

# Final report

## **Minimization of emissions from heavy duty vehicles by information enabled control**

Project 310 10 1725

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## Summary

The project has focussed on computational studies aiming at investigating the potential of predictive energy management for improved fuel economy and reduced NO<sub>x</sub>-emissions.

Optimal control of a parallel hybrid vehicle has been studied with different methods. A fuel consumption reduction of 3-4 % has been achieved with only changing the torque distribution between the electric motor and the combustion engine for a typical city bus route. When also the gear selection and start/stop of the combustion engine was optimized, the fuel consumption decreased with 12-19 %. It was possible to simultaneously decrease the NO<sub>x</sub>-emissions with more than 70 %.

Real-time controllers have been implemented in the simulation environment. The controllers have been rule-based or based on fuzzy logic. More than half of the potential fuel consumption decrease was utilized with the real-time controllers in the simulations.

A new method for finding the optimal control algorithm has been developed by Chalmers. The dynamic vehicle model is automatically simplified into static relations without the need for detailed understanding of the model. Dynamic programming is used to solve the optimization criteria chosen by the user, e.g. fuel consumption and NO<sub>x</sub>-emissions.

## Sammanfattning

Projektet har fokuserat på simuleringsstudier med målsättningen att undersöka potentialen för minskad bränsleförbrukning och emissioner med hjälp av förhandsinformation.

Optimal reglering av en parallell hybridfordon har studerats med olika metoder. En minskad bränsleförbrukning på 3-4 % för en typisk stadsbusslinje har uppnåtts enbart genom att ändra momentfördelningen mellan elmotorn och förbränningsmotorn. När även växelval och start/stopp av förbränningsmotorn optimerades minskade bränsleförbrukningen med 12-19 %. Det var möjligt att samtidigt minska NO<sub>x</sub>-utsläppen med mer än 70 %.

Realtidsregulatorer har utvecklats och testats i simuleringsmiljön. Regulatorerna har utvecklats antingen med hjälp av fuzzy logic eller regelbaserade strategier. Mer än hälften av den potentiella bränsleförbrukningsminskningen kunde erhållas med hjälp av realtidsregulatorerna i simuleringarna.

En ny metod för att hitta en optimal styralgorithm har utvecklats av Chalmers. De dynamiska fordonsmodellerna förenklas automatiskt till statiska relationer utan att det krävs detaljerad förståelse av modellen. Dynamisk programmering används sedan för att lösa de optimeringskriterier som valts av användaren, t.ex. bränsleförbrukning och NO<sub>x</sub>-emissioner.

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# 1 Background

Emission legislation for heavy duty vehicles is based on fulfilling specified test cycles in an engine dynamometer. The test cycles are based on logged vehicle data, but do only represent a certain mix of different applications. In real use, different vehicles may be operated very differently from each other depending on the application. The in-use emissions may be both lower and higher than the emissions measured during a certification procedure.

One way to lower the emissions for vehicles on the road is to take into account the operating conditions that will occur in an upcoming time frame. By estimating the torque and engine speed that the engine will operate at, it is possible to adjust the present operating point so that the integrated fuel consumption and exhaust emissions become as low as possible.

There are several ways in which it is possible to predict the upcoming operating points for the vehicle, but the most obvious and perhaps easiest to fully utilize is route information coupled to the geographical position of the vehicle (by *e.g.* GPS system). For a bus, the route information would include bus stops and red lights. Other sources on information may include traffic information and vehicle sensors that analysis the surroundings of the vehicle.

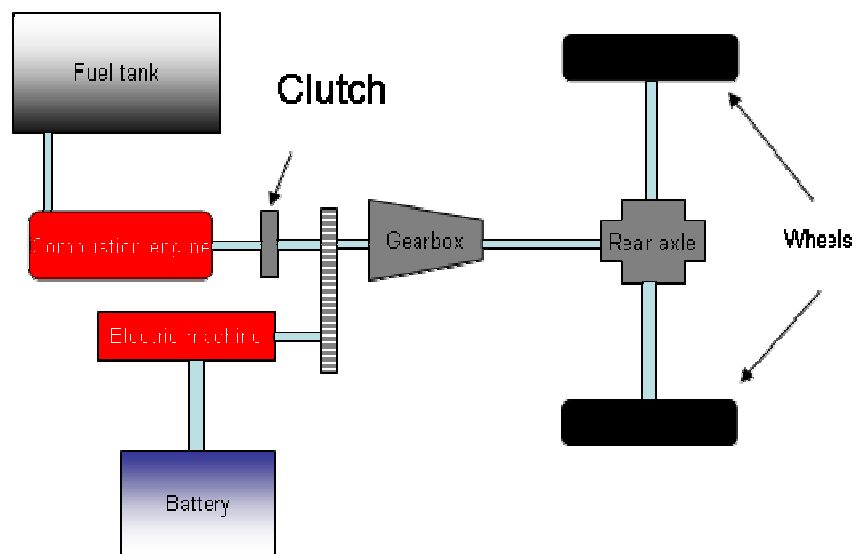
Preview information is most useful when there are vehicle states that changes in the order of several seconds to several minutes. Typical slow changes are the charging and discharging of a battery, especially in a hybrid vehicle, the air temperature inside a bus and the regeneration and soot accumulation in a particulate filter. All these state changes correspond to use of energy for the vehicles, and it is often possible to minimize the total use of energy by properly selecting the time for the transition. A typical example is that it is often better to wait with recharging the batteries of a hybrid vehicle until the vehicle has passed the top of a hill.

