CHALMERS
UNIVERSITY OF TECHNOLOGY

Energy management for a tractor and semitrailer combination using control allocation

Master’s thesis in Systems Control and Mechatronics

Robert Hjelte Ulmehag

Department of Signals and Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016
Master’s Thesis EX005/2016

Abstract

Of both social, environmental and economic reasons it is of interest to reduce today's societies dependence of fossil fuels. The Transformers project is an EU-funded project that aims at reducing fuel consumption for long haul heavy trucks with 25% on a tonne.km basis. One approach towards fulfilling this goal is to introduce electric propulsion in the trailer. In this thesis, a model of an electrified semitrailer is implemented and tested through simulation. A proposed communication interface which is based on the idea of centralized control between tractor and trailer is implemented and validated. Furthermore, both energy management strategies and a strategy for optimal actuator utilization called *Control Allocation* is implemented. Three energy management strategies are tested and evaluated for their effects on the fuel consumption. The *Constant SoC 50* is a robust non-predictive strategy. Its main advantage is that it guarantees charge sustainability. The *Predictive Heuristic Controller* (PHC) extends the common heuristic controller by introducing a maximum limit for the energy level in the battery. This limit is forcing the battery to deplete before an approaching descend and thereby allocates "room" in the buffer for regeneratable energy. The final strategy called the *Equivalent Consumption Minimization Strategy* (ECMS) is solving an optimization problem in every time instance to find the optimal power distribution between the two propulsion systems. However, the implementation of the ECMS proved to be challenging. Since ECMS is based on optimal control theory it is expected to yield the best results but is in this implementation outperformed by the much simpler Constant SoC 50 strategy. It is believed to be due to the use of non representative engine maps. 4% and 5% lower fuel consumption is achieved for the two strategies respectively compared to a conventional vehicle. The PHC yielded the smallest improvement with a reduction of 1% with respect to the conventional vehicle.

KEYWORDS: Hybrid, Control, Allocation, Energy management, Heavy duty vehicle

Acknowledgements

First and most important I want to send many big hugs to everyone from home. Thank you for your support and for your patience. Hopefully, now that I am finally finished, I will be able to come visit you all much more frequent. Next I want to send a big hug to all other thesis workers with whom I shared many fun moments with at Volvo Group Trucks Technology. You all know who you are. Finally I want to thank my supervisor Leo Laine and my examiner Jonas Fredriksson who supported me through my work and many times helped me with problem solving and encouragement. And thank you for showing me that you can be an engineer and a really fun guy at the same time.

CONTENTS

1 Introduction

1.1 Background

In a globalized world of constantly increased need of on land transport, the demands on cost efficient and environmentally friendly vehicles grow accordingly. More sophisticated vehicle combinations are subject to ongoing research and development in search for constant improvement. Projects are being initiated both on corporate level but also on higher levels. One out of many resulting projects as such is an EU-funded project named Transformers which aims at increasing both cost- and energy-efficiency for heavy duty trucks used for transportation [11]. It is within the frames of Transformers that the work presented in this report is carried out. The overall objective of the Transformers project is to reduce energy consumption with 25% on a tonne.km basis whilst reducing the impact of road infrastructure. Three approaches are made to fulfill these goals

- Develop and demonstrate Hybrid-on-Demand Driveline for Truck-trailer combination
- Develop toolbox with aerodynamic measures
- Develop toolbox with loading efficiency measures

The work presented in this report is linked to the first out of the 3 approaches: Develop and demonstrate Hybrid-on-Demand Driveline for Truck-trailer Combination. The work has been carried out at Volvo Group Trucks Technology (VGTT) who plays a leading role in the Transformers project.

1.2 Purpose

In this thesis it will be investigated if introducing electric propulsion in the trailer of a truck-semitrailer combination can result in lowered fuel consumption. Energy management and actuator coordination is therefore a major part of this thesis. A new communication interface between tractor and trailer in order to allow communication and energy management control of the semitrailer has to be designed. A proposed interface as such has been developed by engineers at Volvo and is to be validated in this work. The outcome of this thesis will serve as a base for the physical implementation planned to take place in 2016.

1.3 Questions to be answered

This work aims at answering the following questions

- Can the fuel consumption over a given driving cycle be made to decrease? How much?
- Is Control Allocation and Energy Management compatible?
- Is the proposed communication interface between tractor and semitrailer sufficient?

1.4 Delimitations

The following delimitiations are made

- Specifications for semitrailer and electric components are fixed and given by Transformers project.
- The given mission used as reference consists of the route Landvetter-Boras-Landvetter
- VGTT provides high fidelity vehicle plant models and simulation framework to be used within the project.

1.5 Main contributions

In this thesis a proposed signal interface between tractor and semitrailer was verified for three different energy management strategies. The additional functionality that comes with the electrified semitrailer was implemented in simulation environment and thereby extended an already existing high fidelity model. The extended model can be used to further investigate how the electrified semitrailer can be used to improve vehicle dynamics and reduce fuel consumption even further than what is shown in this thesis.

1.6 Reading guidelines

Chapter 2 introduces the vehicle configuration and how the new components are integrated. The two vehicle units (tractor and trailer) have separated control units and a communication interface is therefore introduced in the same chapter. Last in this chapter is a simple vehicle model and some equations that have been used througout the work introduced. In chapter 3 the system control loop and the model and the implementation of the model in software outlined. This gives a good overview of the interconnection between the subsystems that are involved. It is recommended to read this chapter thoroughly before moving on to chapter 4, 5 and 6 where the different subsystems involved are explained in more detail. The simulation setup and the results from the simulations are explained and commented in chapter 7. The conclusions are presented in chapter 8 followed by the final chapter 9 that contains suggestions for how to improve and extend the simulation model.

2 Vehicle and vehicle modeling

As mentioned in the introduction, the model configuration to be investigated is determined by the Transformers project. This chapter will first introduce the vehicle configuration that is to be considered followed by a more detailed description of the communication interface that also was mentioned in the introduction. The remainder of the chapter will be used to present the mathematical models that have been used throughout the work.

2.1 Vehicle

2.1.1 Vehicle configuration

The vehicle configuration and the specification for the electric driveline components are given by the Transformers Project. As illustrated in figure 2.1 it consists of 2 units where the tractor is referred to as unit 1 and the semitrailer is referred to as unit 2. Unit 1 is a 4x2 tractor where axle 2 is propelled by an Internal Combustion Engine (ICE). It is combined with a 3-axled electrified semitrailer where the battery and electric motor (EM) are placed in the trailer. The EM is connected to axle 5 of the trailer via a one-geared transmission. All brakes are individually controlled and the first axle is steered.

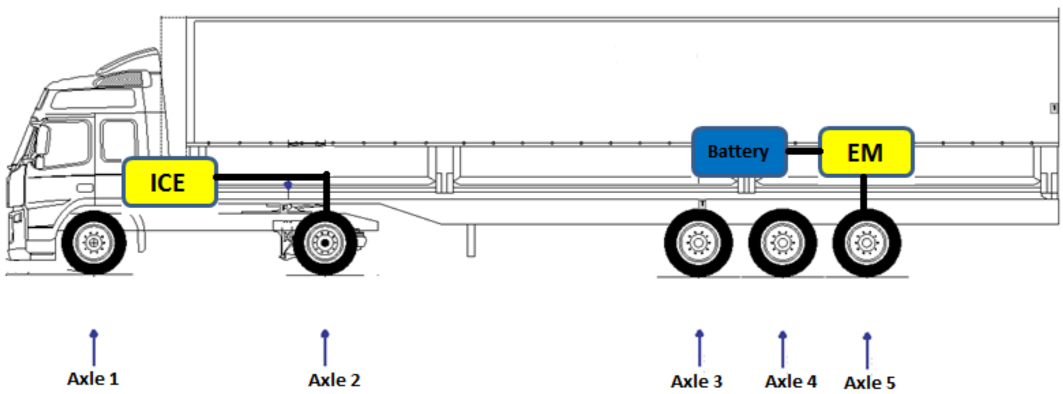

Figure 2.1. Truck configuration, illustration originally from [2]

2.1.2 Communication interface

An important issue to address is how the communication interface between trailer and tractor should be designed, see figure 2.2. The hardware involved that handles the communication is the trailer control unit named Trailer Driveline Management System (TDMS) and the tractor unit named Vehicle Energy Management System (VEMS). All data between the two units is being sent over the CAN-bus. A suggestion for a standardized interface has been developed by engineers at VGTT and was investigated in this thesis, see table 2.1. The interface has been designed with the use of Control Allocation, explained in chapter 5 in mind. For Control Allocation to work it is of interest to know each actuators capability and status. It is also of great importance that the driveline control is centralized so that no conflict of control can arise between tractor and trailer unit. The information flow is therefore proposed as following

