Fuel Optimal Powertrain Control for Heavy Trucks Utilizing Look Ahead

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The road topography in highways affects the powertrain control of a heavy truck substantially since the engine power is low in relation to the vehicle weight. In large road gradients constant speed is not possible to keep, which would have been beneficial otherwise, and in some uphills shifting gears becomes inevitable. If information about the road ahead, i.e. look ahead information, is available, then the powertrain can be controlled in a more fuel efficient way. Trial runs are performed, where the velocity trajectory that minimizes energy consumption, is calculated and communicated in real time as set points to the conventional cruise control. This look ahead control gives significant fuel consumption reductions compared to a standard cruise control, while keeping to the same mean speed. The results are the inspiration to further studies in how powertrain control can benefit from look ahead information. An engine with a non-linear fuel map is studied to understand its impact on fuel optimal speed. It is shown that for a significant fuel map non-linearity, quantified by a threshold value, constant speed in small road gradients is no longer optimal. Further, an automated manual transmission (AMT) optimal gear control is studied. It is shown that the reduced propulsion of a typical AMT gear-shifting process must be considered when choosing when to shift gears. Thus, additional reductions of fuel consumption are obtained with a look ahead control based on knowledge of engine and transmission characteristics.
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I Introduction

1 Truck driving
   1.1 Implications of the long haulage business ....................... 4
   1.2 Look ahead control .............................................. 4
   1.3 Objective – difficulties and potentials ............................. 5
   1.4 Powertrain control and road topography ............................. 6
      1.4.1 Optimal speed .................................................. 6
      1.4.2 Fuel map – engine efficiency .................................. 7
      1.4.3 Shifting gears ................................................... 8
   1.5 Outline and contributions ........................................... 10

References ................................................................. 13

II Papers

1 Look-ahead Control for Heavy Trucks to Minimize Trip Time
   and Fuel Consumption ................................................. 17
   1 Introduction ........................................................... 18
   2 Truck model ........................................................... 19
      2.1 Reformulation ....................................................... 21
   3 Look-ahead control ................................................... 21
      3.1 Objective .......................................................... 22
4 Model adapted for optimization ........................................... 76
4.1 Numerical optimization .................................................. 76
4.2 Verification of gear shift model ........................................ 78
5 Climbing a hill .................................................................. 80
6 Results .............................................................................. 81
6.1 Not to gear down unnecessarily ......................................... 82
6.2 When to shift gears if necessary ....................................... 83
6.3 Implications of a very heavy truck .................................. 90
7 Discussion .......................................................................... 92
7.1 Gear shift model .............................................................. 92
7.2 Gear shift comfort ........................................................... 92
8 Conclusions ........................................................................ 92
References ............................................................................ 94
Part I

Introduction
Truck driving

Heavy trucks, defined as trucks with a gross vehicle weight of more than 16 tonnes, are built according to widely varying specifications. They are used in mining or construction applications as well as to distribute goods in cities or in long haulage driving. These applications all imply different requirements on functionality, robustness and driveability of the truck.

In long haulage for example, long distance highway driving is the most frequent driving scenario. In such stationary driving conditions, some automatic systems developed for heavy trucks are particularly suitable. A requested and commonly used automatic system is the cruise control, another is the automated transmission. Besides being a convenient help system in long haulage driving, the cruise control is sometimes also the most fuel efficient way of driving, depending on the road topography of the driving scenario and the efficiency of the engine.

In a market which is becoming more and more global, there is an increasing demand of transporting goods. This indicates an increasing need of long haulage heavy trucks in the long term. Still, a concern is the global warming of today, an effect partly due to combustion of fossil fuels, since the greenhouse gas carbon dioxide, $CO_2$, is a residual product when e.g. truck diesel is combusted. Fuel optimal powertrain control, i.e. control of engine and transmission, is thus of great interest and will be developed and evaluated. The take-off point is that fuel optimal control can benefit from look ahead information. In the following two sections, characteristics of long haulage operation is presented as well as the definition of look ahead control. Subsequently, the objective is stated and the potentials and difficulties in finding the optimal solution are discussed. There-
after, the reader is briefly guided through some fundamentals of powertrain control and previous research in this area.