This project has focused on hybrid vehicles, as the potential benefits from preview information were identified to be much larger than for commercial vehicles. A summary of potential benefits for conventional drivelines is given in Chapter 4, Auxiliary control.

## 2 Parallel hybrid vehicle control

Parallel hybrid vehicles have a relatively high potential of fuel saving by use of predictive control. They carry a significant energy buffer in form of a battery and they also have the ability to blend torque from the combustion engine and electric motor, respectively.

A schematic view of a parallel hybrid vehicle, as used in this project, is shown in Figure 1. A clutch is located between the combustion engine and the gearbox, which makes it possible to run the vehicle by using only the electric machine for short distances, for example during take-off and at low speeds.



**Figure 1. Schematic view of a parallel hybrid vehicle**

Preview-information-based optimization of the torque blend enables running of the ICE (Internal Combustion Engine) in high-efficiency load points, thanks to the possibility to be closer to the battery state of charge (SOC) limits. The SOC can also be allowed to be closer to levels at which the storage efficiency is higher. The largest fuel saving can be obtained if optimization of the torque split is combined with optimization of the gear selection. This enables significant improvement of the efficiency in the ICE operating points.

A realistic estimation of the possible reduction in fuel consumption may be around 5-10 % when optimizing torque split and gear selection for a vehicle experiencing a large number of accelerations and decelerations. However, to reach this, one must succeed in translating the optimal control strategy to an efficient strategy that is implementable on board.

### 2.1 Potential of Predictive Control for Parallel-Hybrid City Bus

A diploma work regarding predictive control of the powertrain of a parallel hybrid was carried out by Erik Manderstedt and Magnus Nilsson. The title

of the study was “Potential Fuel Savings by Using Information Enabled Control in a Hybrid Diesel-Electric Bus”.

The aim of this work was to investigate the fuel-saving potential of using preview-information-based control of the torque blend in a parallel-hybrid city bus. The fuel saving potential was determined by comparing a reference control strategy with the optimal control strategy that was determined by dynamic programming. The degree of improved fuel economy for the optimized power split between combustion engine (ICE) and electric motor (EM) was dependent on the drive cycle. Four different drive cycles were investigated, one short and one long city bus cycle, one highway cycle (Landvetter-Borås) and one refuse-truck drive cycle.

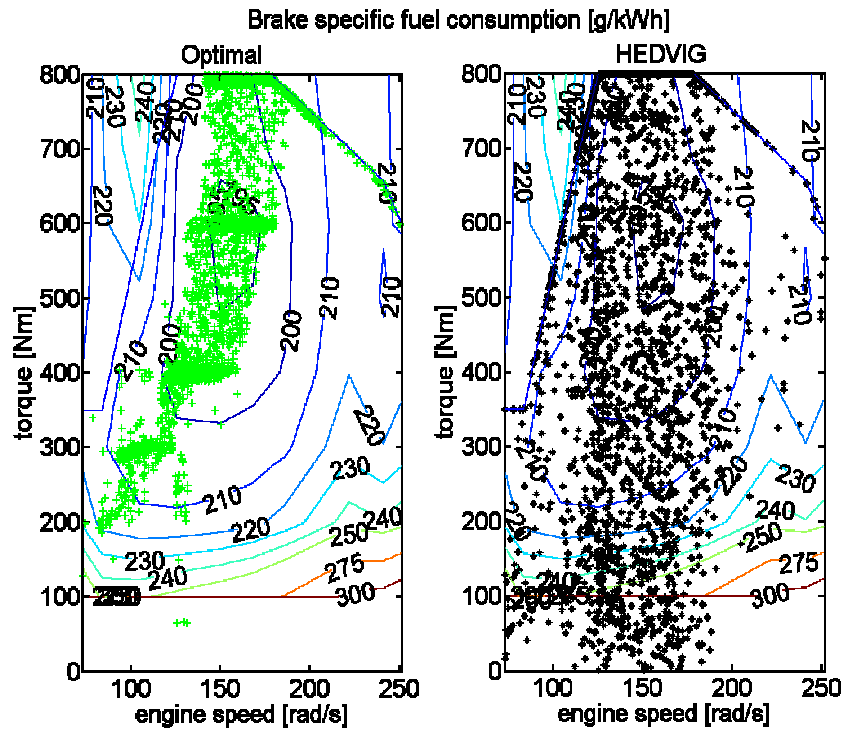
For the long city-bus cycle, the difference in fuel consumption between the optimal control strategy and the reference strategy was 3.5 %. For the shorter city bus cycle, the corresponding number was 0.7 %. The fuel consumption on the highway drive cycle was reduced by 0.3 %, whereas for the refuse truck cycle, 2.3 % fuel was saved with the optimal control strategy.

