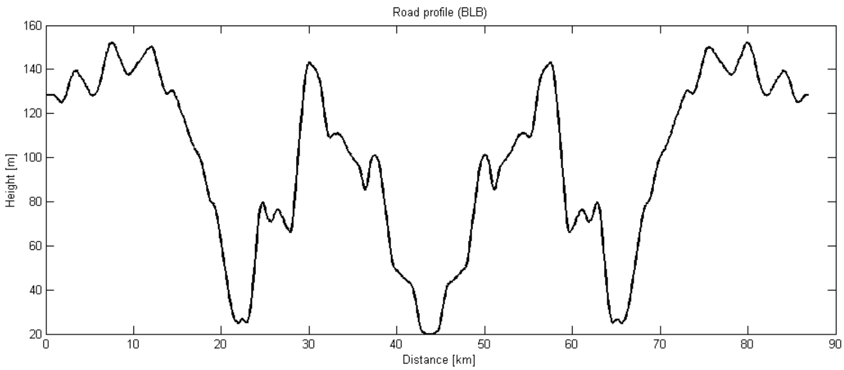
It can be assumed that a road contains smaller road segments with constant slopes. Two basic road segments with a constant slope are constructed to analyse the behaviour of the different platoon controllers, see Figure 3.3. The road slopes are chosen to be steep enough to force the controller to take action. To get a more representative evaluation of the fuel consumption a longer drive cycle is used, for evaluation of the predecessor knowledge PPC of a two-vehicle platoon. The drive cycle, BLB, has been measured between Borås and Landvetter (back and forth) by AB Volvo and the road profile can be assumed to represent a swedish highway route, see Figure 3.3.



(a) Case 1



(b) Case 2



(c) Case 3

Figure 3.3: Case 1 and case 2 show the two basic road profiles that are used in the thesis to evaluate the drive pattern for the different platoon controller. Both slopes have a gradient of 2 degrees. Case 3 shows a longer drive cycle measured back and forth from Borås to Landvetter.

4

Predictive Control for a single vehicle

A vehicle that has knowledge about the upcoming topography and is able to utilize the information to drive in an intelligent way by transforming potential energy into kinetic energy will result in a fuel-efficient drive. In this chapter a predictive controller (PC) that drive according to this pattern is implemented and discussed.

The model over the motion of a vehicle has been derived in Chapter 2 and has been implemented in the simulation environment Simulink. Simulink is block-programming simulation environment provided by MATLAB [10]. The problem formulation has been formulated in a convex form, due to advantage stated in Section 1.4. The convex optimization problem is solved using the additional open source MATLAB package CVX [4] that has been incorporated as an embedded MATLAB function in Simulink.

4.1 Optimal control

The optimization problem should minimize the fuel consumption by constructing a velocity profile that considers the information in the upcoming topography. To keep the problem formulation on a convex form, some modifications need to be done.

The aerodynamic force for a single vehicle, see Section 2.2, does not need to consider the potential reduction from surrounding vehicles. However, due to the quadratic term of the velocity in equation (2.13) the formulation is not on convex form. The expression of the motion of a vehicle is sampled in the spatial domain and is expressed in kinetic energy E_{kin}. By these two modifications and the knowledge that the aerodynamic force can be expressed in E_{kin} an expression on a vehicle in motion, see Equation (2.26), on convex form is given. Since the gravitational force and the roll resistance force are predetermined by the topography, the optimization variables will be the engine torque and the brake force for creating an optimal velocity profile.

To describe a system in a correct way some additional constraints need to be added to the model. The optimization for a single vehicle, based on the topography information is formulated as

$$
\begin{aligned}
&\text{minimize} \quad T_{\mathrm{e}} && \text{(4.1a)}\\
&\text{subject to}\\
&\quad \text{for k = 1 to Hp}\\
&\qquad E_{\mathrm{kin}}(k+1) = E_{\mathrm{kin}}(k) + (F_{\mathrm{engine}} - F_{\mathrm{brake}} - F_{\mathrm{airdrag}}(v,d) -\\
&\qquad\qquad F_{\mathrm{roll}}(\alpha) - F_{\mathrm{gravity}}(\alpha))\Delta s && \text{(4.1b)}\\
&\qquad t_{\mathrm{tot}}(k+1) = t_{\mathrm{tot}}(k) + \frac{\Delta s}{\sqrt{2E_{\mathrm{kin}}(k)/m_a}} && \text{(4.1c)}\\
&\quad \text{end}\\
&\quad E_{\mathrm{kin}}(0) = E_{\mathrm{kin}}^{0} && \text{(4.1d)}\\
&\quad E_{\mathrm{kin}}(\mathrm{H}_p) = E_{\mathrm{kin}}^{\mathrm{ref}} && \text{(4.1e)}\\
&\quad E_{\mathrm{kin}} \in [E_{\mathrm{kin}}^{\mathrm{min}} \quad E_{\mathrm{kin}}^{\mathrm{max}}] && \text{(4.1f)}\\
&\quad T_{\mathrm{e}} \in [T_{\mathrm{min}} \quad T_{\mathrm{max}}] && \text{(4.1g)}\\
&\quad F_{\mathrm{brake}} \in [0 \quad F_{\mathrm{brake}}^{\mathrm{max}}] && \text{(4.1h)}\\
&\quad t_{\mathrm{tot}}(H_p) \leq \frac{\mathrm{H}_p\Delta s}{v_{ref}} && \text{(4.1i)}
\end{aligned}
$$

where H_p is the length of the prediction horizon and T_e is the torque of the engine which can be directly translated to the fuel consumption using Equation (2.3). The definition of the forces used in (4.1b) are described in Equation (2.26). The constraints (4.1c), (4.1i) translate the time each sample in distance takes and set a constraint on the total travel time for the platoon over the prediction horizon, to control that the average velocity is kept. In (4.1d) and (4.1e) the initial and final conditions for the velocity are given. (4.1f) helps to keep the vehicle within a given lower and upper speed limit. (4.1g) and (4.1h) bound the optimization variables. T_{min} is the decelerating torque produced when no fuel is input in the model, see Equation (2.3). T_{max} is upper limit of the maximum produced torque from the engine. $F_{\mathrm{brake}}^{\mathrm{max}}$ is an upper limit of the produced brake force.

4.2 Optimal solution

The optimization problem for a single vehicle that only considers the topography when calculating the optimal velocity profile is shown in Figure 4.1 (road profile 1) and Figure 4.2 (road profile 2). In both cases the average velocity was set to 75km/h and the allowed minimum and maximum velocity were 70km/h respective 80km/h. The prediction horizon was set over the whole drive cycle (2480m) and the sample distance chosen to be every 80m. Both figures show that the constraints that were given in the problem formulation are followed.

In Figure 4.1 the engine cannot provide enough power to maintain the velocity and start to decelerate during the uphill segment. To compensate for this behaviour, the vehicle starts to accelerate before the uphill which results in a smoother velocity profile. Since the decelerated aerodynamic force depends on the square of the velocity, deviation from the average velocity should be kept small and this drive pattern is therefore beneficial. The vehicle hits its maximum speed at the beginning of the uphill segment and its minimum speed at the end of uphill. The vehicle does not need to utilize the brake because it stays within the specified speed limit.

In Figure 4.2 the vehicle starts to decelerate rather early from the downhill because it wants to prevent hitting the upper speed limit, which will results in usage of the brakes. Before the start of the downhill, the vehicle hits the minimum speed limit and the vehicle then starts to accelerate during the downhill segment and before the hill ends the vehicle hits the maximum allowed speed limit which forces the vehicle to utilize the brake. The usage of the brake results in energy losses, however, an upper speed limit is an external constraint that needs to be followed.