- The TDMS sends information about capabilities, status etc. of the trailer components to the VEMS
- VEMS uses the information from the TDMS when calculating control signals for each actuator in the trailer that is then being sent back to the TDMS

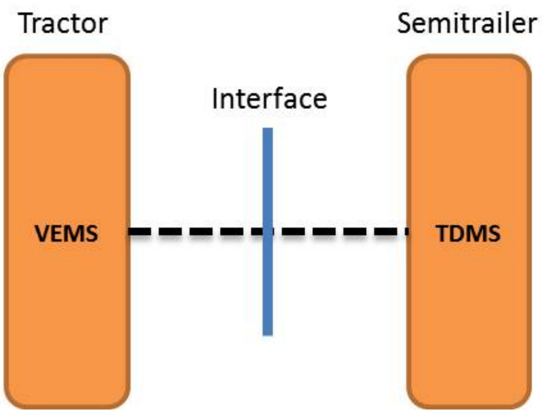

Figure 2.2. Illustration of control units + communication interface

The considered actuators in the trailer are the EM and the brake actuators. Even though arguably not a motion actuator, the battery's capability and status also influences the control and usage of the other actuators and is therefore referred to as an actuator in this chapter. Each actuator can be controlled individually and signal vectors for request, status, and capabilities are therefore used in order to handle them separately. The semitrailer is equipped with six brake actuators, one for each wheel, and the signal vectors for handling them therefore contains six elements. For the sake of generality and to pave the way for eventual added complexity in the future, signal vectors for the electric driveline are also extended to vectors of six elements. For example, it might be that in a future implementation electric wheelmotors could be mounted in every wheel of the trailer. In that case, each individual wheelmotor can be controlled separately when using this interface. The interface as shown in table 2.1 was tested and concluded to be sufficient for the three energy management strategies explored in this thesis.

Parameter Name	units	values
Control type signals (VEMS → TDMS)		
WheelTorqueElectricalRequest	Nm	[T1 T2 T3 T4 T5 T6]
WheelTorqueMechanicalRequest	Nm	[T1 T2 T3 T4 T5 T6]
Capability type signals (TDMS → VEMS)		
WheelTorqueElectricalMaxCapability	Nm	[T1 T2 T3 T4 T5 T6]
WheelTorqueElectricalMinCapability	Nm	[T1 T2 T3 T4 T5 T6]
WheelTorqueMechanicalMaxCapability	Nm	[T1 T2 T3 T4 T5 T6]
WheelTorqueMechanicalMinCapability	Nm	[T1 T2 T3 T4 T5 T6]
WheelTorqueElectricalMaxDerivCapability	Nm/s	[T1 T2 T3 T4 T5 T6]
WheelTorqueElectricalMinDerivCapability	Nm/s	[T1 T2 T3 T4 T5 T6]
WheelTorqueMechanicalMaxDerivCapability	Nm/s	[T1 T2 T3 T4 T5 T6]
WheelTorqueMechanicalMinDerivCapability	Nm/s	[T1 T2 T3 T4 T5 T6]
Capability type signals for propulsion or braking configuration (TDMS → VEMS)		
ElectricalTopologyConfiguration	-	[s1 s2 s3 s4 s5 s6]
MechanicalTopologyConfiguration	-	[s1 s2 s3 s4 s5 s6]
Capability type signals (TDMS → VEMS)		
ElectricStorageAvailableStateOfChargeCapability	kWs	[W]
ElectricStorageTotalEnergyCapability	kWs	[W]
ElectricStorageChargePower Capability	kW	[P]
ElectricStorageDisChargePowerCapability	kW	[P]
Status type signals (TDMS → VEMS)		
ElectricStorageStateOfCharge	-	[e]
ElectricStorageStateOfChargeDrain	W	[p]
ElectricStorageStateOfHealth	-	[P]
Status type signals, efficiencies (TDMS → VEMS)		
PowerLossMotoring	-	[c_{20} c_{02} c_{10} c_{01} c_{12} c_0]
PowerLossGenerting	-	[c_{20} c_{02} c_{10} c_{01} c_{12} c_0]
WheelTorqueActualAverage	Nm	[T1 T2 T3 T4 T5 T6]

Table 2.1. Signals handled by interface

2.2 Vehicle modeling

In this thesis, only longitudinal motion will be considered which implies that there is no articulation angle between the two units and that all wheels are in line (no steering involved). Since only longitudinal motion will be studied the only force of interest is the longitudinal force F_X. The longitudinal force of the vehicle is a function of the traction force and losses. A simple but sufficient model to describe the vehicle in its operating environment is a Newtonian planar model. This model assumes rigid body and only includes longitudinal forces.

$$F_X = ma = F_T - F_r - F_a - F_g \tag{2.1}$$

The forces involved are traction force F_T, rollingresistance F_r, aerodynamic resistance F_a and gradient resistance F_g. The disturbances are modeled as following

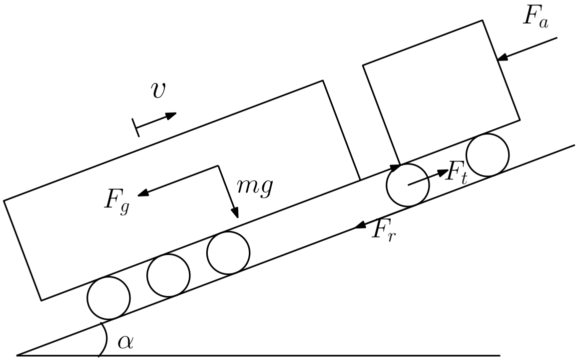

Figure 2.3. Planar Newton Model

$$F_a(v) = \frac{1}{2}\rho_a A_f c_d v^2 \tag{2.2}$$

where ρ_a is the density of air, A_f is the frontarea and c_d is the dragcoefficient.

$$F_r(\alpha) = c_r mgcos(\alpha) \tag{2.3}$$

where c_r is the rolling resistance coefficient, m is the vehicle's mass and g is the gravitational constant. The gradient resistance is expressed as

$$F_g(\alpha) = mgsin(\alpha) \tag{2.4}$$

The total generated traction force F_T is the sum of wheelforces.

$$F_T = \sum_{i=1}^{10} F_{t_i}^w \tag{2.5}$$

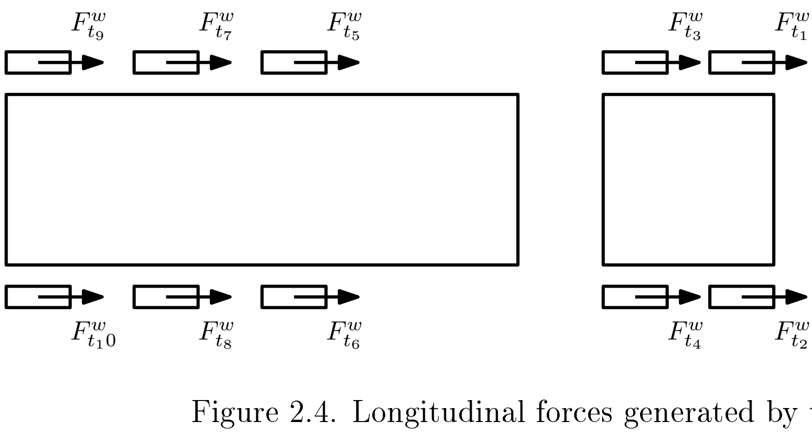

Figure 2.4. Longitudinal forces generated by the wheels

Forces generated at wheel level are superscripted with the letter w. The numeration is explained by figure 2.4. The traction forces generated by the vehicle are all transferred to the ground via the tires. A tyre model describing how force is transferred from tyre to ground is therefore necessary. There exist many different approaches to model tires, some of which are empirical and some of which are mathematical. They can differ a lot in complexity and computational requirements so it is necessary to find a sufficient model for the application. The test case handled in this work will be characterized by low accelerations/decellerations and no curvatures. By also neglecting tyre inertia and rolling resistance of tire, the final tyre model is achieved

$$F_{t_i} = T_{ti}^{w} R \tag{2.6}$$

where R is the tyre radius and T_{ti}^{w} is the torque applied to the axle of wheel i. This torque is generated by the actuators described in chapter 4.

3 System overview

This chapter starts by introducing the control design which provides an overview of the functionality of the system. The essential subsystems and how they interact is outlined. Each subsystem is then separately explained in more detail in chapter 4,5 and 6. The second subchapter explains how the vehicle was modeled and structured in Matlab's Simulink.