The reference strategy used for controlling the vehicle was mainly based on three rules:

1. The electric motor was used for assisting the combustion engine only when the torque demand from the driver was higher than what was available from the combustion engine.
2. The electric motor was used for retarding the vehicle before applying the mechanical brakes, thereby recharging the batteries during retardations.
3. During all other conditions, the electric machine was used to control the state-of-charge of the battery by either charging or discharging.

Significantly larger fuel savings could be obtained if also the gear selection and the option to keep the combustion engine running or not were included in the optimization. When including this, the fuel consumption for the longer city bus cycle was reduced by 13.2 %.

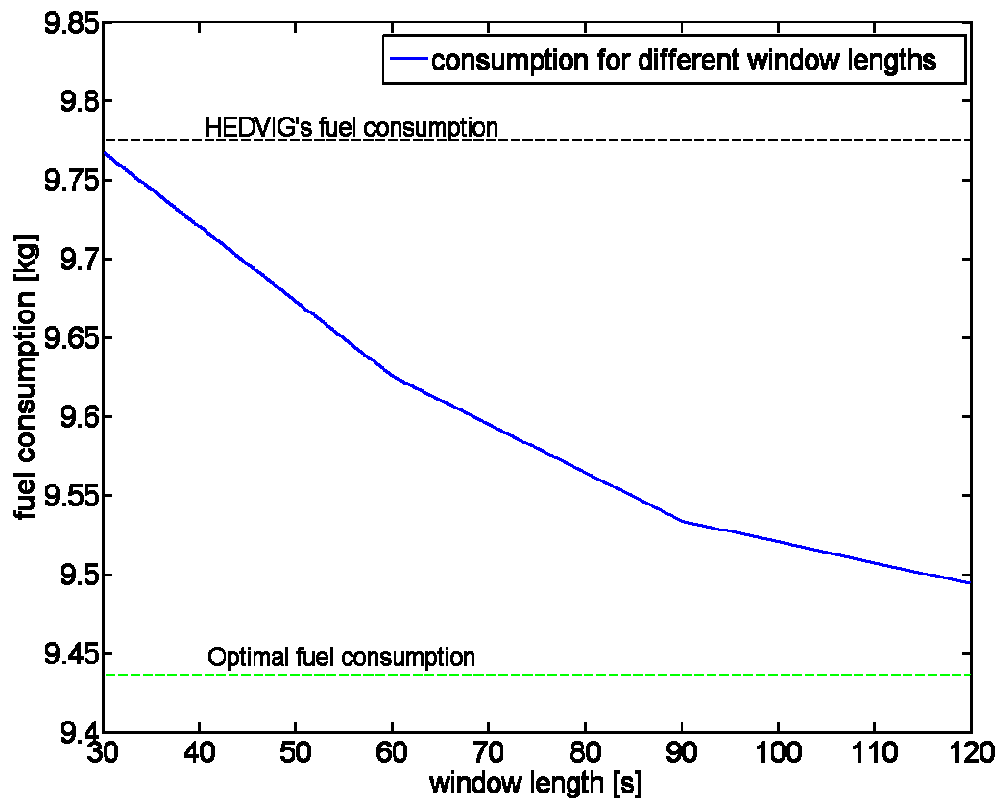
The effect of allowing an optimal gear selection is clearly shown in Figure 2. Almost all operating points for the optimized vehicle are close to the operating point with the lowest fuel consumption for the given torque demand. There are also a fairly large number of engine operating points with low or negative torque demands for the non-optimized vehicle. The optimized vehicle does not use the engine during those conditions, instead the engine is either operating at a higher load or turned off.



**Figure 2. Operating points for bus with optimized gear selection (left), and without optimization (right).**

The fuel consumption when only part of the drive cycle was known was also investigated. For the long city-bus cycle, 2.9 % fuel was saved with only 120 seconds of the future driving route known, see Figure 3. Notice that for 30 seconds of preview information, only a very small effect could be found. The optimization was however performed without allowing for new gear strategies.

The influence of the sizes of the electric machine and the battery were also studied. For a hybrid with a large electric motor, the effect of the optimal control will be larger, since a large EM increases the possibility of finding ICE operating points with high efficiency. On the other hand, with increasing size of the battery, the effect of a preview optimal control strategy will decrease. Thus, with optimal control, the battery size becomes less important for fuel economy.



**Figure 3. Effect of the length of preview information for the total fuel consumption.**

## 2.2 Rule-based Predictive Control for City Bus

During 2007, Joakim Persson and Thomas Lundberg carried out a diploma work called “Hybrid Powertrain Control: A Predictive Real-time Energy Management System for a Parallel Hybrid Electric Vehicle”. The purpose of this work was to investigate whether it is possible to develop a rule-based controller that mimics the behaviour of an optimal control strategy for a hybrid city bus. The rule based controller was designed for easy implementation into the engine management system.