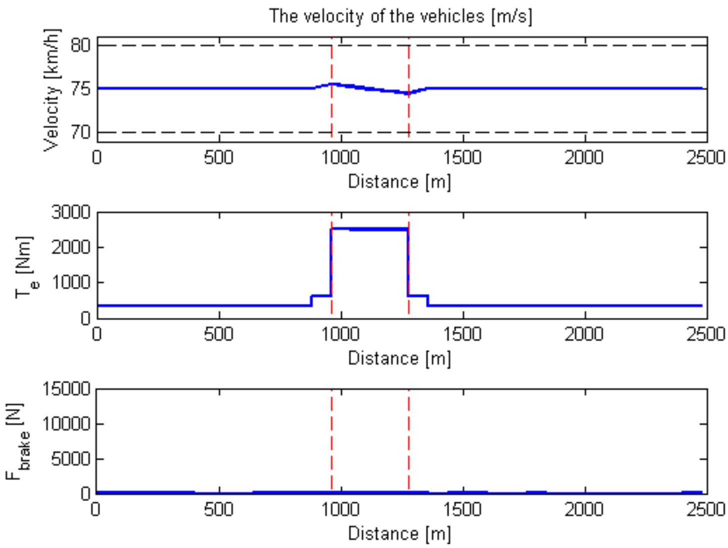


Figure 4.1: The figure shows the behaviour of a vehicle when driving on an uphill road segment (case 1). In the upper graph the velocity trajectory (blue line) is shown. The red dashed line shows where the hill starts and ends and the dashed black line shows the allowed velocity range. The two lower graphs show the torque from the engine and the brake force.

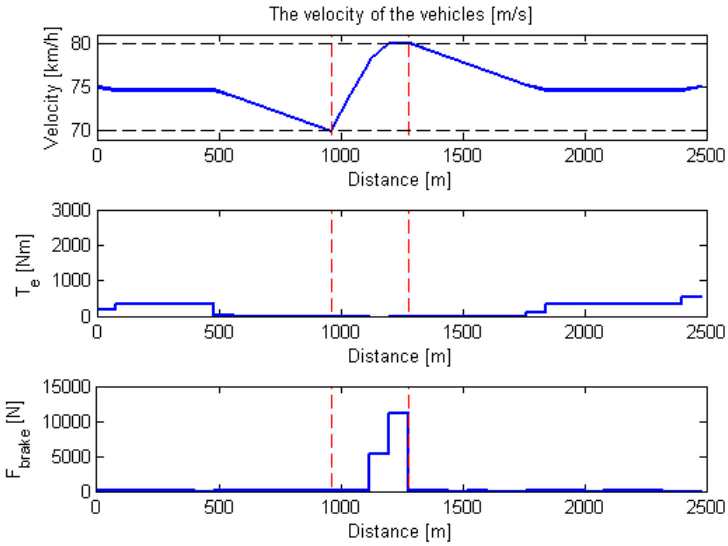


Figure 4.2: The figure shows the behaviour of a vehicle when driving on a downhill road segment (case 2). In the upper graph the velocity trajectory (blue line) is shown. The red dashed line shows where the hill starts and ends and the dashed black line shows the allowed velocity range. The two lower graphs show the torque from the engine and the brake force.

5

Platoon control

To construct a fuel-efficient platoon controller both the topography information and the potential reduction of the aerodynamic resistance need to be considered. In Chapter 4, a fuel-efficient algorithm for a single vehicle was presented. In this chapter, an extension of the optimization formulation, given in the previous chapter is done in order to also be valid for platoon cases. The three different platoon strategies that were mentioned in Chapter 3 are implemented and the result is discussed.

5.1 Optimal control

In a platoon case, the intermediate distance between the vehicles needs to be added in the problem formulation and a constraint that prevents the vehicles from driving too close needs to be added. The distance to the nearest surrounding vehicles also needs to be known to approximate the reduction of the aerodynamic force as correct as possible. Therefore, a relation between time and distance is needed that keeps the problem formulation on convex form. A linear affine approximation of time as a function of the velocity squared is derived. The approximated time, t_{approx} that it takes to traverse a sample distance can then be expressed in terms of E_{kin}. The time it takes to traverse a sample distance, t_s, is expressed as

$$t_s \approx t_{\text{approx}}(k) = a_0 + a_1 \frac{2E_{\text{kin}}(k)}{m_a} \tag{5.1}$$

where the constants a_0 and a_1 are obtained by solving

$$\text{minimize} \quad \left\| t_{\text{true}} - (a_0 + a_1 v^2) \right\| \tag{5.2}$$

where $t_{true}=\frac{\Delta s}{v}$ is the true time it takes to travel a sample distance Δs with the velocity, within the range of selectable velocities, v. In order for this approximation to work well a balance on which speed range to be selected must be done. In this thesis, a narrow range of ± 1km from the reference velocity, v_{ref}, was chosen. The assumption is done that the vehicles' velocities will not vary too much from the given v_{ref} and therefore the approximation will work well.

A relation to estimate the distance from the ego vehicle to the predecessor vehicle, $d_p(k)$ can be approximated as

$$\begin{aligned} d_p(k) &= (t_{\text{s}}^p(k) - t_{\text{s}}^e(k))v^p(k) \\ &= (t_{\text{s}}^p(k) - t_{\text{s}}^e(k))\sqrt{\frac{2E_{\text{kin}}^p(k)}{m_a}} \end{aligned} \tag{5.3}$$

where $t_s^p(k)$ and $t_s^e(k)$ is the current sample k for the predecessor and the ego vehicle. The kinetic energy, $E_{kin}^p(k)$, is used to calculate the velocity of the predecessor vehicle, $v^p(k)$.

The aerodynamic drag force, see Equation (2.13), is non-convex since it depends both on the kinetic energy, E_{kin}, and the intermediate distance, d. To be able to implement the aerodynamic drag, a first-order Taylor expansion is done around $E_{\text{kin}}^{\text{ref}}$ and d_{ref}.

The safe constraint that needs to be added to the optimization problem, to keep the intermediate distance between the vehicles sufficient is added as

$$(t_{\text{s}}^p(k) - t_{\text{s}}^e(k)) \leq \frac{d_{\text{ref}}}{v_{\text{ref}}} \tag{5.4}$$

where $\frac{d_{\text{ref}}}{v_{\text{ref}}}$ is a predetermined time interval.

Equation (4.1i) is only considering the average velocity over the prediction horizon. In order to keep the correct average velocity over a longer trip the equation needs to be modified as

$$t_{\text{travel}} + \sum_{H_p} t_s(k) \leq \frac{d_{\text{travel}}}{v_{\text{ref}}} + \frac{\text{H}_p \Delta s}{v_{\text{ref}}} \tag{5.5}$$

where t_{travel} and d_{travel} are stored in memory. This additional condition helps to keep the correct average velocity over the whole drive route and not only over the prediction horizon. For a longer drive route, this is a necessary condition to keep the travel time similar between the different controllers to enable a fair comparison.

A simple knowledge PPC

The simplest platoon strategy would be to let the first vehicle calculate a velocity profile based on the topography information in same way as is described in Chapter 4. The vehicles on the positions number 2, 3 and 4 in the platoon have knowledge about their predecessor velocity profile and keep the constant predetermined intermediate distance. This system can be considered as a simple form of the CACC technology where the V2V-communication enables all the vehicles to simultaneous make changes in their velocity profiles.

