

Optimal Vehicle Control for Fuel Efficiency

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ABSTRACT

CONVENIENT is a project where prediction and integrated control are applied on several subsystems with electrified actuators.

The technologies developed in this project are applied to a long-haul tractor and semi-trailer combination. A Volvo truck meeting the Eu6 emission standard is rebuilt with a number of controllable electrified actuators. An e-Horizon system collects information about future road topography and speed limits. Controllable aerodynamic wind deflectors reduce the wind drag. The tractor is also equipped with a full digital cluster for human machine interface development.

A primary project goal is to develop a model-based optimal controller that uses predictive information from the e-Horizon system in order to minimize fuel consumption. Several energy buffers are controlled in an integrated and optimal way using model predictive control. Several buffers are considered, such as the cooling system, the battery, and the vehicle kinetic energy. This paper presents details on the model predictive controller of the battery system and of the cooling system.

Another project goal is to reduce fuel consumption by using adaptive aerodynamics. Controllers are developed that automatically sets an optimal roof deflector angle and the optimal side deflector angle. The results presented in this paper are encouraging.

A third focus is the human machine interface and especially the communication between the driver and the control system during driving. This project develops a driver interface that encourages the driver to use the adaptive cruise controller when appropriate.

The CONVENIENT project will be finalized this year. This paper presents the main project findings.

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INTRODUCTION

Truck manufacturers are challenged with increasing demands to improve fuel efficiency. Fuel costs are a significant proportion of the total cost for owners of heavy duty long-haul trucks. There is a growing understanding in the industry that there has to be a holistic perspective on vehicle control in order to reduce fuel consumption. It is not enough to focus on optimizing isolated components or subsystems.

The ambition of this project is to capture the benefit of holistic solutions for fuel efficiency. Three different technology areas are studied: energy management, adaptive aerodynamics and Human Machine Interface (HMI). The goal of the project is to explore the

potential of predictive optimal control rather than focusing on the hardware (HW) setup. The fuel consumption gain (FC) is shown by simulation. The purpose of the real truck is to solve implementation problems, and to prove functionality in a real application.

Energy Management through Predictive Optimal Control

A number of technical development steps enable a holistic view on vehicle control in order to improve fuel efficiency:

- Powerful control units and increasingly sophisticated development tools make it possible to use computationally-intensive control methods.



- There is an increased number of electrical actuators in the vehicle. This trend is accelerated as the hybrid electric powertrain makes its entrance in heavy duty vehicles. Electrification of actuators increases the controllability and degree of freedom for the control system.
- By using technologies such as GPS, camera and radar it is possible to predict the vehicle motion. This knowledge makes it possible to fully control and utilize the energy stored in the vehicle. An example is that if the truck is approaching the crest where an uphill will change into a downhill, the coolant temperature could temporarily be allowed to be higher than the nominal temperature knowing that the heat produced by the engine will drop during the descent.

This paper presents an integrated optimal controller for the cooling system and the battery system using Model Predictive Control (MPC).

Adaptive Aerodynamics

There are several controllable aerodynamic devices on a truck that reduce the aerodynamic drag. Among the ones that would be of significant influence to aerodynamics and fuel consumption are: grill shutter or radiator shutter, adjustable ground clearance (ride height) by use of air suspension setup, adjustable gap size between tractor and trailer, automatically deployed boat tail device, automatically adjusted roof deflector and automatically adjusted side deflector.

In this project, Volvo has chosen to study:

- Automatically adjusted roof deflector by means of an actuator and a control loop that optimize its position with respect to trailer geometry (height, width, type of cargo etc.). The optimal position is assessed by pressure sensors that reflect aerodynamic loading.
- Automatically adjusted side deflectors by means of an actuator and control strategy that is based on pre-defined data indicating the relation between the side wind angle and optimum side deflector position. The side wind angle is measured using a yaw wind sensor.

Human Machine Interface

Automation in vehicles is a current trend in the automotive industry. The work on developing enabling technologies, e.g. sensors and regulating systems is progressing. The range of automation levels vary from assisted to full automation (SAE standard J3016). However, vehicles that are not defined as fully automated require a human being either to drive the vehicle and/or to monitor the automation system to various extents. This means that the traditional roles and tasks of the driver need to be redefined. It also means that the automotive industry is facing a complex challenge to design the HMI between the human and the automated system/vehicle in terms of graphical, audio and haptic interfaces. The underlying design principles for safe and efficient HMI need to be revised.

This project focuses on the interaction between the adaptive speed controller [1] denoted eACC¹ and the driver. The driver's understanding of the eACC functions and limitations is crucial, and to a great extent is related to the system's ability to communicate with the driver. This is also important for the drivers to feel trust in the system and to gain acceptance which is central in the area of HMI.

Hardware Setup

The technologies developed in this project are applied to a long-haul tractor and semi-trailer combination. A Volvo 6×2 tractor, see [Figure 1](#), with a 13 L 460 hp Euro 6 SCR engine is rebuilt with a number of controllable electrified actuators such as electrical fans, a radiator shutter, an electrical water pump, an additional generator, controllable thermostat and an electrohydraulic power steering servo. The battery is an AGM lead-acid battery. An e-Horizon system is used to predict the future road topology. The tractor is equipped with controllable aerodynamic wind deflectors; side deflectors and a roof deflector. A full digital cluster is used for HMI development. A dSPACE rapid prototype controller is used for control implementation.



Figure 1. The CONVENIENT prototype truck.

MODEL

Much effort is spent on developing a simulation environment that, with an acceptable accuracy, imitates the parts of the vehicle that need to be controlled and analyzed. This model is denoted *plant model*.