Dynamic programming was used to find an optimal solution which in turn was used as a blueprint for a rule-based controller. The transition from optimal control to rule-based control was carried out by use of fuzzy logic. On board the vehicle, preview information will be given from a topographic map combined with a GPS for vehicle positioning. This information together with a speed curve will give information about the future power demand. To simulate this behavior, parts of the drive cycle in front of the vehicle was used. The relevant preview information was road inclination and the desired speed. The preview information both for a shorter time period (~10 s) and for a longer time period (~60 s) was used for training the fuzzy logic matrix. In addition to the preview information, the state-of-charge and the torque demand was also used to train the fuzzy logic matrix.

The optimal and rule-based control was compared with the ISAM control system as a reference system. The simulations showed that the fuel saving on a city-bus route was about 3.5 %, when using the optimal control strategy determined by use of dynamic programming instead of the ISAM

control system. When the rule-based control was used, the fuel reduction was about 2 %, compared with the ISAM control. These results have been obtained by controlling the torque split between the internal combustion engine and the electrical machine, without optimizing the gear selection and the on/off state of the combustion engine.

Simulations including optimization of gear selection were also carried out. These simulations resulted in a fuel reduction of about 12 % compared with the ISAM control. However, these results were based on unrealistic presumptions, e.g. instantaneous gear shifting and these results were thus not considered in the rule-based controller. The study also showed that with the rule-based controller, the energy flow to and from the battery was reduced, which prolongs the battery lifetime.

## 2.3 Optimization of Fuel Economy and NO<sub>x</sub> Emission of a Hybrid Bus

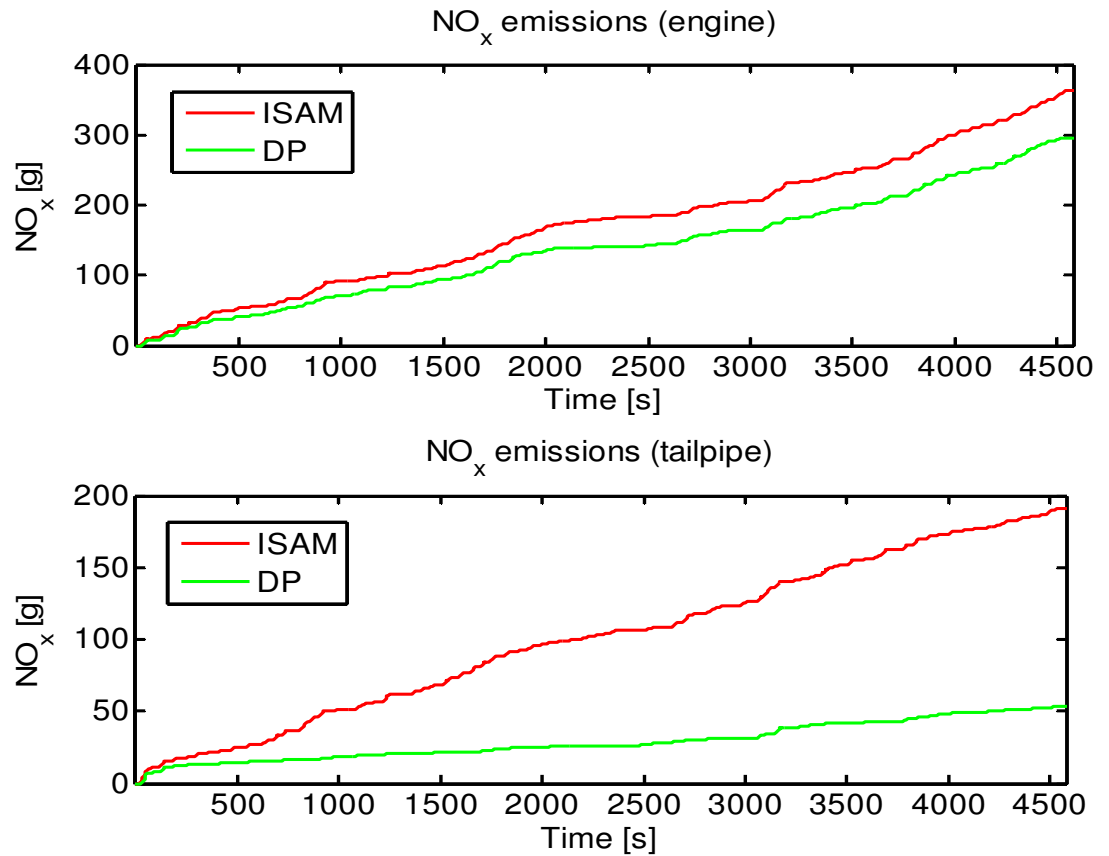
Maja Winstrand, the first Ph.D. student at Chalmers, developed methods during the first part of the project for reducing the NO<sub>x</sub> emissions occurring during engine transients. After having built up understanding of how the diesel engine works, and how the available signals related to one another, it was concluded that the NO<sub>x</sub> sensor was too slow to detect any large transient effect, although verified engine models predicted a contribution to the total NO<sub>x</sub>-emissions due to transient operation. Although these results were disappointing, the insights have been useful in the rest of the projects and in the diploma work “Optimized fuel economy and NO<sub>x</sub> emission for a hybrid vehicle” carried out by Karl Eberth and Erik Botö. In this work, the potential benefits of hybridization in terms of lowered fuel consumption and tailpipe NO<sub>x</sub> was investigated by simulation studies and dynamic programming on a parallel hybrid city bus. The bus was equipped with a 7 litre diesel engine and an SCR (Selective Catalytic Reduction) system.

