Look-ahead Control of Heavy Vehicles

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To Gabriella
Trucks are responsible for the major part of inland freight and so, they are a backbone of the modern economy but they are also a large consumer of energy. In this context, a dominating vehicle is a truck with heavy load on a long trip. The aim with look-ahead control is to reduce the energy consumption of heavy vehicles by utilizing information about future conditions focusing on the road topography ahead of the vehicle.

The possible gains with look-ahead control are evaluated by performing experiments with a truck on highway. A real-time control system based on receding horizon control (RHC) is set up where the optimization problem is solved repeatedly on-line for a certain horizon ahead of the vehicle. The experimental results show that significant reductions of the fuel consumption are achieved, and that the controller structure, where the algorithm calculates set points fed to lower level controllers, has satisfactory robustness to perform well on-board in a real environment. Moreover, the controller behavior has the preferred property of being intuitive, and the behavior is perceived as comfortable and natural by participating drivers and passengers.

A well-behaved and efficient algorithm is developed, based on dynamic programing, for the mixed-integer nonlinear minimum-fuel problem. A modeling framework is formulated where special attention is given to properly include gear shifting with physical models. Fuel equivalents are used to reformulate the problem into a tractable form and to construct a residual cost enabling the use of a shorter horizon ahead of the vehicle. Analysis of errors due to discretization of the continuous dynamics and due to interpolation shows that an energy formulation is beneficial for reducing both error sources. The result is an algorithm giving accurate solutions with low computational effort for use in an on-board controller for a fuel-optimal velocity profile and gear selection.

The prevailing approach for the look-ahead problem is RHC where main topics are the approximation of the residual cost and the choice of the horizon length. These two topics are given a thorough investigation independent of the method of solving the optimal control problem in each time step. The basis for the fuel equivalents and the residual cost is formed from physical intuition as well as mathematical interpretations in terms of the Lagrange multipliers used in optimization theory. Measures for suboptimality are introduced that enables choosing horizon length with the appropriate compromise between fuel consumption and trip time.

Control of a hybrid electric powertrain is put in the framework together with control of velocity and gear. For an efficient solution of the minimum-fuel problem in this case, more fuel equivalence factors and an energy formulation are employed. An application is demonstrated in a design study where it is shown how the optimal trade-off between size and capacity of the electrical system depends on road characteristics, and also that a modestly sized electrical system achieves most of the gain.

The contributions develop algorithms, create associated design tools, and carry out experiments. Altogether, a feasible framework is achieved that pave the way for on-board fuel-optimal look-ahead control.
Populärvetenskaplig sammanfattning

Lastbilen står för majoriteten av landtransporterna av gods och är därmed en grundpelare i den moderna ekonomin men även en stor konsument av energi. Ett dominerande fordon i sammanhanget är en tung lastbil som används för långa transporter. Syftet med framförhållningsreglering (engelska: look-ahead control) är att minska denna energiförbrukning genom att använda information om framtida förhållanden, med fokus på vägtopografi framför fordonet, för energiminimal reglering.

Vägens topografi är snart tillgänglig ombord på fordon tack vare billiga enheter för satellitnavigatoringssystemet GPS kombinerat med tredimensionella kartor som är under utveckling idag. Målet är att utnyttja att den här informationen är tillgänglig för att minska bränsleförbrukningen i tunga lastbilar. Dessa fordon är redan idag förhållandevis effektiva eftersom förbränningsmotorn ofta körs i fördelaktiga arbetspunkter på grund av stor last i förhållande till motoreffekten. Samtidigt förbrukar de mycket bränsle totalt sett och därfor har även små framsteg stor effekt; enligt industrin är en möjlig förbättring om 0.5% i bränsleekonomi värd att utforska. I en serie experiment med framförhållningsreglering på en svensk motorväg visas att förbättringspotentialen är 3.5%, utan ökad körtid, jämfört med traditionell reglering.

Principen för framförhållningsreglering beskrivs i figuren nedan med hjälp av bilder från den video om projektet som finns på YouTube.†

(a) Koordinater för den aktuella positionen tas emot med en GPS-enhet ombord på fordonet.
(b) Med hjälp av positionen och en databas med vägtopografi fås information om vägens lutning.
(c) Algoritmen beräknar den mest bränsleefektiva regleringen utifrån tillgänglig information.
(d) Lösningen kommuniceras till fordonet där den verkställs och förfarandet börjar om.