A predecessor knowledge PPC

The formulation of the optimization problem differs depending of the vehicle's position within the platoon. The first vehicle is seen as a special case, and solves a problem based on the topography information as is seen in Chapter 4. The following vehicles in the platoon solve an optimization problem based on both its predecessor's velocity profile and on the upcoming topography information. The vehicles on the positions 2, 3 and 4 have a predetermined distance constraint to their predecessor, see Equation (5.4). The information is sent stepwise backwards. Since no information is sent forward, the vehicles cannot influence the velocity profiles of the vehicle in the front of the platoon. The predecessor vehicle also assumes that the intermediate distance to the vehicle behind is the predetermined $\frac{d_{\text{ref}}}{v_{\text{ref}}}$ in order to calculate the aerodynamic model as correct as possible.

A full knowledge PPC

For a full knowledge PPC, the information about all vehicles is known to the coordinator. The overall coordinator solves the optimization problem and returns velocity profiles for all the vehicles to follow. The difference from the predecessor knowledge PPC is that the coordinator is able to change velocity profile for the predecessors' since information can be sent forward within the platoon. The coordinator solves an optimization problem that is most fuel-efficient for the whole platoon. The same constraints that are added in the predecessor knowledge controller are also added in the full knowledge controller.

5.2 Optimal solution

A simple knowledge PPC

The velocity profiles are the same for all vehicles and the intermediate distance is kept constant. The velocity profiles are the same as for the single vehicle case, see Figure 4.1 (road profile 1) and Figure 4.2 (road profile 2).

A predecessor knowledge PPC

The velocity profiles and the intermediate vehicle distance from the predecessor knowledge PPC can been seen in Figure 5.1 (road profile 1) and in Figure 5.2 (road profile 2).

In Figure 5.1 the velocities for the four vehicles are driving in an identical behaviour. Each vehicle has the same velocity profile as the PC for a single vehicle, see Figure 4.1. The produced power from the engines decrease for the vehicle in the rear platoon due to reduction of the aerodynamic drag force. The vehicles are able to drive in a constant close intermediate distance through the whole drive cycle.

It is seen in Figure 5.2 that the vehicles in the rear platoon will reduce their velocities earlier than the vehicles in the front platoon. This behaviour is due to that the vehicles in the back region of the platoon will catch up to the vehicles in the front region of the platoon, because of the reduced aerodynamic drag force for the following vehicles. The controller allows the intermediate distance between the vehicles to deviate quite far from the smallest allowed intermediate distance. The vehicles need to utilize the brakes in the end of the downhill to avoid to hit the upper speed limit.

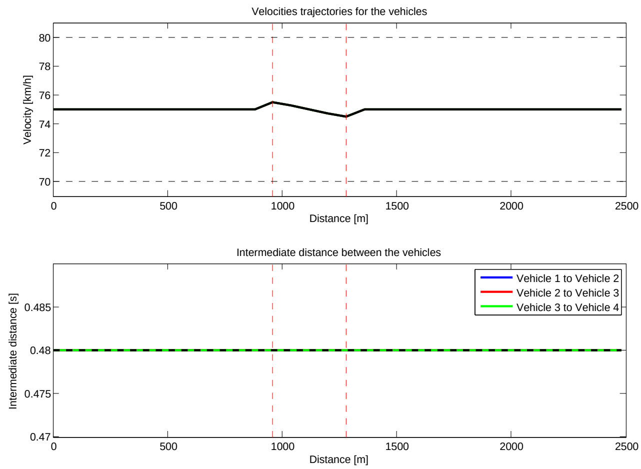


Figure 5.1: The figure shows the behaviour of a platoon of four vehicles when drive on an uphill road segment (case 1) controlled by predecessor knowledge PPC. The upper figure shows the velocity profiles of all vehicles (blue, red, green and black). The red dashed line shows where the hill starts and ends and the dashed black line shows the allowed velocity range. The lower figure shows the intermediate distance between the vehicles. The black dashed line shows the nearest safe intermediate distance that needs to be kept.

A full knowledge PPC

The results from the full knowledge PPC are visualized in Figure 5.3 (road profile 1) and in Figure 5.4 (road profile 2).

Figure 5.3, shows the same behaviour as seen when the predecessor knowledge PPC method was used. The intermediate distances between the vehicles are kept constant close to the safe distance constraints and no vehicles need to use the brake.

A difference between the two control methods, the predecessor and the full knowledge PPC, are seen when the platoon drives in a downhill segment, compare Figure 5.4 with Figure 5.2, The full knowledge controller is increasing the speed for the vehicles in the front of the platoon, which results in that the predetermined intermediate distance is obtained without that the vehicles in the rear platoon need to use the brakes. The close intermediate distance is kept through the whole drive cycle, which reduces the aerodynamic drag influence. The increase of the intermediate distance is small and it can be assumed that external interferences will have

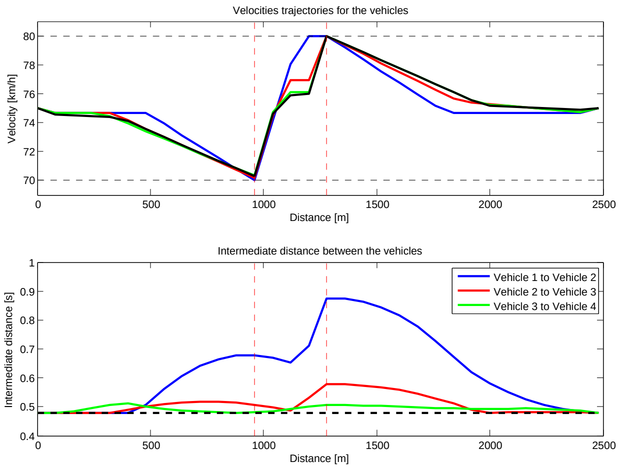


Figure 5.2: The figure shows the behaviour of a platoon of four vehicles when drive on a downhill road segment (case 2) controlled by predecessor knowledge PPC. The upper figure shows the velocity profiles of all vehicles (blue, red, green and black). The red dashed line shows where the hill starts and ends and the dashed black line shows the allowed velocity range. The lower figure shows the intermediate distance between the vehicles. The black dashed line shows the nearest safe intermediate distance that needs to be kept.

a larger impact. It would therefore be preferable to do an evaluation with a more representative drive cycle in order to evaluate the variable intermediate distance.

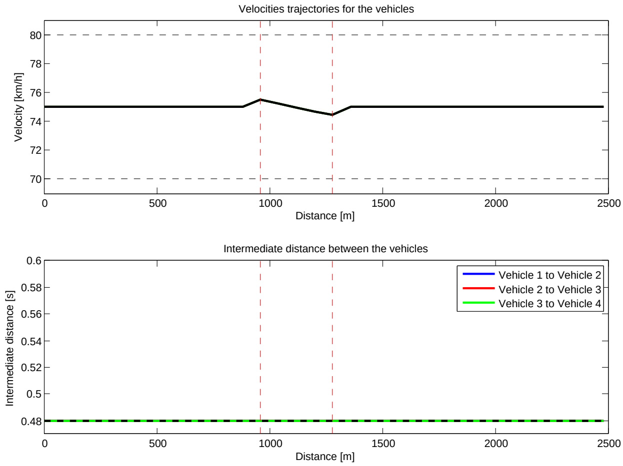


Figure 5.3: The figure shows the behaviour of a platoon of four vehicles when drive on an uphill road segment (case 1) controlled by a full knowledge PPC. The upper figure shows the velocity profiles of all vehicles (blue, red, green and black). The red dashed line shows where the hill starts and ends and the dashed black line shows the allowed velocity range. The lower figure shows the intermediate distance between the vehicles. The black dashed line shows the nearest safe intermediate distance that needs to be kept.