The NO<sub>x</sub>-emissions may be lowered by either running the engine at operating points with lower NO<sub>x</sub>-emissions, or by improving the catalyst efficiency in the vehicle. The most important parameters for the catalyst efficiency are the temperature of the catalyst and the exhaust flow rate. The SCR-catalyst was modelled by dividing the catalyst into 5 blocks, each block having a uniform temperature and NO<sub>x</sub>-concentration. A steady-state model of the engine was used for estimating the NO<sub>x</sub>-emissions during the drive cycles.

A simple, real-time control strategy for fuel and NO<sub>x</sub> emission reduction was implemented in the vehicle simulation to show that most of this potential can be exploited using a rule-based controller.

Dynamic programming (DP) was used to optimize the torque distribution between the combustion engine and the electric machine with respect to fuel consumption and tailpipe NO<sub>x</sub> emissions.

Results of the drive cycle optimization showed an improvement of 19 % in fuel consumption and a reduction of NO<sub>x</sub> by 73 %, compared with the original control strategy, see Figure 4.



**Figure 4. NO<sub>x</sub> emissions from engine (top) and after SCR-catalyst (bottom). Red curves are without optimization, green curves are from optimized vehicle.**

The results for the real-time controller showed reduced fuel consumption by 18 % and reduced tailpipe NO<sub>x</sub> emissions by 56 %, thus utilizing most of the potential gain of the optimal control.

Comparing the amount of NO<sub>x</sub> before and after the SCR catalyst showed that the greatest reduction in NO<sub>x</sub> emission resulted from raising the temperature in the SCR catalyst and not from reducing the amount of engine out NO<sub>x</sub>.

The potential for fuel saving in this thesis work, approximately 20 %, is higher than reported in the previous diploma work by Joakim Persson and Thomas Lundberg. This is a due to the fact that a larger engine was used in this later work and that the torque region for which the engine is most efficient lies higher. The reference control strategy's conservative use of the EM prevents it from using the larger engine in its most effective region, and, thus, performs quite badly for this engine. Another reason for the large improvement is that the most efficient region in the larger engine's BSFC-map is wider and thus more exploitable.

It was found that the low tailpipe NO<sub>x</sub> emission and low fuel consumption was quite correlated. This is mainly caused by the effect that operating points at low loads are both inefficient from a fuel consumption perspective, and that low load operating points cool the SCR catalyst causing the NO<sub>x</sub> conversion efficiency to decrease.

### 3 Tool for generation of optimal control strategies for hybrid and conventional vehicles

Testing new ideas and products in industry is usually costly, time consuming and not seldom viable. For this reason automobile industry, among others, attempts to create realistic vehicle models to address real-life test scenarios in simulation environment. In order to meet the behaviour of the real-life systems, the simulation models are being constantly extended and upgraded leading to longer simulation time and depending on the driving cycle this can take up to several minutes or hours. In optimization routines where many simulations are to be repeated the required time is as bigger as impractical. The simulation time can be reduced by simplifying the vehicle model and traditionally this is conducted in several lookup tables for the prime movers and the battery. Typically, all states describing transients when demanded torque is changed are removed, and slow varying states, such as the state of charge of the battery and the chosen gear, are kept. Many vehicle parameters and losses of the components are eventually neglected resulting in inaccurate model even in steady state conditions.

This work proposes a user friendly tool for generation of optimal control strategies over a given driving cycle, Figure 5. The dynamic vehicle model is first automatically simplified into static relations without taking apart the vehicle components and then optimized adhering to the optimization criteria given by the user without requiring broad knowledge of the vehicle model. The tool has been developed by Nicolce Mugorski, Ph.D. student at Chalmers. Nicolce began his Ph.D. studies in August 2007, replacing Maja Winstrand in the project.