1.1 Implications of the long haulage business

The objective of all heavy truck contractors is of course to fulfill their commitments whilst associated costs are minimized. However, the distribution of costs varies between different businesses. The two largest costs for a long haulage contractor are the truck driver salary and the fuel consumption of the truck. Fuel consumption accounts for as much as 25-30% of total life cycle cost. As all the costs are added there is most often not a wide margin to make a profit. Since fuel consumption is a big part of the haulier’s total cost, a reduction of fuel consumption as small as one percent is significant to reduce the total cost and thus make long haulage more profitable. Moreover, the goods must still be delivered in time which means that the required final time of the driving scenario must not be violated while trying to minimize fuel consumption.

There is a wide range of skills of truck drivers. A skilled driver can reduce the fuel consumption with more than 10% compared to an unexperienced driver, by reducing the need of braking and by adapting speed and gear to e.g. the surrounding traffic and according to the topography of the road ahead, and still deliver the goods in time. However, automatic systems are commonly used in highway driving and consequently the impact of the driver’s experience is decreased. A conclusion to be drawn is that there is potential of reducing fuel consumption, and hence diminishing costs of the haulier, if information about the road ahead is available to the control systems.

1.2 Look ahead control

Control strategies that use information about the road ahead, i.e. look ahead control, could improve functionality of the vehicle in many senses. This is particularly true for a heavy truck since it often has a large vehicle mass in relation to its engine power, generating a slow longitudinal dynamics of the vehicle. Input data to a look ahead system could include various attributes such as topography, road curvature, stop lights, speed limits, road restrictions and surrounding traffic. The vehicle continuously evaluates its position, by e.g. GPS, and sets up a look ahead horizon of a predicted future route, see Figure 1.1. The desired attributes are collected from a database for the distance ahead of the truck, the look ahead horizon. There are many systems that could benefit from look ahead information and the examples are diverse. Example applications go from powertrain control such as engine and transmission control, to control of brakes, state of charge in hybrid vehicles or control of auxiliary units such as coolant pump, cooling fan or air compressor. The benefits could be reductions of fuel consumption or enhancements in comfort or active safety.
1.3 Objective – difficulties and potentials

By respecting the scenario of global warming and how combustion of diesel relates to that, in combination with the financial difficulties that hauliers are facing every day to make a profit out of their business, a strong demand on all sides is to decrease fuel consumption for heavy trucks. The objective is thus to find the fuel optimal way of driving a heavy truck, while trip time is respected. Optimal control of engine fueling and gear shifting, which generates an optimal vehicle speed profile and an optimal engine speed profile, is studied for long haulage highway driving missions. For this application and purpose, only the effects of topography are assumed to affect the objective and thereby only this look ahead attribute is considered. Topography maps are expected to be available for commercial purposes in a near future. However, since a long haulage truck often completes the same route many times, the gradient of the road traveled could alternatively be estimated off-line, see (Sahlholm, 2008), and used for control purposes in the coming drives.

The difficulties that arise with this problem formulation are various, e.g. the system models may be non-linear, and in order to find the optimal gear of a discrete transmission in combination with the optimal control of fueling, a hybrid optimization is required. Further on, this is very much a problem close to the real application, where the effects of a real environment must be evaluated in terms of unknown disturbances.

To conclude, an automatic powertrain control system, using look ahead information, has the potential to reduce fuel consumption in long haulage driving missions, independent of the experience of any specific driver. This is beneficial from many perspectives, both for environmental and economical reasons. Leg-
islation will eventually force reductions of $CO_2$ and consequently reductions of fuel consumption but, again, the greatest incentive of reducing fuel consumption is already present as the haulier significantly increases his profit with a low fuel consumption.