3.1 Control design

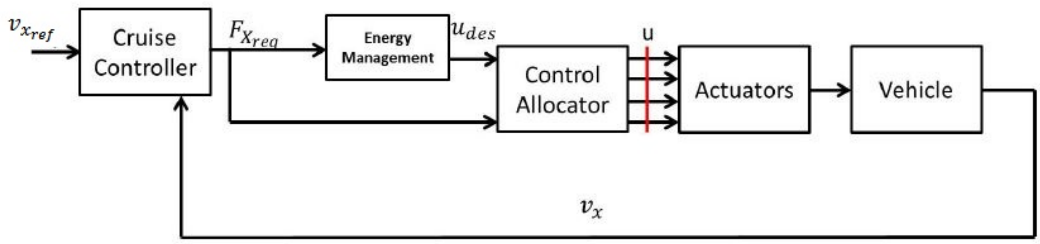

Figure 3.1. Blockscheme of implementation

As mentioned in the introduction, a major part of the thesis consists of actuator coordination and energy management. A blockscheme describing the system can be seen in figure 3.1. First, a speedreference v_{ref} for the vehicles desired longitudinal motion acts as input to the system. The cruisecontroller is then comparing $v_{x_{ref}}$ to the actual speed v_x in order to form the global force request $F_{X_{req}}$. To form the requested global force there are several actuators at hand namely brakes, the ICE and the EM. A Control Allocator (CA) is mapping the requested global force into actuator signals u, by solving an optimization problem. In doing this, the Energy Management is trying to steer the solution of the optimization problem and by that the output of the CA, into a desired actuator usage u_{des}. After the CA has found the optimal solution, the resulting set of actuator signals u are distributed to their respective actuator causing the vehicle to move accordingly.

3.2 Model implementation

The vehicle model was built using a Simulink library named Virtual Transport Model (VTM) that has been developed at Volvo. The VTM-toolbox includes dynamic models of vehicle components and Electronic Control Units (ECU's) that all together simulate the dynamic behavior of the full vehicle combination. The large number of signals involved calls for a well structured model architecture. The architecture

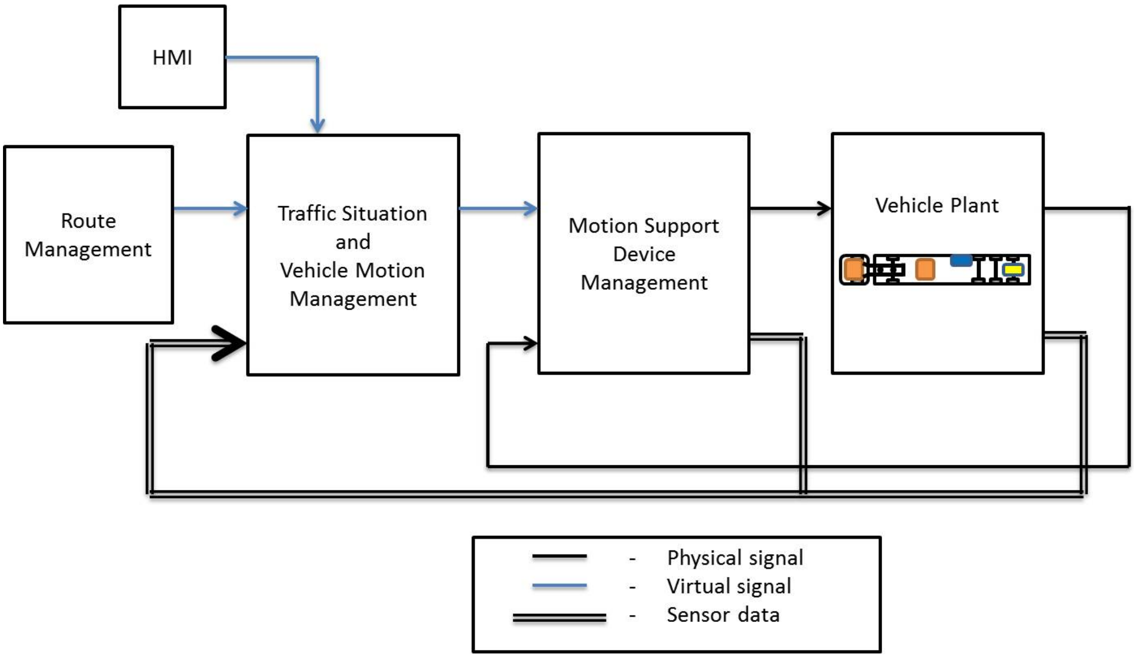

Figure 3.2. Blockscheme of model architecture

as used by Volvo has been implemented according to figure 3.2 where the blocks separate functionality intuitively.

Starting from the left is the Traffic Situation and Vehicle Motion Management (TSVMM) block. This block contains the ECU's of the vehicle and even a modelled CAN-bus which handles all control and logic in the vehicle such as the speedcontroller and the Control Allocator introduced in previous subchapter. Sensordata together with the signals provided by the driver, obtained from the Human Machine Interface (HMI), are used by the ECU's to calculate requested actuatorusages that is being sent to the Motion Support Device Management (MSDM). This block contains all the actuator models. The outputs from the MSDM- block are both the physical signals generated by the actuators (such as wheel torques and steering angles) and readable sensor measurements of actuator status that is being sent back to the TSVMM. The physical signals being generated by the MSDM is the input to the Vehicle Plant model (VP). The VP-block contains models of the external environment and the vehicle itself. All measurements of the trucks motion are being fed back to the TSVMM where the control algorithms in the ECU's use that data to calculate the next set of signals to be generated.

4 Modeling of components

The VTM-library provides most of the component models but some additional components had to be made for this thesis. In this chapter the models of the additional components are presented. All components except the battery can be considered as motion actuators in the sense that they generate torques on their respective axle. The obtained wheel torques from every actuator can then be translated into longitudinal force using equation 2.6.

4.1 Brakes

Models of brakes are already available in the VTM-library but due to some compatibility issues with the Matlab version being used, they could not be used and a new model had to be explored. Due to the simple cycle characteristics where no hard brakings will take place, a first order system is believed to be sufficient to model the dynamics of the brakes

$$T^w_{b_i}(s) = \frac{1}{\tau_b s + 1} T^w_{b_{req_i}}(s) \tag{4.1}$$

where $T^w_{b_{req_i}}$ is the requested wheel torque generated by the CA, $T^w_{b_i}$ is the actual brake wheel torque and τ_b is the time constant of the brakes.

4.2 Electric motor/Generator + transmission

The specifications for the EM are given by the Transformers project. It included a 120kW motor that is connected to the tires via a one geered gearbox and a drive axle. The mechanical integration is illustrated in figure 4.1 where also gear ratios are visible. Its dynamics is described by a first order system

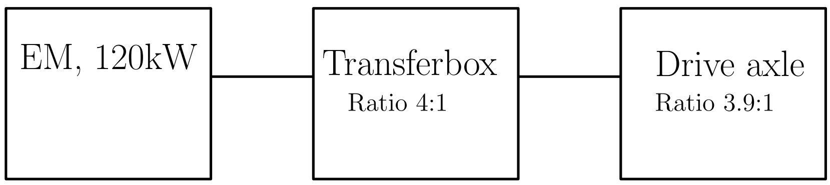

Figure 4.1. Mechanical integration of the electric driveline

$$T^w_{EM}(s) = \frac{K_{rEM}}{\tau_{EM} s + 1} T^w_{EM_{req}}(s) \tag{4.2}$$

where $T^w_{EM_{req}}$ is the requested wheel torque generated by the CA, T^w_{EM} is the actual wheel torque applied at the wheels and τ_{EM} is the time constant. The efficiency map and maximum torque curve of the EM can be seen in figure 4.2. The color coding stretches from blue (efficiency=0) to brown (efficiency=0.9). Its Optimal Operating Point (OOP) is marked and, as can be seen, the efficiency over most of its operating range is rather high. Similar to an ICE, the efficiency of the EM does not vary significantly unless demanded torque is approaching 0. The maximum torque curve is depicted by the thick blue line. The EM can also be utilized in the second quadrant and act as a generator by applying a negative torque. It is assumed that the EM has the same characteristics for negative torques i.e. the same map is used to model the generator.