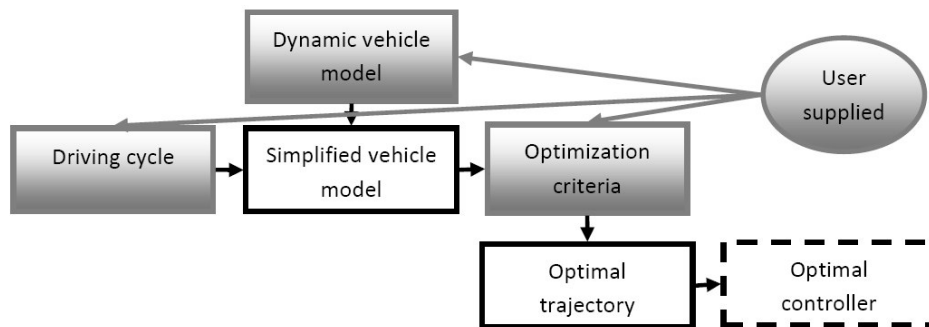
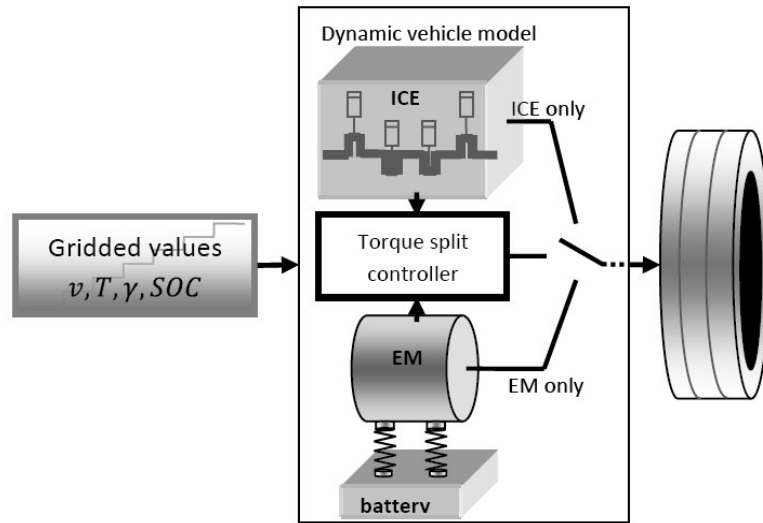


Figure 5: Tool for generation of optimal control strategies.

#### 3.1 Automatic vehicle model simplification

Traditionally, HEV vehicle models were being simplified component-wise, meaning that separate static maps were being considered for different vehicle components, for instance a map for the internal combustion engine (ICE), the electric motor (EM), several maps for the battery state of charge (SOC), battery open circuit voltage ( $V_{OC}$ ), battery charge/discharge resistance ( $R_{c,d}$ ) and eventually gear losses. Generation of the maps primarily requires uncoupling the vehicle components from the rest of the dynamic model, a process which, if attainable, necessitates deeper understanding of the vehicle model.

In this work the vehicle is simplified as a whole and the procedure is explained through an example of simplified vehicle model of a mild parallel HEV that is used for optimization of the fuel consumption.



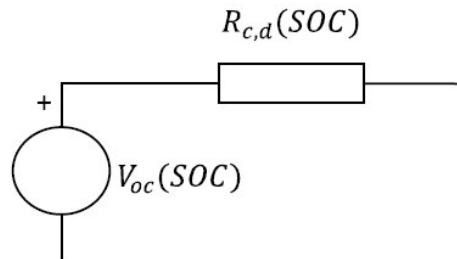
**Figure 6: Manual selection of a prime mover**

The dynamic model is simplified in two lookup tables,  $f_{ICE}: R^3 \rightarrow R$  and  $f_{EM}: R^4 \rightarrow R$ . The first map  $f_{ICE}$  gives the ICE fuel-flow  $\dot{m}_f$  as a function of the vehicle speed  $v$ , traction torque  $T$  and selected gear  $\gamma$ . The map is generating with EM inactive during the whole drive. The second map  $f_{EM}$  gives  $\dot{SOC}$  as a function of  $v$ ,  $T$ ,  $\gamma$  and  $SOC$ . When this map is generated ICE is held inactive. For this to be feasible, the dynamic vehicle model must possess an option for turning off the torque split controller and running the vehicle by only one prime mover at a time, see Figure 6. The novelty in this approach is the  $f_{EM}$  map which now unifies the  $SOC$ ,  $V_{oc}$ ,  $R_{c,d}$  and EM maps and can be merely extracted without requiring advanced knowledge of the vehicle model. When static model is being used for the battery, see Figure 7, the only state in the model is found as:

$$SOC(t) = SOC_{init} - \int_0^{t_f} \dot{SOC}(t) dt \quad (1)$$

$$\dot{SOC}(t) = \frac{V_{oc}(SOC) - \sqrt{V_{oc}(SOC)^2 - 4(T_{EM}(t)\omega_{EM}(t) + P_{aux})R_{c,d}(SOC)}}{2R_{c,d}(SOC)Q} \quad (2)$$

where  $T_{EM}$  and  $\omega_{EM}$  are the torque and speed of the electric motor,  $P_{aux}$  is the power consumption of the auxiliary devices and  $Q$  is the total battery capacity.



**Figure 7: Static battery model.**

The change of  $\dot{SOC}$  depends only on the change of  $T_{EM}$ ,  $\omega_{EM}$  and  $SOC$  and when these are kept constant, a constant value for  $\dot{SOC}$  is expected

as well. More accurate battery model which involves some extra parameters (for example temperature) will entail these parameters be included in the  $f_{EM}$  map generation.