1.4 Powertrain control and road topography

The topography affects powertrain control of heavy trucks strongly, since uphill driving requires a much higher torque compared to going downhill and some hills are not possible to climb without shifting gears. Since the considered driving scenarios are restricted to highways, also the considered road gradients, $\alpha$, are restricted. According to the Swedish Road Administration (2004), a highway classified as high standard has road gradients according to $-6\% \leq \alpha \leq 6\%$, where uphill gradients are positive and downhill gradients are negative. The road gradient unit [%] corresponds to a 1 meter vertical elevation/hollow in a horizontal move of 100 meters. There are also restrictions in speed, and the maximum speed allowed for heavy trucks is 89 km/h.

Large road gradients, also denoted as significant hills, are defined in (Fröberg et al., 2006), as gradients where the vehicle looses speed when going uphill, even with maximum fueling, and gains speed when going downhill, even with no injected fuel. Large highway gradients are interesting in order to find slopes that enforce gear shifting, whereas small gradients are interesting when studying the characteristics of the fuel map. In the following subsections, general results from previous automotive research and common know-how in powertrain control are presented in terms of optimal speed, engine efficiency and gear shifting.

1.4.1 Optimal speed

In a driving mission on small gradients with a constraint on trip time, constant speed has been found to be fuel optimal by several publications, see (Chang and Morlok, 2005; Fröberg et al., 2006; Hellström, 2007), when assuming an affine relationship between injected fuel and engine torque. In roads with steeper slopes the propulsive control signal, i.e. injected fuel or engine torque, runs into its upper or lower limit and constant speed is no longer possible to keep only by controlling the propulsion. This is more often the case when driving a heavy truck, in contrast to passenger cars, due to its high vehicle weight in relation to engine power.

In a driving mission with significant hills trying to keep constant speed, as e.g. a standard cruise control, is not beneficial. Figure 1.2 shows a large uphill gradient followed by a large downhill gradient, classified for a 18000 kg truck with a 13 liter engine. The optimal speed is plotted for a required final time corresponding to a mean speed of 80 km/h. Prior to a large downhill gradient it is beneficial to decelerate, to let the potential energy gained when climbing up the hill accelerate the vehicle without violating the constraint of maximum
velocity. To fulfill the constraint on final time it is optimal to accelerate prior to large uphill gradients.

Compared to the optimal speed profile, a vehicle with a standard cruise control would have a lower speed when starting to climb the uphill, which might lead to the need of shifting gears. Moreover, the cruise control would have a higher speed when the downhill gradient starts, compared to the optimal speed profile, which leads to braking at the end of the slope, i.e. a waste of energy. The optimal acceleration before significant uphills is achieved by using maximum engine fueling and the optimal deceleration prior to significant downhills is achieved by using minimum engine fueling (Fröberg et al., 2006), assuming an affine relation between engine torque and fueling.

1.4.2 Fuel map – engine efficiency

When driving in small road gradients, fueling is not constrained by its upper or lower limit. Hence, for such a driving mission, the characteristics of the engine in partial loads is interesting. A fuel map contains data from measurements in an engine test cell for various stationary operating points, in a range from no load to maximum load and with various engine speeds. The fuel map studied describes the efficiency of the engine in terms of specific fuel consumption \([\text{g/kWh}]\), sfc, which is proportional to engine fueling over engine torque on the output shaft. In a traditional combustion engine, without any electric control system, the sfc map typically has a concave shape, see Figure 1.3.