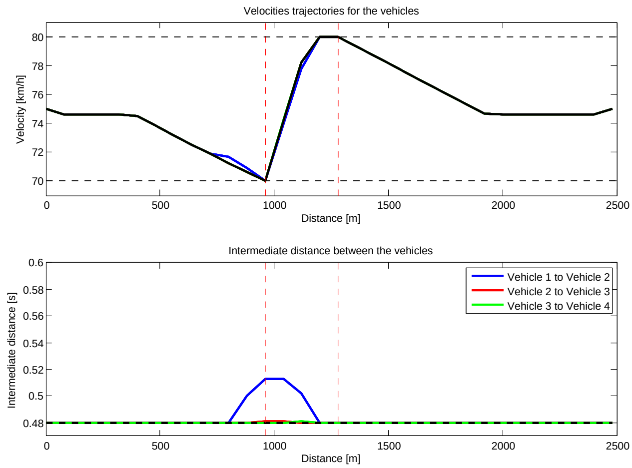


Figure 5.4: The figure shows the behaviour of a platoon of four vehicles when drive on a downhill road segment (case 2) controlled by a full knowledge PPC. The upper figure shows the velocity profiles of all vehicles (blue, red, green and black). The red dashed line shows where the hill starts and ends and the dashed black line shows the allowed velocity range. The lower figure shows the intermediate distance between the vehicles. The black dashed line shows the nearest safe intermediate distance that needs to be kept.

6

Minimization of energy losses

A fuel-efficient velocity profile, for a vehicle in a platoon, can be obtained by minimizing the retarding forces. In this chapter the energy losses in the system from the simulations in Chapter 5 are presented. The first section focuses on a comparison between the different platoon cases. The second section focuses on the different positions of vehicles in the platoon and the controllable retarding forces.

6.1 Comparison between the different platoon cases

The velocity profiles for the vehicles in the different platoon cases are presented and discussed in Chapter 5. The behaviour is due to different constraints; average speed, closest intermediate vehicle distance, speed limit etc. A vehicle's velocity profile has a great significance of the energy losses of the system. The four main energy losses for a vehicle in motion are shown in the Table 6.1. The two simple test road cases (case 1 and case 2) are used to evaluate the result.

When a platoon drives into an uphill segment, case 1, the velocity profiles for the vehicles in the three platoon strategies do not differ and the energy losses the in system are the same regardless of which of the controllers that is used. When the platoon drives into a steep downhill segment, case 2, the velocity profiles differ between the three controllers. Each vehicle in the platoon needs to utilize the brake to avoid hitting the upper speed limit. Since all platoon cases have knowledge about the downhill they are decelerating before the start of the hill, to limit the usage of the brake. The vehicles with the simple knowledge PPC, are keeping the constant close intermediate distance to their predecessors, through the whole route. This keeps the retarding aerodynamic forces low, the slight increase between the two drive cycles can be explained by the higher variance of the velocity in case 2. During the downhill segment the vehicles use the brake to avoid driving too close to predecessors, which increase the energy losses from the brake force. For the predecessor knowledge PPC, the vehicles in the rear region of the platoon start to decelerate further away from the downhill segment. The aerodynamic losses will increase but the usage of the brake to avoid driving too close is no longer necessary. Since information only is sent backward within the platoon, the vehicles on positions 1, 2 and 3 assume that they have a reduced aerodynamic drag from a vehicle behind on a distance of 10m. This might give a misleading result but the main aerodynamic reduction is from the vehicle in front, the reduction from the vehicle behind is approximately 10% of the total aerodynamic reduction when an intermediate distance of 10m is used, see Equation (2.16). In the full knowledge PPC, the vehicles in the rear region have the opportunity to influence their predecessors' velocity profiles. This enables the vehicles in the platoon to keep the close intermediate distance by letting the vehicles in the front of the platoon to accelerate instead of the vehicles in the rear using the brakes. The slightly increased aerodynamic energy loss is due to the higher velocity variance.

As a summary, on a steep uphill segment the behaviour of the different strategies does not differ as long as all vehicles can keep the predetermined constraints. In a steep downhill road segment the platoon controllers differ. The increased aerodynamic energy losses for the predecessor knowledge PPC and the full knowledge PPC compared to the simple knowledge PPC are negligible, 0.3% and 0%. The energy losses from the brake are far less in the predecessor knowledge PPC and the full knowledge PPC compared to the simple knowledge PPC, -13% and -17%. An intelligent controller is able to minimize the unnecessary usage of the brake where the main energy losses occur.

Table 6.1: The energy losses from the repulsive forces for the three different platoon cases. The test road segments, case 1 and case 2, are used and energy losses are average losses per km for the whole platoon.

		A simple knowledge PPC	**A predecessor knowledge PPC**	**A full knowledge PPC**
Case 1	Air drag Energy	4 120kJ	4 120kJ	4 120kJ
	Brake energy	0	0	0
	Roll energy	2 354kJ	2 354kJ	2 354kJ
	Gravity energy	7 068kJ	7 068kJ	7 068kJ
	Total energy	**13 542kJ**	**13 542kJ**	**13 542kJ**
Case 2	Air drag Energy	4 135kJ	4 167kJ	4 139kJ
	Brake energy	312kJ	239kJ	220kJ
	Roll energy	2 354kJ	2 354kJ	2 354kJ
	Gravity energy	-7 068kJ	-7 068kJ	-7 068kJ
	Total energy	**-267kJ**	**-308kJ**	**-355kJ**

6.2 The controllable retarding forces

As seen in the previous section the PPCs are not able to influence the energy losses from the rolling resistance part and the gravitational part. The two energy losses that are to some extent controllable are the aerodynamic drag energy and the brake energy. In an uphill segment, the vehicles are able to obtain a close intermediate distance without usage of the brake, see Table 6.2, therefore the more advanced

PPCs are not able to make use of the possibility to increase intermediate distance in order to avoid usage of the brake.

In a downhill segment, the unnecessary usage of the brake can be minimized by the two more advanced PPCs, see Table 6.3. The high energy losses from brake in the simple knowledge PPC is due to that the vehicles on positions 2, 3 and 4 utilize the brake to avoid driving too close. The predecessor knowledge PPC is increasing the intermediate distance, which result in a slightly higher decelerating aerodynamic energy but on the other hand usage of the brake can be reduced. The full knowledge PPC is able to keep the intermediate distance by letting the vehicles in front increase their speeds. The controller can therefore benefit from both a low aerodynamic energy loss and a minimal usage of the brake.

Table 6.2: The controllable energy losses (aerodynamic drag energy and brake energy) for each vehicle in the three different platoon strategies. The drive cycle contain an uphill segment (case 1) and energy losses are average losses per km.

	Aerodynamic energy		
	A simple knowledge PPC	**A predecessor knowledge PPC**	**A full knowledge PPC**
Vehicle 1	1 551kJ	1 551kJ	1 551kJ
Vehicle 2	931kJ	931kJ	931kJ
Vehicle 3	790kJ	790kJ	790kJ
Vehicle 4	848kJ	848kJ	848kJ
Total	**4 120kJ**	**4 120kJ**	**4 120kJ**
	Brake energy		
	A simple knowledge PPC	**A predecessor knowledge PPC**	**A full knowledge PPC**
Vehicle 1	0	0	0
Vehicle 2	0	0	0
Vehicle 3	0	0	0
Vehicle 4	0	0	0
Total	**0**	**0**	**0**

Table 6.3: The controllable energy losses (aerodynamic drag energy and brake energy) for each vehicle in the three different platoon strategies. The drive cycle contain a downhill segment (case 2) and energy losses are average losses per km.