†Videon hittas genom att söka på frasen look-ahead control på http://www.youtube.com/ eller genom följande länk: http://www.youtube.com/watch?v=waCxqRs6v8
De besparingar som är möjliga att uppnå med framförhållningsreglering utvärderas genom att utföra experiment med en lastbil på motorväg. Ett realtidssystem för reglering, baserat på prediktionsreglering, tas fram där optimeringsproblemet löses ombord i ett iterativt schema som, i varje iteration, betraktar en viss horisont framför fordonet. Resultaten från experimenten visar att en betydande minskning i bränsleförbrukning är möjlig och att reglerstrukturen, där algoritmen beräknar börvärdet för regulatorer på lägre nivå i en regulatorhierarki, har den robusthet som krävs för att fungera väl ombord under verkliga förhållanden. Betentet hos regleringen har den önskvärda egenskapen att vara intuitivt, och det uppfattas också som naturligt och bekvämt för de förare och passagerare som deltar i test och demonstrationer.


Reglering av en hybrid drivlina, där ett elektriskt system också kan driva fordonet, kombineras med reglering av hastighet och växel. För att effektivt lösa bränsleminimeringsproblemet för det här fallet används fler bränsleekvivalenter och en energiformulering. En användning demonstreras i en designstudie där det visas hur den optimala kompromissen mellan storlek och kapacitet för det elektriska systemet beror av vägens karaktäristik där det visar sig att ett relativt litet system uppnår större delen av vinsten. Bidragen utvecklar algoritmer, skapar relaterade designverktyg och utför experiment. Sammantaget åstadkommer ett realistic ramverk som banar väg för energiminimal framförhållningsreglering ombord på fordon.

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Acknowledgments

This work has been carried out at the division of Vehicular Systems, department of Electrical Engineering at Linköping University. First of all, I would like to express my gratitude to my supervisor Professor Lars Nielsen for letting me join the group and all of his encouragement and valuable input during the project. I am fortunate to have had such a dedicated supervisor who always made me feel that our work was important and who always stand by me at critical times.

My second supervisor Jan Åslund is a great thinker and I am utterly thankful for the time he put into the project. Anders Fröberg and Maria Ivarsson have been valued colleagues and co-authors; we have had interesting discussions and fruitful collaborations on the subject of look-ahead control. Per Sahlholm, Anders Jensen, and Nils-Gunnar Vägstedt at Scania are appreciated for their efforts concerning the realization of the demonstrator vehicle and the experiments. Erik Frisk is thanked for helping me scrutinize the layout of the dissertation.

The work was funded by the Swedish Foundation for Strategic Research SSF through the research center MOVIII. The support is gratefully acknowledged.

The many dinners together with my dear friends Frisk and Janne really brightened up everyday life, and I look forward to many more. Everyone at the division is appreciated for jointly creating a positive and nice atmosphere to work in.

I will forever owe a debt of gratitude to my parents, Britta and Svenny, for always supporting me. I am also blessed with my sisters and brothers Karin, Andreas, and John. My love goes to family, friends and to my wife Gabriella.

Erik Hellström
Linköping, April 2010
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Chapter 1

Introduction

Efficient transportation is a matter of vital importance in the modern economy and the backbone is road vehicles that, e.g., in Europe and in the United States account for more than 70% of inland freight transport (Noreland, 2008; Bradley, 2000). It is therefore attractive to reduce the energy consumption of vehicles, both from an environmental and an economical point of view. To reduce the energy consumption, the losses in the chain of steps from a basic energy source to a completed drive mission should be targeted. This chain starts at a basic energy source, from which a fuel is extracted that can be converted, on-board the vehicle, into mechanical energy.

One approach to reduce the losses of the on-board energy conversion is look-ahead control where knowledge about future conditions is utilized to increase fuel efficiency. A source of such information is the combination of road topography maps with the global positioning system (GPS). This has become economically viable with the decreasing cost of GPS devices, and road databases including elevation are now emerging from map providers. The road topography naturally has a large influence on the motion of vehicles with low engine power compared to the vehicle mass. The topic of this dissertation is how the knowledge of the road topography ahead of such a vehicle can be utilized for reducing the fuel consumption. This is achieved by longitudinal control that, for example for a conventional powertrain means controlling velocity and gear in the most fuel-efficient way with respect to the upcoming topography.