For this type of fuel map the common assumption of affine relation between torque and fueling is most often a good approximation. However, the best efficiency of a combustion engine is traditionally at about 80% of maximum torque, and not at maximum torque as is the result of an affine relation. This concave phenomena is captured in one way in (Schwarzkopf and Leipnik, 1977) where the sfc model is a product of a second order polynomial in engine torque and a second order polynomial in engine speed. Another way of modeling the
concave fuel map is as a piece-wise affine relation between fueling, engine speed and torque, as in (Fröberg and Nielsen, 2007). The operating point, in terms of engine speed and torque, with the best engine efficiency is not always the best operating point from a complete vehicle perspective, since an optimal velocity profile on a non-constant road gradient requires a varying engine torque, and for large road gradients also a varying engine speed. The optimal torque/speed profile is a balance between a high engine efficiency and a low total energy consumption.

Modern engines may have other characteristics compared to the traditional concave fuel map, like peaks and valleys in sfc (see Figure 1.4), because of control strategies that today are possible to implement as for example after treatment of exhaust gases, optimization of gas flows and engine cooling control that are now common for combustion engines of heavy trucks. Modern fuel maps often contain non-linearities such that neither the assumption of affine relation between engine torque and fueling is valid nor are models fitted to concave fuel maps.

1.4.3 Shifting gears

Gear shifting is necessary in large road gradients if the maximum engine torque on the direct gear is not high enough to manage propeling the vehicle within an acceptable speed range. However, when cruising with fuel injection not in the limit, then as stated earlier the optimal speed, $v$, is constant. In this driving condition, when the power demand at the wheels, $P_w$, is low, it is always optimal to choose a low gear ratio and the reason to this is due to how the engine efficiency depends on engine speed for a certain power level. The demanded power is generated by the engine, $P_e$, and in the ideal case with no losses

$$ P_e = T_e \omega_e = T_w \omega_w = \frac{P_w}{T} = P_w $$

where $T_e$ is engine torque and $\omega_e$ is engine speed. The rotational speed of the wheels, $\omega_w$, is a function of wheel radius, $r$. As $T_w = T_e i$ and $\omega_w = \frac{w}{i}$ it can be seen that delivered power is not affected by gear ratio, $i$. A certain power
can accordingly be generated by a low engine speed and a high engine torque or vice versa. If the fuel map is assumed to be affine in fueling, $\delta$, and engine speed, according to

$$T_e = c_\delta \delta - T_{e,loss}(\omega_e) = c_\delta \delta - (c_\omega \omega_e + c_c)$$  \hspace{1cm} (1.2)

then if engine speed is low and engine torque is high, the engine has a high efficiency as the engine losses are relatively small. For a realistic concave fuel map (as in Figure 1.3) and realistic gear ratios of a discrete transmission, the gear ratio that gives the best efficiency is still the lowest gear ratio. This is true for the relatively low power demand in small road gradients. In large road gradients, the demanded power is higher and in this case maximum torque is required in combination with a high engine speed, which leads to the need of a higher gear ratio. If gearing down is necessary, gear shifting control determines when to switch gears.

Heavy trucks in long haulage are often equipped with a manual gear box which is automatically controled, i.e. an automated manual transmission (AMT). In Figure 1.5 a typical AMT gear shifting process is illustrated, in terms of engine torque and speed. An AMT system does not contain a clutch or torque converter. Instead engaging/disengaging of gears is enabled by engine torque control (as shown in Figure 1.5). This leads to a lower propulsive force for a couple of seconds. For tenths of a second, while shifting gears, there is no propulsive work produced at all. Of course, the traction of the vehicle is affected by the AMT gear shifting process. The low propulsive work during a gear shift leads to that vehicle speed is, for a short period of time, only determined by the driving resistance. The driving resistance varies along the road profile and consequently vehicle speed is differently affected dependent on when the gear shift is executed.