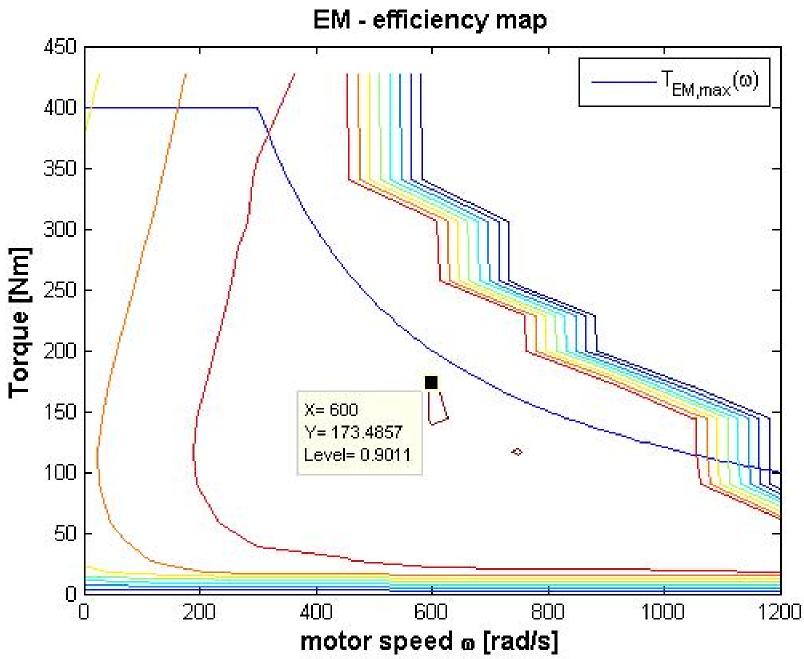

Figure 4.2. Efficiency map for EM

4.3 Battery

The battery is modeled as a static buffer with a constant efficiency over the whole range (independent of direction of powerflow). Its specifications as given by the Transformers project and are displayed in table 4.3

Energy content [kWh]	22.2
Power (discharge) [kW]	120
Power (charge) [kW]	80

Table 4.1. Battery specification

5 Control allocation

Control allocation provides an approach to manage and coordinate overactuated systems. The method as posed in this thesis was first introduced in [4] where it was tested in an aircraft application. It has also been proven to work well in car applications such as in [6] and has the potential to play an important role in future control of over actuated systems such as most vehicles. An over actuated system arises when there are more actuators than global forces to control. Typical examples of global forces in a vehicle application are yaw moment, lateral force and longitudinal force. In some cases there can be several global forces that intervene which creates a conflict meaning that not all requests can be met at the same time. With this in mind, the task to solve for the control allocator is to find the best actuator usage in every time instant, according to some criteria.

5.1 Mathematical formulation

Assume a vector $v \in \mathbb{R}^k$ where k is the number of global forces, and a vector $u \in \mathbb{R}^m$ where m is the number of available actuators. Sometimes v is referred to as the *virtual input*. In order to map the virtual input into actuator signals, a so called efficiency matrix B is formed where B is of size $m \times k$. The efficiency matrix is a description of how every actuator contributes to each global force. It can be that not all global forces can be met at the same time and it is therefore desirable to minimize the error $Bu - v$ in a least square sense

$$\Omega = arg \min_{\underline{u}<u<\overline{u}} \parallel W_v(Bu - v) \parallel^2 \tag{5.1}$$

Ω is the obtained solutionspace with feasible solutions under the constraint of the max/min actuatorsaturations depicted by $\underline{u}$ and $\overline{u}$. These will be explained later. W_v is a diagonal weighting matrix that can be used to decide the priority between the different global forces to be met in case of a conflict. However, with this formulation there is no prioritization between different actuatorusages and it can be that usage of some actuators are preferred to others. A second term is therefore added to the minimization problem

$$u = arg \min_{\underline{u}<u<\overline{u}} = \parallel W_u(u - u_{des}) \parallel^2 + \lambda \parallel W_v(Bu - v) \parallel^2 \tag{5.2}$$

where u_{des} is a vector stating the desired actuator usage and W_u is a diagonal weighting matrix that can be used to decide the priority between the different actuatorusages in case of a conflict. The new term is used to steer the solution of the problem into the desired actuatorusage u_{des}. A coefficient λ has also been added to the first term. This coefficient is often set to a high value to ensure that in case of a conflict, meeting the global force requests always is of higher priority than a desired actuatorusage. The solution space is constrained by $\underline{u}_{min}$ and $\overline{u}_{max}$ which are describing how much actuation that is available for every actuator. Maximum available actuation is a function of the maximum capability for each actuator and, due to the discretization of the system, the minimum rate of change. Same idea applies to $\underline{u}$ but instead the minimum capability and maximum rate of change is considered.

$$\begin{aligned} \underline{u}(t) &= \max\left(u_{min}, u(t-T_s) + T_s\rho_{min}\right) \\ \overline{u}(t) &= \min\left(u_{max}, u(t-T_s) + T_s\rho_{max}\right) \end{aligned} \tag{5.3}$$

Where T_s is the samplingtime and ρ_{min}/ρ_{max} are the minimum and maximum rate of change respectively for every actuator. The optimization problem is solved in every time instance and it should be clear that for Control Allocation to work properly in the truck-semitralier combination, the semitrailer must share information about the capabilities (max/min and max/min-derivative) of its actuators with the tractor unit.

5.2 Implementation

In this thesis the only global force to be controlled is the longitudinal force F_x

$$v = [F_X] \tag{5.4}$$

In order to control the longitudinal force F_X there are several actuators available namely: 10 individual wheelbrakes, ICE and EM. They are used to form the u-vector

$$u = [T^w_{b_1} \dots T^w_{b_{10}}\ T^w_{ICE}\ T^w_{EM}]^T \tag{5.5}$$

Note here that the torques in u are all at wheel level, indicated by the superscript w. This means that conversions have to be made outside the allocator to achieve the correct control signals to the actuators since they are generally not equal to the wheel torque signals. An example is the actual gear ratio between the powertrains and the wheels that have to be considered to obtain the correct actuator signals. As a consequence, the actuator saturations are all described on wheel level as well. The maximum and minimum capabilities from the powertrains are obtained from their respective enginemaps while the brakes are modelled with constant capabilities. The max and min rates for all actuators are set to constants for simplicity.

As explained previously, the B-matrix shows how every actuator contributes to each global force. Since the allocator is acting on wheel level the wheel torque is simply transferred to longitudinal force using equation 2.6.

$$B = [\frac{1}{R}\ \frac{1}{R}\ \frac{1}{R}\ \frac{1}{R}\ \frac{1}{R}\ \frac{1}{R}\ \frac{1}{R}\ \frac{1}{R}\ \frac{1}{R}\ \frac{1}{R}\ \frac{1}{R}\ \frac{1}{R}] \tag{5.6}$$

W_u is chosen so that emphasis is on minimizing the actuator usage error of the desired powertrain torques.

$$W_u = diag\begin{bmatrix}1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 2 & 10\end{bmatrix} \tag{5.7}$$

The choice is being motivated by the fact that the focus in this implementation is energy savings, which are mostly related to the use of the EM and the ICE. It can be seen that the error of EM-usage is higher weighted which is to ensure that service brakes are used as little as possible in a brake situation. This is to reduce service brake wear and favour regeneration by the EM. Equal weighting of the brakes is to avoid introducing lateral instability due to uneven braking. Since only one global force is considered, the weighting matrix W_v simply becomes a coefficient. The parameter λ is set very high to ensure that the global request is met

$$\begin{aligned} Wv &= 1 \\ \lambda &= 10^6 \end{aligned} \tag{5.8}$$

5.2.1 Setting u_{des}

One of the main benefits of control allocation is the possibility to steer the solution of the optimization problem to a desired actuator usage denoted u_{des}. The forming of u_{des} is made in the EnergyManagement block, see figure 3.1. In case of a positive requested torque at the wheels, the desired utilization of the two drivelines are determined by the energy strategies which are explained in chapter 6. When a negative torque at the wheels is requested a different strategy is needed. The utilization of the brake actuators is depending on the total brake power demand according to table 5.1.

Brake actuators	axle 1	axle 2	axle 3	axle 4	axle 5	EM
Demanded brake power						
$P^w_{dem} > -80$	0	0	0	0	0	P^w_{dem}
$-(80 \times 5) < P^w_{dem} < -80$	$\frac{P^w_{dem}-80}{4}$	$\frac{P^w_{dem}-80}{4}$	$\frac{P^w_{dem}-80}{4}$	$\frac{P^w_{dem}-80}{4}$	$\frac{P^w_{dem}-80}{4}$	-80
$P^w_{dem} < -(80 \times 5)$	$\frac{P^w_{dem}-80}{5}$	$\frac{P^w_{dem}-80}{5}$	$\frac{P^w_{dem}-80}{5}$	$\frac{P^w_{dem}-80}{5}$	$\frac{P^w_{dem}-80}{5}$	$\frac{P^w_{dem}-80}{5}$

Table 5.1. Brake strategy, numbers given in kW at wheel

The strategy is divided into 3 parts. Small brake requests ($P^w_{dem} > -80kW$) are handled solely by the EM in order to regenerate as much energy as possible. The upper limit of 80kW is due to the maximum capability of the battery. When the requested braking power exceeds 80kW the additional required braking power is evenly distributed on the other four axles up to the point where all five axles brake with 80kW of power. For even larger brakerequests ($P^w_{dem} < -(80 \times 5kW)$), brake power is evenly distributed on all five axles. This strategy ensures that as much energy as possible is always regenerated.

6 Energy management

The introduction of electric propulsion in a vehicle may lead to a decreased fuel consumption. This is mainly due to brake energy regeneration and that the operating point of the engine can now be chosen with some degree of freedom. An energy management strategy is needed to decide the power distribution between the ICE and the EM. Three strategies are explored in this thesis but first some useful notations and preqrequisites are introduced before explaining them in detail.