A common heavy vehicle is a class 8 truck, weighing more than 15 tonnes. For such a truck, about ⅓ of the life cycle cost comes from the cost of fuel, see Figure 1.1. These trucks typically travel on open road and have a high annual mileage making them a large consumer of fuel. For example, an average European class 8 truck travels 150,000 km with a fuel consumption of 32.5 l/100km (Schitler, 2003). In the U.S. the average fuel consumption is 37.9 l/100km (Vyas et al., 2003) and class 8 trucks consume about 68% of all commercial truck fuel used where 70% of this amount is spent operating on open road with a trip length of more than 161 km (Bradley, 2000). For this type of vehicles, a technology improving fuel efficiency will thus have good benefit.
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The main challenges faced when trying to reduce the fuel consumption of heavy trucks by control are coupled to the current fuel efficiency of these vehicles and the real-time requirements of an algorithm. Due to the large mass compared to the engine power, heavy trucks on open road typically run at engine operating points with high load and high efficiency. This is also indicated by the fact that, according to the industry, any technology for long-haulage having the promise of saving 0.5% of fuel is considered worthwhile to explore. Further, for a minimum-fuel control to be feasible on-board, an efficient solution of a complex optimization problem is required. These challenges are taken up in this dissertation and the contributions develop computationally efficient algorithms and show that significant fuel savings are possible.

1.1 Outline and Contributions

The continuous link in the contributions is the successive development of the framework for look-ahead control in Paper A through C and the transfer of the methodology for also studying hybrid electric vehicles in Paper D.

Paper A describes an implementation and evaluation of look-ahead control in a demonstrator vehicle. A real-time control system is implemented based on receding horizon control (RHC) where the optimization problem is solved repeatedly on-line for a given horizon. The controller structure, where the algorithm calculates set points fed to lower level controllers, is proven to perform well on-board in a real environment. An experimental evaluation, on Swedish highway in normal traffic, shows a significant fuel consumption reduction of 3.5%, without increased trip time, compared to traditional cruise control. The controller behavior is characterized and found to be intuitive, and is appreciated by drivers and passengers.
The development is continued in Paper B where an efficient algorithm, based on dynamic programming (DP), is designed for the on-line optimization problem. A model structure is defined that allows general velocity dynamics and proper physical modeling of gear shifts through a set of functions describing the shift process. Fuel equivalence factors for time and kinetic energy are introduced, and these are used to reformulate the problem into a tractable form and to construct a residual cost to be used at the end of the horizon. Furthermore, analysis of the errors due to discretization of the continuous dynamics and due to interpolation shows that an energy formulation is beneficial for reducing both error sources. The result is a computationally efficient algorithm giving accurate solutions for use in an on-board controller for a fuel-optimal velocity profile and gear selection.

The main topics in RHC, the prevailing approach for the look-ahead problem, are choosing a residual cost and selecting a proper horizon length, and these are addressed in Paper C. The basis for the fuel equivalents and the residual cost is substantiated by adding mathematical interpretations in terms of the Lagrange multipliers used in optimization theory. Measures for suboptimality, independent of the optimization method, are introduced that enables choosing horizon lengths with the appropriate compromise between fuel consumption and trip time. A subsequent evaluation shows how the road characteristics and the vehicle mass influence the choice of horizon length.

In Paper D, control of a hybrid electric powertrain is put together with control of velocity and gear which gives a framework for the simultaneous management of kinetic and electric energy. An efficient solution is obtained by employing more fuel equivalence factors and an energy formulation. The formulation is applied to a design study where it is shown how the optimal trade-off between size and capacity of the electrical system depends on road characteristics.

The contributions altogether achieve a feasible framework for look-ahead control by developing algorithms, creating associated design tools, and carrying out experiments. A theme is the exploration of physically intuitive approaches. These have lend themselves to mathematical analysis where important ideas have been an energy formulation and the use of fuel equivalents.

1.2 Publications

In the research work leading to this dissertation, the author has published the following conference and journal papers.


Chapter 1. Introduction


Chapter 2

Prelude

As a prelude to the publications, some additional background is given in this chapter with the purpose of putting the contributions of the papers into perspective. The main challenges for look-ahead control, the high fuel efficiency of heavy trucks and the requirements for real-time control, were briefly presented in Chapter 1 together with the contributions. This chapter elaborates on these topics, and first an examination of the energy use in a heavy diesel truck is made in Section 2.1 to indicate the potential increase in fuel efficiency. In Section 2.2, the possibility for on-board control is examined and examples are used for showing how fuel-optimal control differs from traditional control. Finally, in Section 2.3, the literature in the field is surveyed more comprehensively than there was room for in the included papers, and the contributions are put into this perspective.