A difficult problem for a truck driver is to choose the optimal gear prior to and whilst in a steep slope. To ensure driveability, comfort and performance...
Chapter 1. Truck driving

An experienced driver plans the necessary gear shifts when approaching steep slopes, according to his/her knowledge of the behaviour of the truck while shifting gears in a certain driving resistance and for a given speed. However, finding the fuel optimal gear shift control is not as intuitive. The AMT aims at optimizing all criteria, but since the future road gradient is not known, the system chooses gears with a safety margin necessary if the driving conditions would change suddenly, e.g. if the slope would become steeper. However, the safety margin leads to that gear shifts are most often not performed in an optimal manner. With look ahead information the need for safety margins is decreased and the system becomes more reliable in all driving scenarios.

1.5 Outline and contributions

The contributions are hereby stated, also giving an outline of the thesis. This thesis is based on three papers with the same objective, reducing fuel consumption while keeping to a set trip time, by using look ahead information.

Paper 1 is an article published in Control Engineering Practice Volume 17 no. 2, pp. 245-254, 2009;

Look-ahead Control for Heavy Trucks to Minimize Trip Time and Fuel Consumption, Erik Hellström, Maria Ivarsson, Jan Åslund and Lars Nielsen.

It is an extended version of a conference paper with the same title and authors presented on the Fifth IFAC symposium on advances in automotive control, California, 2007, (Hellström et al., 2007). A control algorithm previously developed, (Hellström et al., 2006), is in this paper adapted and evaluated in real trial test runs. In (Hellström et al., 2006) it was shown in simulations that for heavy trucks it is possible to reduce fuel consumption by controlling vehicle speed in an optimal way. Another result from the simulations is that gear shifting is less likely to occur when driving with an optimal speed profile compared to driving with a standard cruise control. The model used in the optimization assumed an affine relation between injected fuel and engine torque. In Paper 1 the same optimization is performed in real time in a heavy truck, where the optimal solution is executed by adjusting the set speed of the standard cruise control. It is shown that the predicted fuel reductions are possible to obtain also in a real environment with its disturbances, model errors and time lags. Paper 2 and Paper 3 present studies that are inspired from the results of Paper 1.

Paper 2 is an extended version of the conference paper, Optimal Speed on Small Gradients – Consequences of a Non-Linear Fuel Map, Maria Ivarsson, Jan Åslund and Lars Nielsen, presented at the IFAC World Congress in Korea 2008 (Ivarsson et al., 2008);
1.5. Outline and contributions

**Look Ahead Control – Consequences of a Non-Linear Fuel Map on Truck Fuel Consumption**, Maria Ivarsson, Jan Åslund and Lars Nielsen.

Engines with non-linear dependencies between injected fuel and engine torque are studied. The commonly used efficiency measure sfc, specific fuel consumption, is studied in a realistic fuel map. Peaks and valleys in sfc indicate that some operating points of the engine are more efficient than others. To investigate how the characteristics of the fuel map non-linearities affect the fuel efficiency of the vehicle, driving missions with small road gradients are considered. It is shown that for some significant sfc non-linearities, constant speed is not optimal, as is the case when engine torque is affine in fueling. The critical threshold value of a significant non-linearity is defined, and the resulting behaviour is investigated.

**Paper 3** is a technical report at the Departement of Electrical Engineering, Linköpings Universitet, LiTH-ISY-R-2883;

**Impacts of AMT Gear-Shifting on Fuel Optimal Look Ahead Control**, Maria Ivarsson, Jan Åslund and Lars Nielsen.

A model is set up of a standard AMT gear-shifting process reflecting the characteristics that influence final time and fuel efficiency. In order to minimize fuel and time, optimal engine fueling and gear control is found for realistic uphill slopes. The optimal solutions show that gearing down unnessecarily is always unbeneifical, but still not an uncommon scenario for a standard AMT. Further on, it is shown that the reduced propulsion of a typical AMT gear-shifting process, and the resulting vehicle retardation, must be considered when choosing when to shift gears, in order to ensure an adequate engine speed and a sufficient engine power after the gear shift and consequently to achieve a reduction of fuel consumption and final time.
Chapter 1. Truck driving
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