6.1 Introduction

There are today many proposed energy management strategies that vary a lot in complexity and performance, see [3]. The most basic strategies are based on heuristic rules and are referred to as heuristic controllers. An example of a heuristic controller is illustrated in figure 6.1. In this example the boundaries for the different driving modes are determined by the requested torque at wheel level and the State of Charge (SoC) of the battery. The driving mode is characterized by the choice of the Torque Split Factor (TSF) which is defined to be

$$TSF = \frac{T^w_{EM}}{T^w_{req}} \tag{6.1}$$

The TSF can be interpreted as

- $TSF = 0$, pure thermal mode - only ICE is used for propulsion
- $0 < TSF < 1$, hybrid mode - both drivelines are used for propulsion
- $TSF = 1$, pure electric mode - only EM is used for propulsion
- $TSF < 0$, charge mode - ICE used to charge battery

It happens that the requested torque T^w_{req} can not be fullfilled with only the EM due to saturation. To indicate that the EM is being used maximally we denote $TSF = TSF_{max}$. The ICE adds the extra torque needed to fullfil the torque request. In a similar manner, the denotion $TSF = TSF_{min}$ is used for when maximum negative torque for the EM is applied. The EM only outputs a negative torque when $T^w_{req} < 0$, in which case the brake strategy explained in chapter 5.2.1 is used, or when the vehicle is operating in charge mode. Operating in charge mode means that a negative torque is applied to the wheels by the EM which then instead acts as a generator. The ICE will have to compensate for this negative torque by applying a greater torque, or else the requested torque is not fullfilled. The total efficiency for the stored energy in the battery will approximately be $\eta_{charge} = \eta_{ICE} \cdot \eta_{EM}$ which

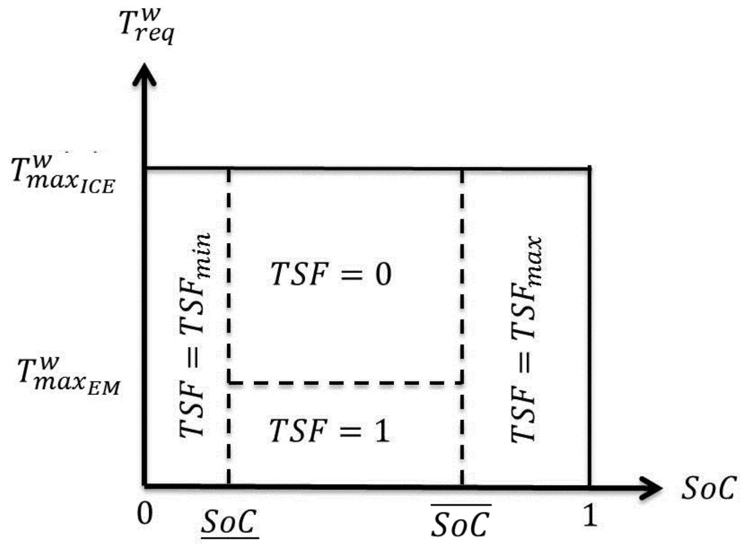

Figure 6.1. Example of a heuristic controller using Torque Split Factor (TSF)

always yields a low value. The hybrid should therefore be avoided to operate in charge mode. For this reason the hybrid will only operate in charge mode when a lower constraint of the batterys State of Charge (SoC) is violated, call it $\underline{SoC}$. An upper constraint of the SoC is also introduced, call it $\overline{SoC}$. Brake energy should always be regenerated as long as $\overline{SoC}$ is not violated. For this implementation the limits are set to $\underline{SoC} = 0.2$ and $\overline{SoC} = 0.8$. Since charge mode is to be avoided the main problem then becomes how to

- Maximize brake energy regeneration whilst avoiding upper battery saturation
- Distribute the regenerated energy in the most efficient way over the mission
- Maintain charge sustanance

Heuristic controllers are intuitive and easy to implement but have several drawbacks

- Performance is directly related to choice of thresholds and thereby varies a lot depending on character of mission
- Charge sustenance is not considered
- Choice of TSF is rarely optimal and can be enhanced to achieve lower fuel consumption
- Battery saturation is still possible

Even though battery saturation in some situations may be inevitable there exist other approaches that aims at reducing the possibility to end up in such a situation.

One such approach is to use a predictive controller. If the future drive was perfectly known a priori the global optimum could be reached to obtain the lowest possible fuel consumption over a mission. This is equivalent to choosing the optimal TSF-factor in every time instance. However, such non-causal systems are impossible to implement in a real application. Instead, a suboptimal predictive controller is considered in this thesis. The suboptimal controller uses information about the *estimated* future energy usage to maintain charge sustain. This estimation comes from mission data that, for this thesis, was given in form of GPS-coordinates and a speedcycle acting as the speedreference over the mission. Three energy managment strategies are tested and compared in this thesis. The first and simplest strategy is called *Constant SoC 50* and is a non predictive strategy. The second strategy is called *Telemetric Equivalent Consumption Minimization Strategy* (T-ECMS) and is a predictive strategy. The strategies are presented in more detail in the following subchapters.

6.2 Constant SoC 50

A simple and nonpredictive but robust strategy is to set a constant SoC-reference. The idea is to regenerate as much energy as possible in steep declines which is causing the SoC to increase. When the requested torque at the wheel turns positive and $SoC > 0.5$, the EM is maximally utilized so that SoC decreases until the point where it returns to the constant SoC$= 0.5$ where it once again is switched off.

6.3 Predictive Heuristic Controller (PHC)

One major drawback with using the common heuristic controller is the possibility to end up in a situation where brake energy is not regenerated due to an already fully charged battery - it is instead wasted on the service brakes. The PHC is predicting the amount of brake energy to be regenerated over a descend in order to deplete the battery and allocate room for that energy in the battery. The calculations are made offline and no feedback is provided during the real-time operation. The goal of the PHC is to result in a so called dynamic SoC-limits $SoC_{dyn,max}$ that uses the estimated future energy to be added to the battery in order to constrain the allowed SoC with respect to $\overline{SoC}$. The steps taken to implement the PHC are listed as following

- From topological data (GPS), detect troughs and peaks over the mission. This was achieved by using the algorithm developed in [12]. Figure 6.2 shows the detected peaks and troughs.
- For every segment i, defined as the path between two consecutive troughs, estimate the free energy to be regenerated over the descend ΔSoC_i. This is done by using the averaged speed over the descend, obtained from the requested

speedcycle, in the Newton model that was explained in chapter 2.

- The estimated amount of regenerated energy ΔSoC_i is then distributed over the precedent ascend as a linear function of the difference in altitude between trough i and peak i. Since brake energy is always regenerated until SoC_{max} is reached, it is not necessary to set any other limit in the descend although it was implemented here as a linear function of the difference in altitude between peak i and trough $i + 1$. With this approach the function will end up at the same value (SoC) in every trough.

- The function for every segment is then translated to match SoC_{max} in order to obtain the final expression for $SoC_{dyn,max}$.

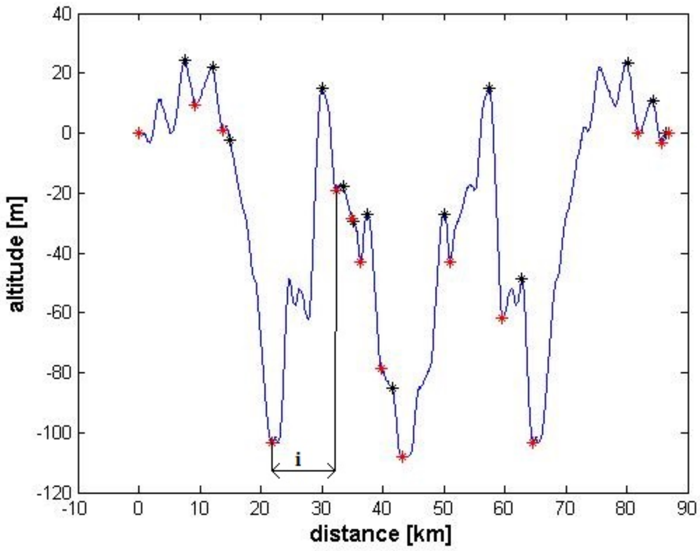

Figure 6.2. Identified peaks and troughs

This approach allocates room in the battery for the estimated energy ΔSoC_i to be regenerated over every detected descend. The resulting curve $SoC_{dyn,max}$ is shown in figure 6.3. When operating in-real-time the actual SoC is controlled using a simple heuristic controller as previously explained which allows the SoC to fluctuate freely within the SoC limitations decided by $\underline{SoC}$ and $SoC_{dyn,max}$. The simple controller used for the implementation of the PHC was designed according to figure 6.4. This controller is similar to the exapmle illustrated previously in figure 6.1. The only difference is that $\overline{SoC}$ is replaced by $SoC_{dyn,max}$. The vehicle operates in electrical mode when possible but if EM ever is saturated it switches to thermal mode. If SoC-limits are violated, necessary action is taken by setting TSF to either TSF_{max} or TSF_{min}.