2.1 Energy Audit

In a heavy diesel truck, the chemical energy $w_c$ stored in the fuel is converted, with an efficiency $\eta$, into mechanical energy through the combustion process in the engine. Some of the mechanical energy is consumed by auxiliary loads, such as the alternator and cooling fan, and by losses in the driveline, such as friction in the transmission and wheel bearings. After these losses $w_l$, the remaining energy $w_p$ is transmitted to the wheels. For an interval of distance $\Delta s$, this energy balance is thus

$$\Delta w_p = \eta \Delta w_c - \Delta w_l$$

The propulsive energy $w_p$ is partly consumed by the work $d$ from the drag forces due to air drag and rolling resistance. Energy is also stored in the vehicle in form of kinetic energy $e$ when accelerating and potential energy $p$ when climbing grades. When braking, energy $b$ is dissipated from the system. The energy balance becomes

$$\Delta w_p = \Delta e + \Delta p + \Delta d + \Delta b$$
for a distance $\Delta s$.

When cruising at constant speed on level road, $\Delta e = \Delta p = \Delta b = 0$. The energy balance obtained by combining (2.1)–(2.2) for these conditions, considering a typical current class 8 vehicle traveling at 105 $\text{km/h}$ ($65\text{ mph}$) with a gross weight of 36.3 t (80,000 lb), is shown in Figure 2.1. These numbers correspond to $\eta = 40\%$ that is a representative overall efficiency; the peak efficiency may reach 46% but engine losses remain the largest individual share among these categories (Bradley, 2000).

For a heavy truck operating on a real road, constant speed is typically not possible. In downhills, the truck may accelerate without engine propulsion due to the large mass and it can be necessary to use the brakes for safety or legal reasons. Clearly, when using the brakes, $\Delta b$ becomes positive and energy is lost to the ambient. To investigate the brake usage, the integral of the energy balance (2.2) over three different routes is calculated, see Figure 2.2. The results are obtained with a model for a truck with a 360 hp powertrain controlled by a cruise controller, and a gross weight of 40 t. The initial and terminal velocity are the same and the routes are traveled back and forth, hence the integral of $\Delta e + \Delta p$ is zero. The set speed is 80 $\text{km/h}$ and the extra speed allowed in downhills, before braking limits the speed, is varied along the horizontal axis in the figure. It is seen that considerable amounts of energy are wasted by braking, there is an intuitively negative correlation with the extra speed allowed in downhills, and the values are dependent on the road characteristics.

2.1.1 Potential Benefits

Knowledge of the upcoming road topography gives a better prediction of the future load and this can be utilized by look-ahead control to improve the fuel economy. Among the categories in the analysis of energy use in Figures 2.1 and 2.2; brake energy, auxiliary
2.2. Realization of look-ahead control

loads, and engine losses are the primary possible targets for look-ahead control. These are shortly discussed below. The other categories can be targeted by, e.g., improved lubricants and innovative design of the vehicle and the tires.

The energy wasted in braking can be reduced by slowing down prior to steep downhills, by using a hybrid powertrain for recovering some of the energy, and by utilizing some of the energy for driving auxiliary units. Electrically driven auxiliary units can also use the conventional battery as an energy buffer for fuel-optimal planning of the load. Moreover, there is a possibility to reduce engine losses since the peak engine efficiency is higher than the overall efficiency on a typical cycle. This can be achieved by controlling the engine to more efficient operating points taking nonlinear engine characteristics and gear shifting into account. A hybrid powertrain gives further possibilities to reduce engine losses by optimizing the energy distribution, between the combustion engine and electrical motor in a hybrid electric vehicle, and by downsizing the engine.

The gains that are possible to obtain in reality by controlling the engine, the brakes, and the transmission are investigated and quantified in Paper A through experiments. The benefits of a hybridization are evaluated in Paper D in a design study performed by computer simulations.

2.2 Realization of Look-Ahead Control

A controller working on-board in a real environment requires a complexity that is manageable in real-time and robustness towards disturbances and uncertainties.