	Aerodynamic energy		
	A simple knowledge PPC	**A predecessor knowledge PPC**	**A full knowledge PPC**
Vehicle 1	1 555kJ	1 555kJ	1 557kJ
Vehicle 2	936kJ	958kJ	937kJ
Vehicle 3	794kJ	802kJ	795kJ
Vehicle 4	850kJ	851kJ	850kJ
Total	**4 135kJ**	**4 167kJ**	**4 139kJ**
	Brake energy		
	A simple knowledge PPC	**A predecessor knowledge PPC**	**A full knowledge PPC**
Vehicle 1	53kJ	53kJ	48kJ
Vehicle 2	83kJ	61kJ	56kJ
Vehicle 3	89kJ	63kJ	58kJ
Vehicle 4	87kJ	62kJ	58kJ
Total	**312kJ**	**239kJ**	**220kJ**

7

Two-vehicle platoon

In this chapter, a two-vehicle platoon with the predecessor knowledge PPC is analysed. The BLB-route is used for evaluation and can been seen as a typical Swedish highway profile. The impact that an increased intermediate safe distance has on the controller is evaluated and the importance of the formation of the platoon consisting of heterogeneous vehicles is addressed. In the last paragraph, AB Volvo's simulation environment, GSP, is used to evaluate the platoon's energy losses.

7.1 Energy losses for a two-vehicle platoon

The test road profiles (case 1 and case 2) are two simple short road segments and for an evaluation of the energy losses for a platoon, a longer and more realistic drive cycle should be used. The BLB-route consists of a long hill profile superimposed with short hills and can be seen as a representative highway road profile. The behaviour from the simple knowledge PPC and the predecessor knowledge PPC are given in Appendix B, see Figure B.1 and Figure B.2. The energy losses for the controllers are shown in Table 7.1. The vehicles in the two platoon cases have similar velocity profiles, both are able to utilize the energy stored in the altitude differences. The difference between the two controllers is that the predecessor knowledge PPC increases the intermediate distance to minimize the usage of the brake. During some part of the route the intermediate distance is so far that the vehicles do not benefit from the reduction of the aerodynamic drag, which results in an average increase of 3.4% of the aerodynamic energy for the more advanced PPC. On the other hand the usage of the brake in the second vehicle is far more reduced in the predecessor knowledge PPC and an average energy savings of -14% is possible with this strategy. The total reduction of the energy losses using the predecessor knowledge PPC compared to the simple knowledge PPC is 2.8% per km for the second vehicle.

Table 7.1: The energy losses from the retarding forces for the the simple knowledge PPC and the predecessor knowledge PPC. Both platoons contain of two identical vehicles and have a upper speed limit of 90km/h. The BLB-route is used and energy losses are the average losses per km.

		A simple knowledge PPC	A predecessor knowledge PPC	Percent (%)
Vehicle 1	Air drag energy	1629kJ	1629kJ	0%
	Brake energy	522kJ	522kJ	0%
	Roll energy	588	588	0%
	Total energy	2 739kJ	2 739kJ	0%
Vehicle 2	Air drag energy	1 039kJ	1 112kJ	3.4%
	Brake energy	853kJ	643kJ	-14%
	Roll energy	588kJ	588kJ	0%
	Total energy	2 480kJ	2 344kJ	-2.8%

7.2 Intermediate distance

A short intermediate distance between the vehicles is desirable because it results in a reduction of the decelerated aerodynamic force. The distance still needs to be sufficient enough for providing safe driving. In the aerodynamic model, the decelerated force decreases quickly as the intermediate distance increases. The predecessor knowledge PPC utilizes the intermediate distance to apply a decelerated force without usages of brake. As the shortest intermediate distance increase, its ability to utilize this performance reduces. Table 7.2 shows that as the predetermined intermediate distance is duplicated and triplicated, the use of a more advanced controller gets less beneficial due to reduction of the aerodynamic force influence.

Table 7.2: The significance of the intermediate distance. The table shows the percentage differences of the total energy losses for a two vehicle platoon controlled by either by a simple knowledge PPC or a predecessor knowledge PPC with three different intermediate distances.

Intermediate time distance	**0.48s**	**0.96s**	**1.44s**
Percent	1.2%	1.0%	0.9%

7.3 Energy losses for a heterogeneous platoon

So far in this thesis, homogeneous vehicles have been considered. In a real case scenario, it is more likely to believe that a platoon containing trucks of different; models, loads and brands. It cannot be assumed that the vehicles will have the same drivability and, therefore, it needs to be investigated if the formation of the vehicles in the platoon influence the energy losses. In this part, two heterogeneous vehicles are obtained by changing the mass of the vehicles. The masses have been decided to be 40 tonne respective 30 tonne and the two different formations of the platoon is simulated and controlled by the predecessor knowledge PPC. The behaviour of the two different cases are presented in Appendix B, see Figure B.3 and Figure B.4 and the energy losses can be seen in Table 7.3.

The energy losses show that for an optimal fuel-efficient solution the formation of the vehicle in a platoon should be considered. A heavier vehicle in the rear platoon will increase the intermediate distance further since it will catch up its predecessor in a downhill section. As the intermediate distance increases also the losses from the aerodynamic part get higher. In a downhill, the heavier vehicle often will catch up the lighter vehicle in front and it needs to utilize the brake, which results in higher energy losses. In an uphill, the energy losses have less impact on the platoon coordination and as long as the vehicles have a close capacity on the drivability the uphill road behaviour does not influence the energy losses.

Table 7.3: The energy losses from the retarding forces for the predecessor knowledge PPC for a platoon containing heterogeneous vehicles. The mass on the vehicles are 40 tonne respective 30 tonne. An upper speed limit of 90km/h is chosen. The BLB-route is used and energy losses are the average losses per km.

		30 tonne - 40 tonne	**40 tonne - 30 tonne**	**Percent (%)**
Vehicle 1	Air drag energy	1 607kJ	1 629kJ	-
	Brake energy	188kJ	475kJ	-
	Roll energy	441kJ	588kJ	-
	Total energy	2 237kJ	2 692kJ	-
Vehicle 2	Air drag energy	1 178kJ	1 098kJ	-
	Brake energy	634kJ	267kJ	-
	Roll energy	588kJ	441kJ	-
	Total energy	2 400kJ	1 806kJ	-
Platoon	Air drag energy	2 785kJ	2 727kJ	-1%
	Brake energy	822kJ	742kJ	-5%
	Roll energy	1 029kJ	1 029kJ	0%
	Total energy	4 638kJ	4 499kJ	-1.5%

7.4 Energy losses simulated in the GSP

The results in Section 7.1 shows that their exists a potential gain of implementing a more advanced PPC strategy. A further evaluation with a more accurate model needs to be done. The first step to get more reliable results is to implement the solver in AB Volvo's own simulation environment, GSP.

To implement the solution into the GSP environment, it has been chosen to beforehand calculate the optimal solution, the velocity trajectory for the first vehicle and the intermediate distance for the second vehicle. These trajectories are submitted in GSP environment for the vehicles to follow, since they are sampled with an 80m distance and smoothing of the curves is done in order to avoid step behaviour. The vehicles' behaviour is shown in Appendix C, see Figure C.1 and Figure C.2. The energy losses from the simulation are then measured, see Table 7.4. Unfortunately, the energy losses are not consistent with the result from the simplified model. Despite that the aerodynamic energy losses are higher for the predecessor knowledge PPC it does not utilize the increased intermediate distance to reduce the braking. The gap controller that is implemented in GSP acts too aggressive and is not able to utilize the increased aerodynamic drag as a braking force.