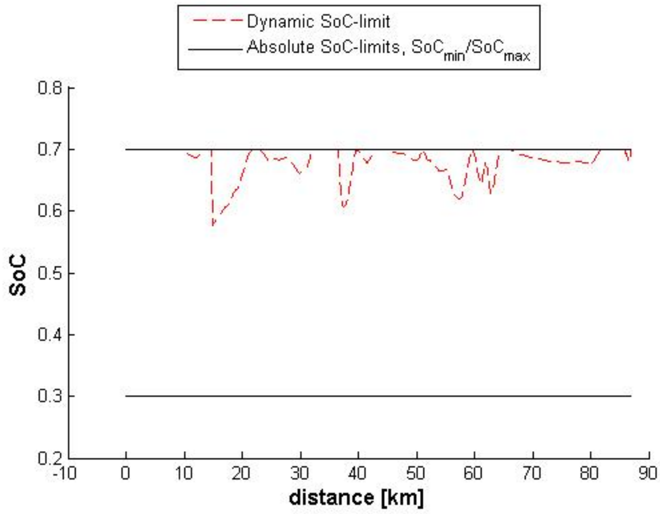

Figure 6.3. The obtained dynamic SoC-limit

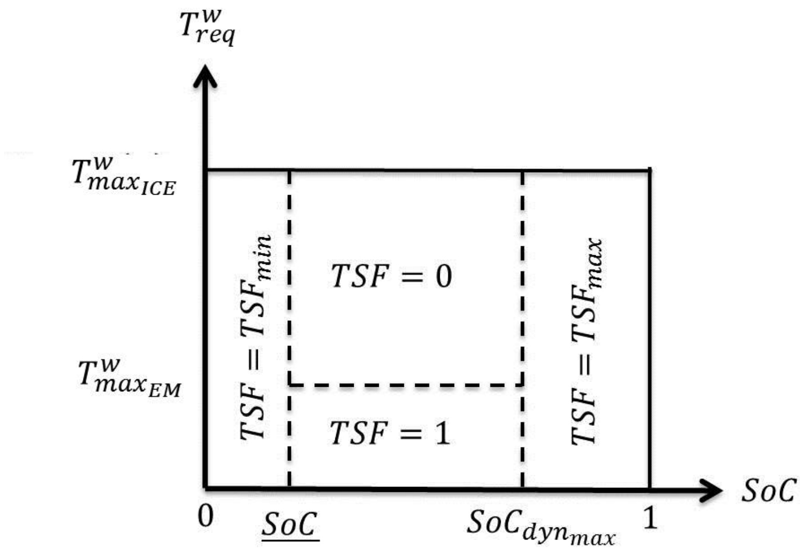

Figure 6.4. The heuristic controller used for the PHC

6.4 Equivalent Consumption Minimization Strategy (ECMS)

ECMS is a well known concept in hybrid vehicle control. The objective of the ECMS-strategy is to find the TSF that in every time instance minimizes the *total* energy consumption. By assuming that roadconditions are unchanged between two consecutive samples this is equivalent to minimizing the total power in each time instance

$$TSF^*(t) = arg\min_{TSF} P_f(t, TSF) + P_e(t, TSF) \tag{6.2}$$

where P_f is the power/energy consumed from fuel and P_{EM} is the consumed electric power/energy from the battery. The consumed power/energy along each *energy path* is calculated by considering the efficiencies for each path respectively. These efficiencies are tabulated and are varying depending on the chosen operationpoint i.e. choice of TSF. Only efficiencies of the drivelines themself are tabulated and eventual losses in transmissions are not included. Equation 6.2 is rewritten to

$$TSF^*(t) = arg\min_{TSF} \frac{P_{ICE}(t, TSF)}{\eta_{ICE}} + \frac{P_e(t, TSF)}{\eta_{EM}} \tag{6.3}$$

where P_{ICE} is the demanded power from then engine and P_{EM} is the demanded power from the EM. The efficiencies for each energy path is depicted η_{ICE} and η_{EM} respectively. If charge sustenance was not considered the EM would be used too frequent, due to its higher energy efficiency, and thereby depleting the battery. In order to maintain charge sustenance, the ECMS approach introduces the equivalencefactor s that is being used to weight the electric energy.

$$TSF^*(t) = arg\min_{TSF} \frac{P_{ICE}(t, TSF)}{\eta_{ICE}} + s(t)\frac{P_e(t, TSF)}{\eta_{EM}} \tag{6.4}$$

If s is low it favours usage of the EM for propulsion which causes the SoC to decrease. A high value of s instead favours usage of the ICE. For very high values of s, the vehicle will go into charge mode. Since ECMS was first introduced many attempts to define the equivalence factor has been made, see e.g. [1] and [7]. The strategy to be further explored in this thesis is called the *Telemetric Equivalent Consumption Minimization Strategy* (T-ECMS). The T-ECMS was first introduced in 2004 by Guzzella [9]. This approach uses a *sliding window* technique that in every timestep uses the given missiondata and the Newtonian model explained in chapter 2 in order to estimate the amount of regenerateble energy within a prediction window of length p_w which is set manually. The obtained information is then used to calculate the probability p of ending up on a positive SoC-deviation in the end of the prediction window compared to the initiated SoC at the beginning of the mission. The probability function can according to [5] be expressed as

$$p(t) = \frac{s_{dis}}{s_{dis} + s_{chg}} + \frac{E_e(t) - \lambda(E_m(t)}{E_m(t)} \frac{\sqrt{s_{dis}s_{chg}}}{s_{dis} + s_{chg}} \tag{6.5}$$

where

- $E_m(t)$ is the mechanical energy that has to be delivered to the wheels within the prediction window (always greater or equal to 0).
- $E_e(t)$ is the electrical energy that has been added to or subtracted from the battery up to the current sampletime (can be negative or positive).
- λ is defined as $\lambda = \frac{E_{recup}}{E_m(t)}$ where E_{recup} is the estimated amount of regeneratable energy within the prediction window. λ can only take values between 0 and 1.

The values that s can take is limited by the probability function $p(t)$ between two carefully chosen end values s_{dis} and s_{chg}.

$$s(t) = p(t)s_{dis} + (1 - p(t))s_{chg} \tag{6.6}$$

The values of s_{dis} and s_{chg} have to be tuned in for good performance and are different for different vehicles and missions. This is the main disadvantage with ECMS since finding suitable values can be time demanding. When correctly implemented and well tuned, the T-ECMS strategy will enforce a depletion of the battery before an approaching descend and by that allocate room in the battery for the energy that is to be regenerated. The benefits of the ECMS-strategy can now be summarized

- The optimal TSF is found in every time instance which should directly lower the fuel consumption
- Battery saturations can be avoided by compensating for predicted energy additions in battery i.e. depletion of the battery before an approaching descend

7 Simulation

7.1 Simulation setup

Mission data for the route Boras-Landvetter-Boras was provided by Volvo. The topography and requested speedprofile for this mission can be seen in figure 7.1.

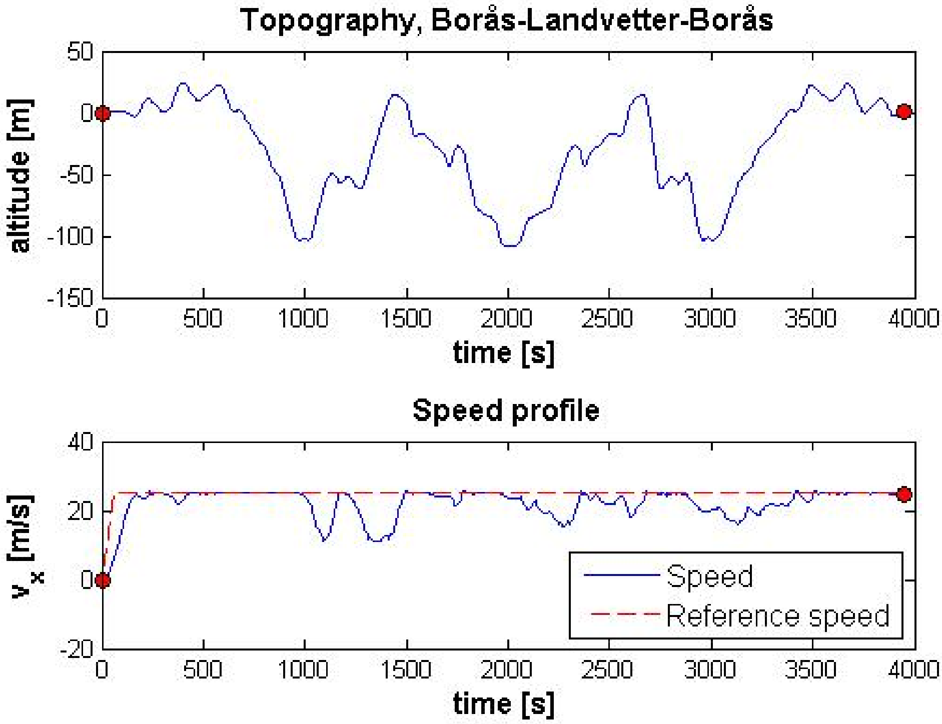

Figure 7.1. Topography, referencespeed and actual speed for one of the hybrid configurations over the Boras-Landvetter-Boras route