The algorithm in Paper A requires tenths of a second on a laptop computer to compute the optimal feedback solution for about 1 min ahead which enabled the realization in a demonstrator vehicle and the experimental evaluation. The development in Paper B increases the numerical soundness of the algorithm and reduces the computation time.
with about a factor of 10. Moreover, the results in Paper C are guiding for choosing a well-founded residual cost and choosing a horizon length with a desired trade-off between suboptimality and complexity. The result is an algorithm feasible to run on an embedded system, this has been verified by an implementation on an embedded system based on a 200 MHz ARM processor with 32 Mb RAM.

The experimental results in Paper A show that the controller structure has satisfactory robustness towards disturbances for performing well in a real environment. Regarding uncertainties, the vehicle mass is an important parameter typically estimated on-line. Simulations have shown that typical estimation errors of about 10% have only minor effects on the performance of the look-ahead algorithm (Krahwalkel, 2010). In conclusion, the contributions in Paper A through C pave the way for on-board fuel-optimal look-ahead control.

2.2.1 Characteristics of fuel-optimal solutions

To get an impression of how look-ahead control differs from traditional control, examples of fuel-optimal solutions, obtained by the algorithm in Paper B, are computed for a typical truck weighing 40 t and equipped with a 360 hp diesel engine. The elevation data for the road segment, shown in Figure 2.3, come from measurements on the trial route between Norrköping and Södertälje used in the experiments in Paper A, see Figure 2.6. For a characterization of the controller behavior in practical driving, see Paper A.

The result from the algorithm is the optimal feedback law for fueling, braking, and gear choice as a function of current position, velocity, and gear. In traditional cruise control, the velocity is controlled towards a given set point and the gear is selected based on current engine speed and load. This strategy is only dependent on the current state of the vehicle whereas the optimal control law also depends on the future topography as can be seen in Figure 2.4 where the optimal fueling level and gear choice are shown. The figure shows the optimal feedback law for the highest gear, and the color represents the control value. The colors dark blue, cyan, yellow, and dark red represent gears 9 through 12. The fueling level ranges through these colors where dark blue is zero throttle and dark red is full throttle. The engine model used is an approximation that is affine in fueling, and the solution in Figure 2.4 for the fueling has the expected bang-singular-bang characteristics where large regions are at the constraint of either zero throttle or full throttle (see, e.g., Fröberg et al. (2006) or Paper C). For the nonlinear engine model using measured data, with the solution in Figure 2.5, there are still large regions at the constraints but the boundary area between them is widened and smoothed. The gear choice is rather similar in the figures, e.g., it is noted that in the uphill after 6 km the solution is, depending on the velocity, either to downshift from gear 12 to 11 or to keep gear 12 and then, if the velocity decreases, to downshift two steps to gear 10.
2.2. Realization of look-ahead control

Figure 2.3: A road segment close to Norrköping.

Figure 2.4: Optimal control law for gear 12, computed with an affine engine model.

Figure 2.5: Optimal control law for gear 12, computed with measured engine data.
An overview of related work is made that is more comprehensive than there was room for in the included papers, and the contributions in this dissertation are put into that perspective.

In the early work by Schwarzkopf and Leipnik (1977), a minimum-fuel problem for a nonlinear vehicle model is formulated and explicit solutions for constant road slopes are obtained by aid of the maximum principle. References to other early works are given by Stoicescu (1995) who also studied analytical solutions. More recent studies are reported in Chang and Morlok (2005); Fröberg et al. (2006); Fröberg and Nielsen (2007); Ivarsson et al. (2009) where the latter two works focus on the connection between the engine nonlinearities and the characteristics of the solution. Fuel-optimal strategies for approaching a leading vehicle are derived analytically by Sciaretta and Guzzella (2005). The related problem of traveling in a slowly moving car queue is treated in Jonsson and Jansson (2004) where numerical results from a DP algorithm are reported.

The analytical studies treat simplistic road profiles while different numerical algorithms have been proposed to solve the problem for a general road profile. Results from a forward DP approach are reported in Hooker et al. (1983); Hooker (1988). Such a technique is also used by Monastyrsky and Golownykh (1993) but the problem is formu-
2.3. Literature overview

lated as dependent on distance instead of time and trip time is added to the objective function besides the fuel use. Later developments, focused on heavy trucks, are reported in Lattemann et al. (2004); Neiss et al. (2004); Terwen et al. (2004) who consider cruise control, by adding a quadratic penalty on deviations from a cruise speed, rather than pure fuel-optimal control. This approach was also taken by Hellström et al. (2006) but in later works by the same authors, e.g., Paper A and B, the method to include time in the objective is adopted. This is basically also the procedure in Huang et al. (2008); Passenberg et al. (2009).