Modeling Working Process

The plant model serves several purposes. It is used to test and evaluate the controllers that are developed and it is used to estimate the FC. The plant model is also used as a reference model when developing less complex models. The low complexity model is needed when designing the model based controllers as described later in this paper.

1. The “e” in eACC has several meanings; *efficiency*, *eco*, *energy*. The eACC is further described in the later chapter Human Machine Interface. The eACC is a system called Adaptive Cruise Control, which is a system on Volvo trucks that helps to maintain the distance (in time, e.g. 3 sec) to other vehicles in front.

the mechanical actuators and they don't suffer from losses in the mechanical clutch. One drawback of electrical actuators is the losses in the electrical system.

The second step uses DP which is a recognized method for solving optimal control problems. DP is typically used for off-board simulation and serves as a benchmark to on-board controllers. The solution found by DP is guaranteed to be globally optimal. DP is a numerical method that performs decision making based on the principle of optimality to arrange a sequence of decisions, which together define an optimal trajectory. In this paper, DP is based on a plant model with reduced complexity and used to compute the behavior of the fans, the water pump and the generator. This analysis shows that, with full knowledge of the BLB drive cycle, a fuel consumption improvement of about 0.4% can be achieved. The next section discusses this result in more detail.

The plant model does not capture the influence of the Electro-Hydraulic Power Steering (EHPS) and the reduced air drag due to improved aerodynamics. Analyzing vehicle aerodynamics by controlling the side deflector angle can contribute to a fuel saving of about 0.29%, or a drag coefficient reduction of 0.0044.

There are further FC reductions to be expected from the CONVENIENT truck that is not included in this analysis. Using the vehicle kinetics as an energy buffer further reduces the FC. This is done by deviating from the set speed when driving in cruise control mode. The allowed deviation from the set speed is set by the driver. This strategy is further described in [1]. Additional FC savings are expected using the radiator shutter, the controllable roof deflector and the EHPS.

Finally, note that the choice of driving cycle and the road topography largely influence the size of the fuel savings. Therefore, several driving cycles will be applied in future work, such as the long haul cycle proposed by the European Automobile Manufacturers' Association (ACEA).

CONTROL DESIGN

The control layout is shown in Figure 20. This paper focuses on the energy buffer control for the thermal system and battery system, the air deflector control and the HMI. The part of the energy buffer that controls the kinetic energy, i.e. the speed controller eACC, is not presented in this paper. This controller is instead presented in detail in [1].

Energy Buffer Control

Prediction

In this work the route map and the driver model are used to predict the future speed and load for at least 200 seconds. According to [4], the length of 100 to 200 seconds is a reasonable horizon for predictive energy management control. Future speed and load are estimated from two factors:

1. Landscape and road attributes are available from the route map and contain the information of altitude, road curvature, speed limits, road signs, traffic lights, sharp turns, etc. The route map and the GPS signal are provided by the eHorizon system provided by Continental as a project partner.
2. Driver behavior and the driver's response to future road attributes. The controller includes a functionality that adapts the prediction depending on the driver behavior. The controller calculates the arrays of future speed and load by kinematics, vehicle longitudinal dynamics, Newton's second law, and the maximal power and torque of the test truck. The controller can also learn the driver's style online by adapting several characteristic parameters, including acceleration, deceleration, and the deviation of the actual vehicle speed from the target speed.

The prediction functionality is implemented in Simulink and Embedded Function blocks with the execution rate of 1 Hz. Its accuracy has been verified with real vehicle measurement in several R&D projects at the Volvo Group. Works on prediction are presented in [5] [6] and [7].

Thermal and Battery System Control

About 2-4% of fuel consumption of commercial vehicles is consumed by auxiliaries, including, the cooling system, the power steering, etc [8]. Among them the engine cooling system is one of the main sources of parasitic loads. Thus optimal control of the cooling system using prediction can contribute to the fuel efficiency improvement. This project studies the benefits of two predictive optimal control methods on reducing the fuel consumption caused by the cooling system. One method is DP and the other is MPC. Relying on the full knowledge of the entire drive cycle, the DP method can find the theoretically optimal control strategy offline. The MPC method, on the other hand, utilizes the online prediction and computes a suboptimal control strategy online. For vehicle onboard implementation, the MPC method is applicable. The DP method is used as a reference to verify the correctness of the MPC method. Figure 4 illustrates the schematic of the simplified automotive thermal system, where T_e is the coolant temperature at the exit of the engine, T_r the coolant temperature at the exit of the radiator. Symbols u_p , u_e , and u_r represent coolant volumetric flow rates through the pump, the engine, and the radiator, respectively. Symbol $\dot{m}_a$ represents the total air mass flow rate through the radiator produced by the radiator fans and the vehicle speed together.

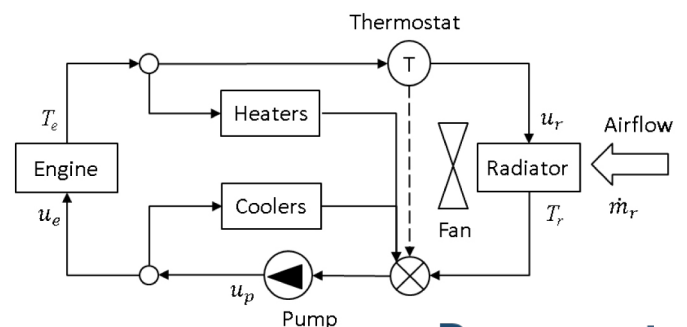


Figure 4. Simplified Schematic of the Truck Cooling System.