One of the benefits of introducing electric propulsion in a vehicle is the opportunity of downsizing the ICE. This implies that the smaller engine can be operated at a higher average load which is normally good for fuel efficiency. It was first investigated how performance changed with using 3 smaller engine sizes than what is typically used for this type of mission. The results are gathered in table 7.1. It can be seen that the travel time differs between the three configurations due to not having enough power available to maintain the requested speed of 25m/s in the steepest ascends. When introducing electric propulsion, the CA (when tuned according to chapter 5) will use the additional power to improve reference-tracking. A conflict then arises since the CA tends to overwrite the desired EM-usage, requested from the Energy Management, which makes it hard to maintain control of the battery's SoC. It happens of two reasons

Engine:	Simulated fuel consumption [L]	Time to finish mission [s]
11L, 370HP	25.94	4146
11L, 410HP	25.61	3957
11L,450HP	25.53	3878

Table 7.1. Simulation results for conventional vehicles of different engine sizes

- If the requested force, F_{Xreq} from the speedcontroller is larger than the maximum force that can be delivered by the ICE, the CA will use force provided by the EM in order to find a solution closer to the requested force. It is the result of the emphasis of meeting the global force requests in the optimization problem of the CA (λ is set high).
- The EM has much faster dynamics which is reflected in the actuator rate used to set $\overline{u}(t)/\underline{u}(t)$ in the optimization problem. Since the EM has power available faster than the ICE, the CA once again may use force provided by the EM in order to find a solution closer to the requested force.

To further emphasize the desired EM-usage the W_u-matrix was changed to

$$W_u = diag\left[1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 2\ 10^6\right] \tag{7.1}$$

This choice helped solving the issue with the CA overwriting the desired EM-usage. The choice of enginesize is not an exact science and since the 3 engines performed similarly for this mission, both in terms of fuel consumption and travel time, the most powerful alternative (11L,450HP) was chosen to be used for the hybrid. Furtheron, the initial SoC for all test cases is set to $SoC_{init} = 0.5$.

7.2 Simulation results

7.2.1 Constant SoC 50

Figure 7.2 shows how the SoC varies over the mission. It can be seen that energy is being recuperated in steep descends which causes the SoC to increase. When traction force is required again, the electric energy is used until the SoC returns to the initial 50%.

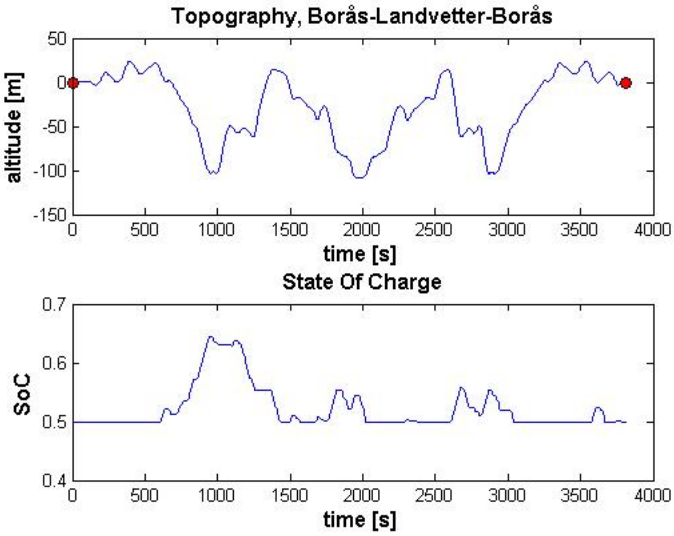

Figure 7.2. Resulting SoC from simulation using the Constant SoC 50 controller

7.2.2 PHC

The resulting SoC of the implemented PHC is seen in figure 7.3. It can be seen that the SoC is never close to violate $SoC_{dyn,max}$. This is mainly due to the big buffersize in combination with the choice of heuristic controller.

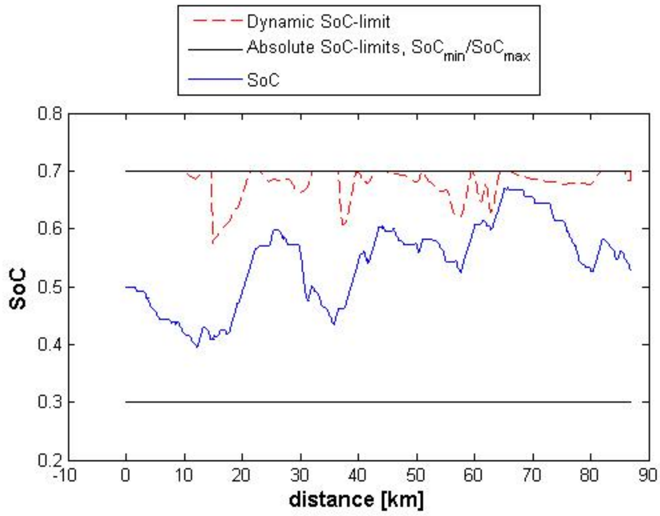

Figure 7.3. Resulting SoC from simulation using the PHC

7.2.3 ECMS

The resulting SoC and equivalence factor can be seen in figure 7.4. Notice how the equivalence factor adjusts before an approaching descend in order deplete the battery. It can be seen that the charge sustenance is acceptable with a deviation of about 1% between start- and end-value of the SoC. By finer tuning of the equivalence factors s_{dis} and s_{chg} it is possible that this deviation can be reduced further.

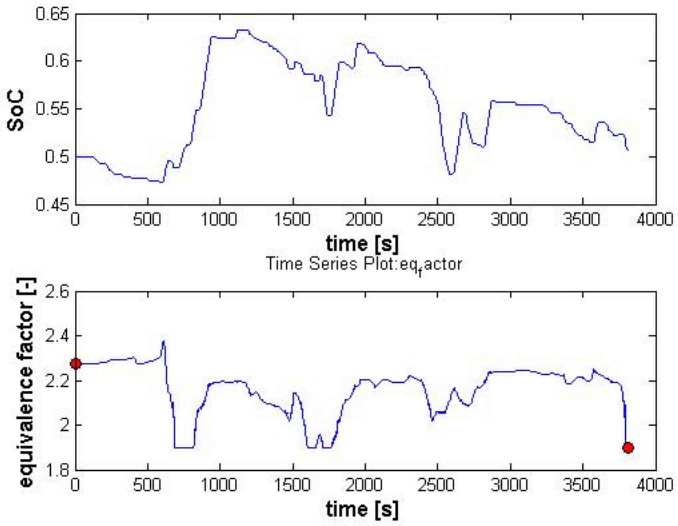

Figure 7.4. Resulting SoC from simulation using the ECMS

7.2.4 Summary and discussion around results

The obtained Specific Fuel Consumption (SFC) for the energy strategies can be seen in table 7.2.4 where the conventional vehicle is also included as a reference. Simple energy calculations can be made to compensate for the final SOC-deviation in the battery and give a more justful comparison of the resulting fuel consumptions. The compensated results are named *equivalent specific fuel consumption* (eSFC). It

Strategy	SFC [L]	SoC [-]	eSFC [L]
Conventional	25.53 (100%)	-	25.53 (100%)
Constant SoC 50	24.23 (95%)	0.50	24.23 (95%)
PHC	25.36 (99%)	0.53	25.21 (99%)
ECMS	24.95 (98%)	0.51	24.90 (98%)

Table 7.2. Resulting fuel consumptions

can be seen that the simple but robust strategy Constant SoC 50 yields the lowest consumption with a total fuel reduction of 5% compared to the conventional vehicle. It is no surprise that the PHC did not perform as well since not much effort was put into tuning the heuristic controller, but the ECMS should perform better than it does. The most likely reason for its poor performance could be that the static efficiencymaps were not representative. Also, neglecting all dynamics could be an invalid assumption. It is known that e.g. the turbolag, as modelled in VTM, can be up to 2 seconds which can be problematic if the requested torque from the engine switches on/off very frequent due to a badly tuned driver model. Some attempts to overcome these issues were made. A hold circuit for the TSF-factor was implemented. Any time TSF was set to 0 it was held at 0 for at least 10 seconds before it was allowed to take any other value. However it did not improve the results. Attempts were also made to improve and smoothen the driver model by e.g. tuning the control parameters and constraining the control signal, but also without resulting in any real improvements. It happens in the steepest descends that the electric energy path becomes saturated and friction brakes have to be used to maintain the requested speed. The limiting component that saturates first is the battery which can therefore be seen as a type of bottleneck. In appendix C it was investigated what would happen if the input/output power of both the EM and the battery increased since this means that more energy can be regenerated. Increasing the power to 150kW for both the EM and the battery resulted in a total fuel reduction of 8% for the Constant SoC 50 and 5% for the ECMS. It is clear that by increasing the size of the elecric components, especially the battery that acts as a bottleneck in the original setup, yields instant improvement of performance.