The PPC controller minimizes the external forces and a correct estimation of these are important to be able to utilize these forces. The simple used model differs too much compared to the GSP model and the precalculated trajectories are therefore not an optimal solution for the GSP model. Since the model is not sufficiently accurate, a further investigation of enabling implementation of the solver in the GSP should be investigated.

Table 7.4: The energy losses from the retarding forces for the the simple knowledge PPC and the predecessor knowledge PPC simulated in GSP. Both platoons contain two identical vehicles and have a upper speed limit of 90km/h.The BLB-route is used and energy losses are the average losses per km.

		A simple knowledge PPC	**A predecessor knowledge PPC**	**Percent (%)**
Vehicle 1	Air drag energy	1 658kJ	1 675kJ	0.5%
	Brake energy	649kJ	681kJ	3%
	Roll energy	1 840kJ	1840kJ	0%
	Total energy	**4 147kJ**	**4 196kJ**	**0.6%**
Vehicle 2	Air drag energy	1060kJ	1 113kJ	2.4%
	Brake energy	847kJ	883kJ	2%
	Roll energy	1 840kJ	1 840kJ	0%
	Total energy	**3 747kJ**	**3 836kJ**	**1.2%**

8

Conclusions

In this thesis it has been shown that a reduction of the fuel consumption is possible with a predictive platoon controller. Depending on the amount of shared knowledge and the possibility to influence other vehicles within the platoon, different levels of fuel reduction is possible.

An even velocity profile, with a close intermediate distance between the vehicles and limited usages of the brake is desirable for a fuel-efficient drive. On a flat road profile, it is possible for vehicles to follow this driving pattern. However, due to the large mass of the trucks and the limited produced engine power, small changes in the road slopes will influence the velocity profiles. The knowledge of the upcoming topography is essential for achieving a fuel-efficient platoon control strategy. To analyse and understand what influences the vehicle's fuel consumption, it has been chosen to analyse the energy losses from the retarding forces. The different PPCs are able to control the energy losses from the aerodynamic drag force and the brake force.

For an uphill road segment the different PPCs all have the same velocity profiles, which results in the same energy losses. In a downhill road segment the velocity profiles differ between the controllers and consequently the energy losses differ. The simple knowledge PPC, keeps the close predetermined intermediate distance through usage of the brake, while the predecessor knowledge PPC increased the intermediate distance before the downhill segment to avoid driving too close. The full knowledge PPC let the predecessors increase their velocities to keep the safe distance. The energy dissipated in the brakes is shown to be the main energy losses and it is therefore favourable to increase the intermediate distance or increase the speed of the predecessor in order to avoid usage of the brakes. The energy losses for the predecessor knowledge PPC and full knowledge PPC could be reduced by 13% and 17% compared to the simple knowledge PPC.

The full knowledge PPC's ability to influence the vehicle in the front of the platoon is favourable, however, the computational complexity will rise as the size of the platoon increases and therefore a further analysis of the predecessor knowledge PPC has been done. For a more reliable result, a typical highway route has been used for evaluation. It has shown that a predecessor knowledge PPC compared to a fix intermediate gap controller can lower the energy losses with an average of 1.2%. The more advanced PPCs utilize the retarding aerodynamic force to reduce the energy losses by increasing the intermediate distance between the vehicles. If the predetermined intermediate distance is increased, the aerodynamic reduction reduces and the advanced PPC loses its ability to utilize the aerodynamic part in the optimization problem. This impairs the controller to drive fuel-efficient compared to the simple knowledge PPC. The formation of a heterogeneous vehicle platoon has an influence on the fuel consumption and future platoon controllers should therefore have some level of ability to coordinate the vehicles in a certain order.

The result from the GSP simulation shows the importance of a correct description of the dynamic of the vehicle's motion. The optimization model utilizes the external retarding forces on the vehicle in motion and since these differ in GSP model the optimal velocity profiles do not match. It is, therefore, difficult to make a conclusion from this result other than that a more advanced model should be implemented.

9 Future work

To evaluate the possibility of fuel reduction for a PPC a simplified model of the vehicle and environment has been used. The different PPC strategies show that a fuel reduction is possible and a potential implementation of the controller may be favourable in future vehicles.

Before implementation is possible some further improvements should be done. In order to simplify the engine model, the dynamic of the gear changes have been neglected. The gearshifts for a truck take considerable time and change the driving pattern, therefore the gearshifts dynamics needs to be added to the model. The aerodynamic force is essential for PPC behaviour. The simple aerodynamic model may indicate the behaviour of the PPC, however, more empirical experiments should be done to further develop a more accurate model.

Further enhancements should be done on the simulation environment to get a more realistic result. More drive cycles and scenarios need to be evaluated. It is reasonable to believe that in a real case platoon the vehicles will have different drivabilities and, therefore, heterogeneous platoon behaviour needs to be analyzed for evaluating the importance of the formation of the platoon. For the result to be confirmed, an implementation of the controller in AB Volvo's own simulation environment, GSP, should be done.

For a future possible implementation, the computational complexity of the different control strategies needs to be evaluated. It is more likely that a PPC with a limited knowledge will be possible to implement due to the lower complexity. Therefore, a discussion over what kind of information that can be shared between the vehicles needs to take place. Different variants of a limited knowledge strategy should be investigated. In this model information was only assumed to be shared stepwise backwards, another strategy could be to send information stepwise forward or multiple steps.

It has been seen in the study that the vehicle's mass and the road's slope have the main influence on the dynamics. A closer study of the errors of the estimates of these parameters and what influence the margin of the errors has on the controller should be done.

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A

Vehicle parameters

Table A.1: A notation over the parameter that are used in this thesis

Parameter	**Notation**	**Value**	**Unit**
Gravitational constant	g	9.81	m s^{-2}
Air density	ρ	1.29	kg m^{-3}
Vehicle mass	m	40 000	kg
Engine ineria	J_e	3.5	kg m^2
Gear ratio	i_c	1	-
Gear efficiency	η_c	1	-
Final drive ratio	i_f	3.0159	-
Final drive efficiency	η_f	1	-
Wheel inertia	J_w	32.9	kg m^2
Wheel radius	r_w	0.5	m
Roll resistance coefficient	c_r	$1.5 \cdot 10^{-3}$	-
Air drag coefficient	c_d	0.56	-
Vehicle front area	A	10.26	m^2

B

BLB simulations

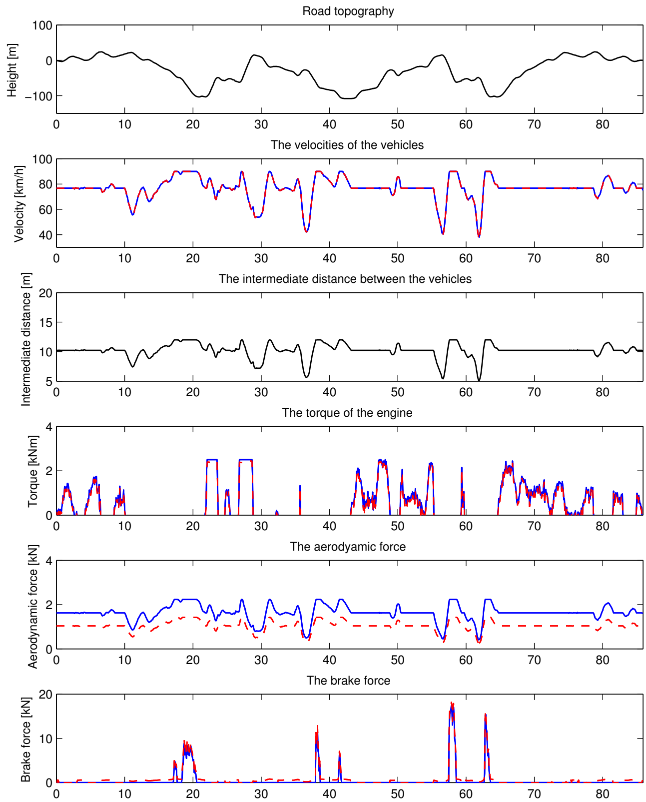

Figure B.1: The behaviour of a two-vehicle platoon with a simple knowledge PPC. The blue line describe the first vehicle behaviour and the red dashed line describe the second vehicle behaviour. The x-axle is the distance (km) of the drive cycle.