### 3.1.1 Validation of the static model

The  $f_{ICE}$  map is validated by comparing  $\dot{m}_f$  generated by the dynamic vehicle model and the static map over the same driving cycle. The dynamic model is run without using the electric motor. In order to be sure that the same speed, torque and gear selection are experienced by the models, first the dynamic model is run on the given driving cycle, its speed, torque and selected gear are measured and then run through the simplified model, see Figure 8. The results in Figure 9 and Figure 10 show that the simplified model gives adequate outputs which are consistent even in transient regions.

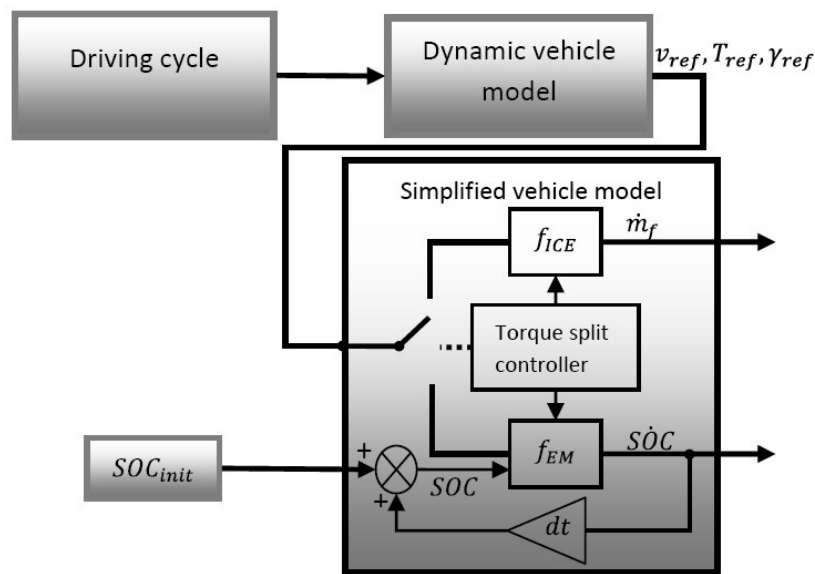


Figure 8: Simulation of the simplified vehicle model.

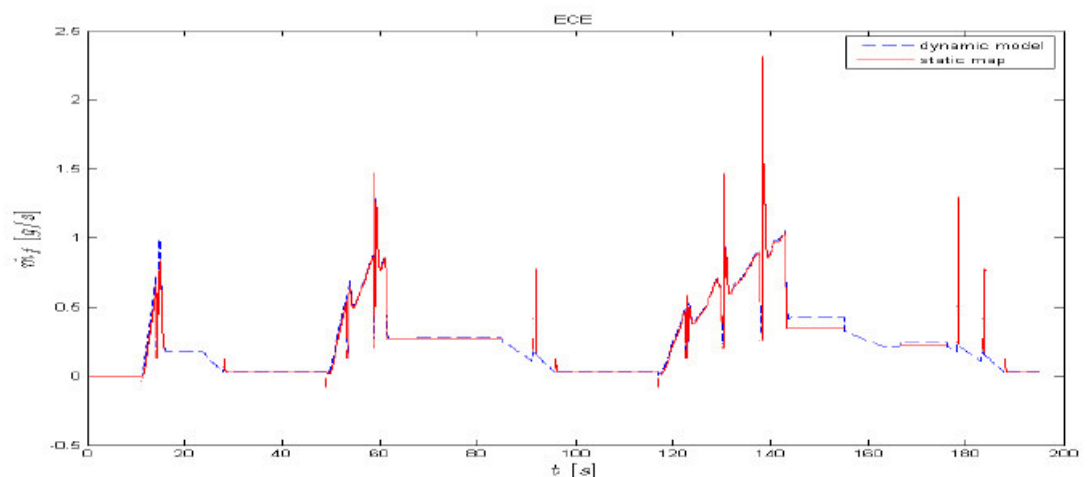


Figure 9: Validation of the  $f_{ICE}$  map.

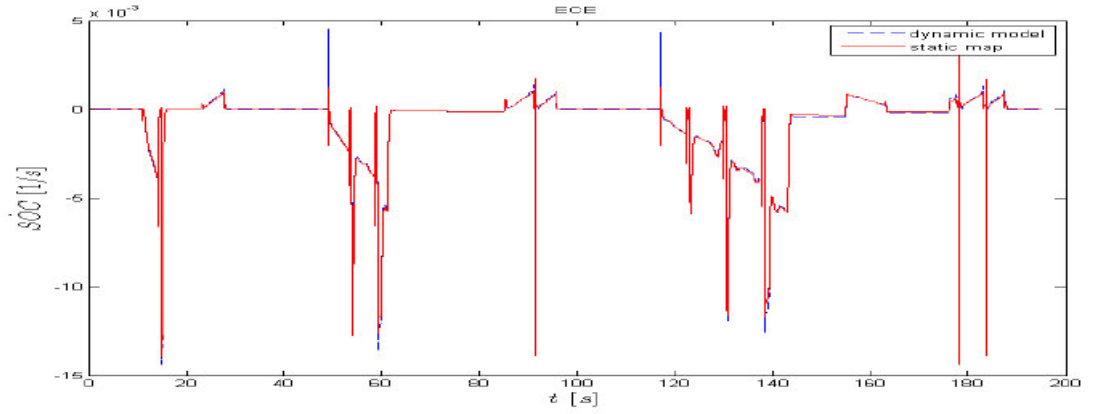


Figure 10: Validation of the  $f_{EM}$  map.