2.3.1 Heavy trucks

The transmission in a heavy truck is typically of the automated manual type due to cost, durability and efficiency in comparison with an automatic transmission (Pettersson and Nielsen, 2000). This has been treated with several approaches, such as assuming that the shift process is autonomous and instantaneous (Lattemann et al., 2004; Neiss et al., 2004; Passenberg et al., 2009) or making a continuous relaxation of the discrete signal (Huang et al., 2008). Analytical and numerical studies have shown that the optimal shift strategy depends on the model (Fröberg and Nielsen, 2008; Ivarsson et al., 2010). These works have suggested that a instantaneous model is too simple and that it is important to model the losses during a shift. Explicit physical models for the shift process are used by Terwen et al. (2004) and in Paper A. In Paper B, an algorithmic framework is proposed that allows a general physical model of the gear shift by specifying functions for the velocity change and the required time, distance, and fuel, respectively, during the shift.

On-board control

When considering on-board control the prevailing approach for managing the complexity, due to changing conditions during a drive mission, is RHC. This approach is taken in Paper A and B as well as in other recent studies on the minimum-fuel problem, e.g., Terwen et al. (2004); Hellström et al. (2006); Huang et al. (2008); Passenberg et al. (2009). RHC is a general method for approximating the optimal control law by solving on-line, at each time step, a finite horizon optimal control problem (see, e.g., the survey paper Mayne et al., 2000). Main topics in RHC are how to select the residual cost at the end of the horizon and how to select a proper horizon length. A residual cost, based on physical intuition, is proposed and justified in Paper B, and the theoretical support for this residual cost is strengthened in Paper C. The choice of horizon length is treated in Paper C where measures are introduced, independent of the particular optimization method used in each time step in RHC, that quantifies the basic compromise between suboptimality and computational complexity when choosing the horizon length.

Demonstrated concepts

In Paper A, experimental results with look-ahead control, first published in Hellström et al. (2007), with significant fuel consumption reductions are reported. Recently, a system adapting the velocity to the road topography was introduced by Daimler Trucks
North America in collaboration with Navteq (Daimler Trucks North America press release, 2009). A related system, although without look-ahead, has been launched by Volvo (Volvo press release, 2006). The system senses the current road slope and utilizes that for controlling the truck powertrain, e.g., engaging neutral gear in certain conditions.

**Other approaches**

The information about road topography has also been used, in other ways than control of velocity and gear selection, with the aim of reducing the energy consumption. Strategies for electrically driven auxiliary units are studied by Pettersson and Johansson (2004) and the control of neutral gear is investigated in Fröberg et al. (2005); Hellström et al. (2006).

### 2.3.2 Hybrid electric vehicles

The control of hybrid electric vehicles for minimum energy consumption has received a lot of attention since the nineties see, e.g., the overview by Sciarretta and Guzzella (2007), the dissertation Back (2006), and the monograph by Guzzella and Sciarretta (2007). The focus has been on vehicles where the largest gain of hybridization is expected, such as passenger cars (Paganelli et al., 2000; Sciarretta et al., 2004) and light-duty trucks (Lin et al., 2003, 2004). These vehicles have a driving pattern rather different than long-haulage trucks and they are not as much affected by the road slope. Therefore, the approaches have mainly focused on the management of the electrical energy and have not considered the potential energy and management of kinetic energy. Long-haulage trucks are treated in Paper D where hybridization, velocity control, and gear control are put in a common framework with equivalence factors for each degree of freedom. By utilizing the formulation for computational efficiency from Paper B, an optimization algorithm is applied on the evaluation of the size of the electrical system.

### 2.3.3 Rail vehicles

The problem of optimal control for energy minimization of rail vehicles seems to have been studied earlier than for road vehicles with papers appearing in the late fifties see, e.g., the work by Kokotovic et al. (1972); Liu and Golovitcher (2003) and references therein. These problems are closely related but road vehicles typically have a transmission making the optimal control problem more complicated. The train problem is however still an important problem of its own as indicated by recent publications see, e.g., Khmelnitsky (2000); Franke et al. (2002); Howlett et al. (2009). The dynamic models for train used in these publications fit well into the algorithmic framework in Paper B as the special case without gear shifts.
References


References