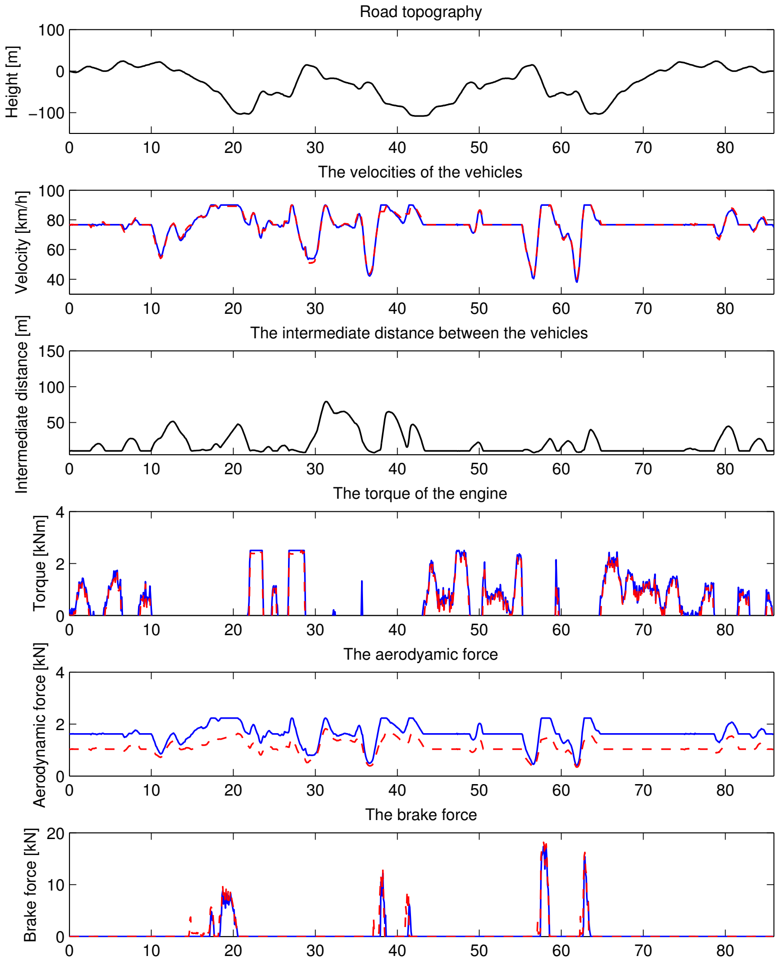

Figure B.2: The behaviour of a two-vehicle platoon with a predecessor knowledge PPC. The blue line describe the first vehicle behaviour and the red dashed line describe the second vehicle behaviour. The x-axle is the distance (km) of the drive cycle.

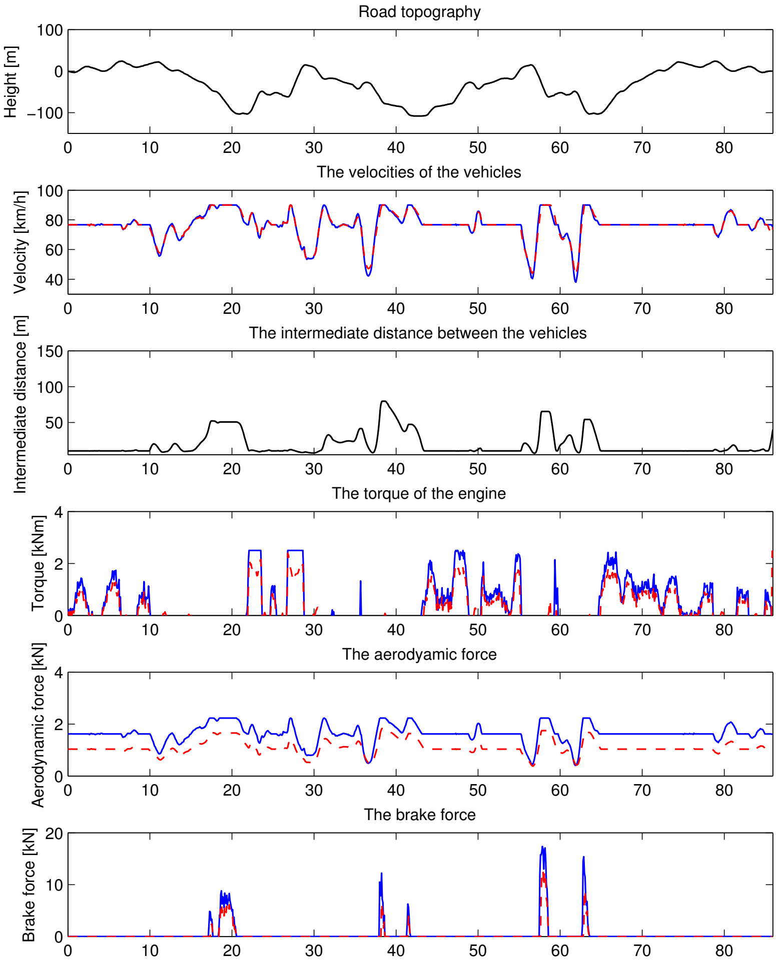

Figure B.3: The behaviour of a two-vehicle heterogeneous platoon with a predecessor knowledge PPC. The first vehicle's mass is 40 tonne and the second vehicle's mass is 30tonne. The blue line describe the first vehicle behaviour and the red dashed line describe the second vehicle behaviour. The x-axle is the distance (km) of the drive cycle.