### 3.2 Optimization of fuel consumption

Once the simplified vehicle model is generated and optimization criteria are chosen by the user, dynamic programming is used for generating the optimal control trajectories throughout a driving cycle. In a plain case of optimization of fuel consumption one state is considered, the battery state of charge SOC and the torque split between the prime movers as a control signal. The reference torque, speed and gear are not directly generated from the driving cycle (this will require some knowledge of the vehicle model), but rather taken from the dynamic model previously run on the driving cycle, see Figure 8. The cost function to be minimized has the form:

$$J(t) = \sum_{t=t_f}^{t_0} \dot{m}_f(t) + \beta(SOC(t_f) - SOC_f)^2 \quad (3)$$

where  $\beta$  is a real positive weighting factor and  $SOC_f$  is the desired SOC value at the final time  $t_f$ . The optimization results in an optimal cost matrix  $J^*(t, SOC)$ , see Figure 11, with as many optimal trajectories as initial SOC values.

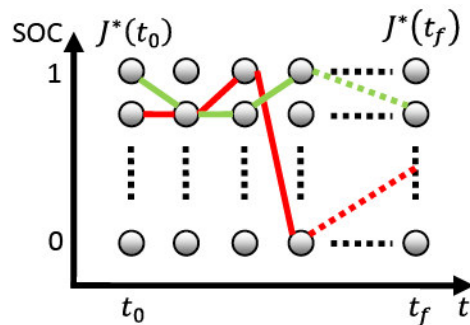


Figure 11: The red and the green line correspond to optimal trajectories for two different initial SOC values.

## 4 Auxiliary Control

In order to implement more efficient controls of the auxiliary loads, it is necessary to control their speed and engagement, which is often not possible in present truck applications. Generally speaking, electrification of auxiliaries or change to hardware with higher efficiency could possibly reduce their power requirement by about 20 % (however, this may vary significantly depending on auxiliary and application). Likely, only a small portion of this can be achieved thanks to preview-information-based control.

A study by Volvo has measured the power consumption of various truck auxiliaries. The main conclusions of the study were as follows:

- The oil pump had the greatest impact on fuel consumption, 1-1.2 % depending on duty cycle
- The cooling fan was not engaged during highway tests.
- It is important to take into account the duty cycle of the component in comparison with that of the engine. For example, an auxiliary load that is only engaged during motoring or engine braking may have a high power consumption, but it will not affect fuel consumption as no fuel is injected during its operation.

In summary, this type of control is probably only worthwhile for certain auxiliaries and in applications where the auxiliary loads are relatively high and not critical to the operation of the vehicle (e.g. AC compressor and cooling fan control in a city bus).

A diploma work on predictive control has previously been carried by Johan Bringhed and Filip Edström by Chalmers and Volvo. The title of the work was "Potential for Information Enabled Control in Heavy Duty Applications". The aim was to investigate the potential of using preview information when controlling applications such as air conditioning (AC) and the engine cooling system in two conventional heavy-duty vehicles; a city bus and a heavy truck.

For the predictive AC control in the bus, the average decrease of the total fuel consumption was roughly 1 %, compared with the best strategy without preview information. In the truck, on the other hand, since both the energy buffer and the energy usage for the AC system were much smaller, the fuel saving for the predictive AC truck control was only 0.06 %.

For the engine cooling optimizations, the average decrease of the total fuel consumption was 1.3 % for the truck and 1.5 % for the bus. However, it should be noted that the above numbers regarding the engine cooling system were calculated assuming that the average power of the cooling fan was about 4 kW. The global average fan power for Volvo trucks is lower, and about 1 kW.

Optimizations were also carried out with limited preview information. These showed that, given that the update of information is done sufficiently often, there is a limit on how much information the optimal control strategy needs, to achieve a result that is as good as when the entire drive cycle is known.

## 5 Results and discussion

The use of preview information has a large potential for reducing the fuel consumption and exhaust emissions from heavy duty vehicles. The largest potential has been shown for hybrid vehicles, where the driveline controller may use either the combustion engine, the electric motor or a combination thereof for propulsion.

The optimal control strategy for the simulated hybrid vehicles has been determined by using dynamic programming. A fuel consumption reduction of 2-3 % has been shown for bus applications when the gear shift strategy was unchanged. Allowing an optimization of the gear shifts and start/stop of the combustion engine increased the fuel consumption reduction to 12-19 % for the studied vehicles. It will not be possible for a real-time controller to match an optimal controller, but a fuel consumption reduction of as much as half of the reduction with an optimal controller will be a very significant contribution for the environmental impact and economy of the vehicle. Two of the diploma works have successfully implemented real-time controllers in the simulation environment. The optimal control strategy will also give clues for building improved rule based control strategies.