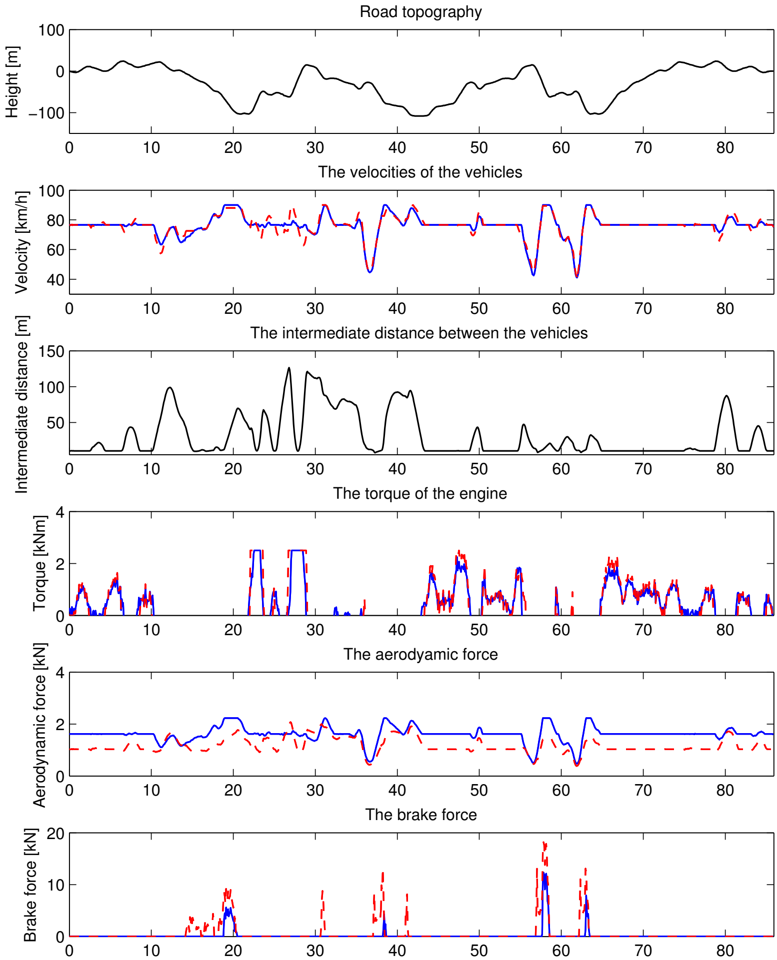

Figure B.4: The behaviour of a two-vehicle heterogeneous platoon with a predecessor knowledge PPC. The first vehicle's mass is 30 tonne and the second vehicle's mass is 40tonne. The blue line describe the first vehicle behaviour and the red dashed line describe the second vehicle behaviour. The x-axle is the distance (km) of the drive cycle.

C

BLB simulations with GSP

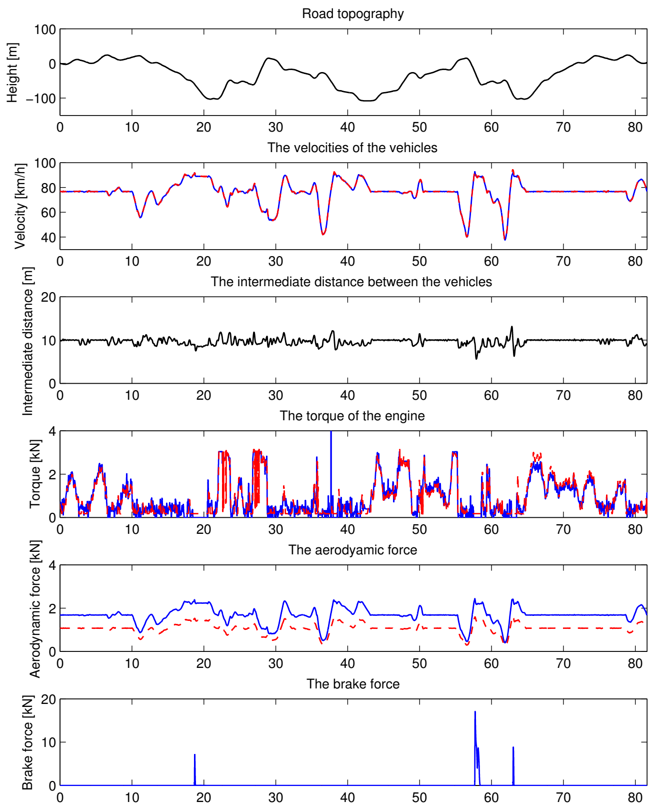

Figure C.1: The behaviour of a two-vehicle platoon with a simple knowledge PPC simulated in GSP. The blue line describe the first vehicle behaviour and the red dashed line describe the second vehicle behaviour. The x-axle is the distance (km) of the drive cycle.

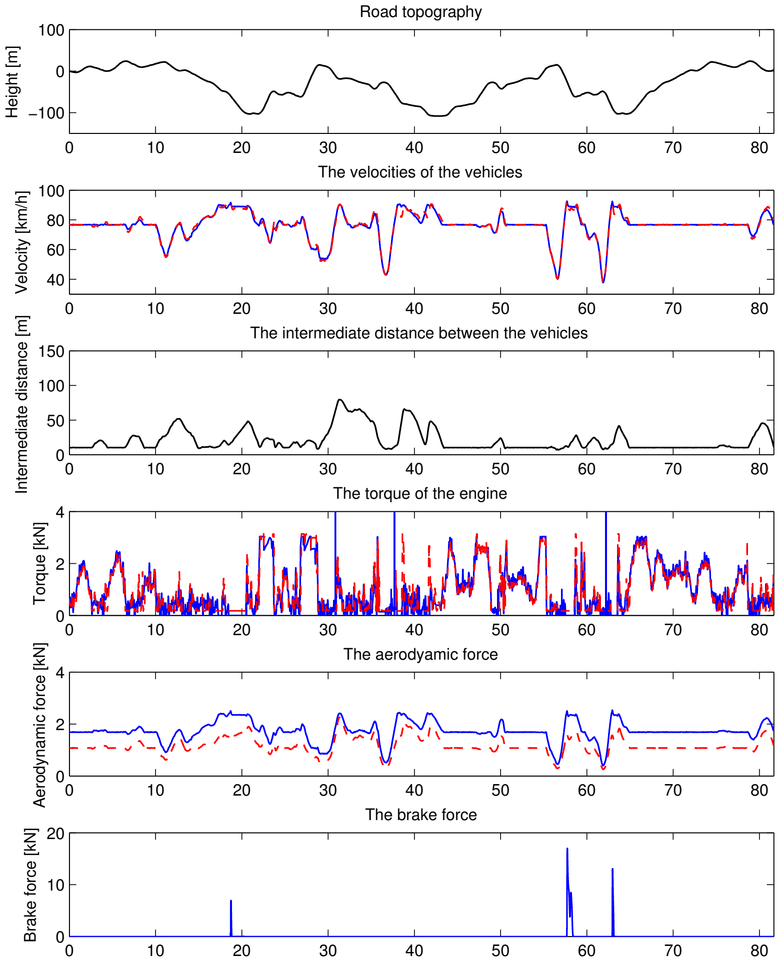

Figure C.2: The behaviour of a two-vehicle platoon with a predecessor knowledge PPC simulated in the GSP. The blue line describe the first vehicle behaviour and the red dashed line describe the second vehicle behaviour. The x-axle is the distance (km) of the drive cycle.

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Title and subtitle
Energy Optimization for Platooning through Utilizing the Road Topography

Abstract

The road haulage industry is a fundamental part of today's society. The companies of haulage stand before a challenge, as the environmental and economic sustainability demands are increasing. The automotive industry tries to meet these demands by developing intelligent systems that will decrease the fuel consumption.

The two systems, predictive controller and platooning, are two intelligent solutions that help to decrease the fuel consumption. A predictive controller uses the knowledge of the future road topography to calculate an optimal velocity profile that utilizes the energy stored in the altitude differences. Platooning describes the concept of driving several vehicles in a close formation. The vehicles are controlled autonomously in the longitudinal direction, which enables a short intermediate distance between the vehicles and a reduction of the decelerating aerodynamic drag force.

In this thesis, a predictive platoon controller has been developed that takes both the topography and the possible reduction of the aerodynamic drag force into account. Two main different platoon control strategies are evaluated. The result shows that the aerodynamic drag has a large influence of the fuel consumption and that a short intermediate distance between the vehicles will often reduce the consumption. However, the road topography has an influence on the driving profile and in some scenarios it would be beneficial to increase the intermediate distance to avoid using the vehicle's brake. The result shows that predictive platoon control enables a fuelefficient velocity profile, though, more scenarios should be analysed to draw further conclusions about the strategy.

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