8 Conclusion

The conclusion aims at answering the questions stated in the introduction chapter.

- **Can the fuel consumption over a given driving cycle be made to decrease? How much?** The results from the simulations show that there is potential for a significant reduction of fuel consumption for the investigated mission. The Constant SoC 50 strategy yielded the lowest overall fuel consumption with a 5% reduction in comparison to a conventional truck. However, for other missions where more energy can be regenerated and battery saturation might become an issue, there are other strategies that may perform better such as the ECMS.

- **Is Control Allocation and Energy Management compatible?** The control allocator performed exactly according to the scheme presented in chapter 5 during the recuperation phases. It is harder to draw conclusions for the propulsion phases due to the priority conflict between what is requested by the driver and what is requested by the Energy Management. If the driver request is given priority it means that whenever the requested torque exceeds what can produced by the engine, the EM is used to add extra torque. This means that the SoC will decrease independantly of what is requested by the Energy Management. If instead the Energy Management is given higher priority the SoC will stay under control but the driver might end up in a unwanted situation due to not having access to the combined total power in the hybrid vechicle.

- **Is the proposed communication interface between tractor and semi-trailer sufficient?** The proposed communication interface was validated and verified to be sufficient for all strategies that were implemented in this work.

9 Future work

The result of this thesis is a first attempt to model a truck with an electrified semitrailer and many improvements can be done. Here follows a list of some improvements that could be made to the model and that could also lead to a better implementation in a real truck combination

- The battery is undersized compared to the other electric components and should be resized for better overall performance.
- The driver model should be improved to give a more justful judging of the performance of the compatibility of the CA+Energy Management. After that, the CA can be extended to handle more types of motion, see appendix A .
- A static battery model is best used in a case where the battery is placed in a protected environment and SoC does not vary a lot. This is not the intended battery usage in this case. A dynamic battery model should be implemented in the Simulink model to better correspond to reality.
- A more sophisticated brake blending could be implemented by combining the strategy used in this work together with the dynamic W_u matrix described in [10]. The brakes are in this work utilized depending on their respective axle load.

  $$W_u = \sqrt{mg}diag\left[\frac{1}{F_{zfl}}\ \frac{1}{F_{zfr}}\ \frac{1}{F_{zml}}\ \frac{1}{F_{zmr}}\ \frac{1}{F_{zrl}}\ \frac{1}{F_{zrr}}\right] \tag{9.1}$$

  In this test case, the investigated vehicle consisted of a 4x2 truck where the notation F_{zi} with $i \in \{fl, fr, ml, mr, rl, rr\}$ is used to depict axle vertical load for the axle corresponding to tyre i, i.e. $F_{zfl} = F_{zfr}$ assuming load is evenly distributed. Note that only brake actuators are considered in this case, the matrix would have to be extended for the test case described in this work. This approach ensures that the wheels with the most traction will also be the wheels that are braked the most, minimizing risque for slip. However, for the test case described in this report, the emphasis is on energy saving and since no hard braking will occur in this test, the slip will be negligible.
- The EMCS-approach resulted in the engine being switched on/off frequently. This is not desirable since it would probably result in a spasmic driving experience in a real truck implementation. A successful attempt to reduce this phenomena was made in [9] where an extra term was added to the cost function to solve the problem.
- The dynamic SoC-limit in PHC could be modified to be updated in-real-time instead of being calculated offline.
- More missions should be tested to further show on the difference in performance between the energy strategies.

- There are many other predictive controllers that can be explored for further reduction of the fuel consumption.

Appendices

A Extended control allocator

A generalized B-matrix for an arbitrary truck configuration was developed in [8]. This appendix shows the extended B-matrix for the truck configuration investigated in this thesis when not only longitudinal force F_X is controlled but also lateral force F_Y, turning moment around the Center of Gravity (CoG) of unit 1 and turning moment around the articulation point between unit 1 and unit 2 depicted M_θ. The parameters that are introduced in the following matrixes are defined in [8].

$$v = \begin{pmatrix} F_x & F_y & M_z & M_\theta \end{pmatrix} \tag{A.1}$$

No new actuators are considered for vehicle motion.

$$u = \begin{pmatrix} T^w_{11L} & T^w_{11R} & T^w_{12L} & T^w_{12R} & T^w_{21L} & T^w_{21R} & T^w_{22L} & T^w_{22R} & T^w_{23L} & T^w_{23R} & T^w_{ENG} & T^w_{EM} \end{pmatrix} \tag{A.2}$$

The B-matrix becomes too large to display at once and is therefore divided into submatrixes. Each line of the B-matrix connects to a global force and each column connects to one actuator.

$$B = \begin{pmatrix} B_{11} & B_{12} & C_1 \\ 0 & B_{\theta_2} & C_2 \end{pmatrix} \tag{A.3}$$

$$B_{11} = \begin{pmatrix} \frac{\cos(\delta_{11})}{R} & \frac{\cos(\delta_{11})}{R} & \frac{1}{R} & \frac{1}{R} \\ \frac{\sin(\delta_{11})}{R} & \frac{\sin(\delta_{11})}{R} & 0 & 0 \\ -\frac{(t_{11}cos(\delta_{11})-2l_{11}\sin(\delta_{11}))}{2R} & \frac{(t_{11}cos(\delta_{11})+2l_{11}\sin(\delta_{11}))}{2R} & -\frac{t_{12}}{2R} & \frac{t_{12}}{2R} \end{pmatrix} \tag{A.4}$$

$$B_{12} = \begin{pmatrix} \frac{\cos(\theta)}{R} & \frac{\cos(\theta)}{R} & \frac{\cos(\theta)}{R} & \frac{\cos(\theta)}{R} & \frac{\cos(\theta)}{R} & \frac{\cos(\theta)}{R} \\ \frac{\sin(\theta)}{R} & \frac{\sin(\theta)}{R} & \frac{\sin(\theta)}{R} & \frac{\sin(\theta)}{R} & \frac{\sin(\theta)}{R} & \frac{\sin(\theta)}{R} \\ -\frac{L_{21L}}{2R} & \frac{L_{21R}}{2R} & -\frac{L_{22L}}{2R} & \frac{L_{22R}}{2R} & -\frac{L_{23L}}{2R} & \frac{L_{23R}}{2R} \end{pmatrix} \tag{A.5}$$

$$B_{\theta,2} = \begin{pmatrix} -\frac{L_{\theta_{21L}}}{2R} & \frac{L_{\theta_{21R}}}{2R} & -\frac{L_{\theta_{22L}}}{2R} & \frac{L_{\theta_{22R}}}{2R} & -\frac{L_{\theta_{23L}}}{2R} & \frac{L_{\theta_{23R}}}{2R} \end{pmatrix} \tag{A.6}$$

$$C_1 = \begin{pmatrix} \frac{1}{R} & \frac{\cos(\theta)}{R} \\ 0 & \frac{\sin(\theta)}{R} \\ 0 & \frac{b_1\sin(\theta)}{R} \end{pmatrix} \tag{A.7}$$

$$C_2 = \begin{pmatrix} 0 & 0 \end{pmatrix} \tag{A.8}$$

B Design parameter settings

The parametersettings in table B were used for the Newtonian planar model and in the implementation of the ECMS.

Parameter:	Value:	Description:
A_f	$9.7\ [m/s^2]$	Front area
c_d	$0.6\ [-]$	Drag coefficient
c_r	$0.005\ [-]$	Roll coefficient
g	$9.81\ [m/s^2]$	Gravitational acceleration
m	$40000\ [kg]$	Total vehicle mass
ρ	$1.184\ [kg/m^3]$	Air density
λ	$-0.0919\ [-]$	Front area
s_{chg}	$1.75\ [-]$	Lower bound of equivalence factor
s_{dis}	$2.35\ [-]$	Upper bound of equivalence factor
p_w	$5\ [km]$	Length of prediction window

Table B.1. Parameter used for Newtonian planar model and ECMS

C Simulation with increased size of battery + EM

In order to investigate what happens to the resulting SoC and fuel consumption with a different setup the EM, generator and battery were resized to 150kW. The resulting SoC for the Constant SoC 50 strategy and the ECMS are seen in figure C.1 and C.2 respectively. Resulting fuel consumptions are presented in table C. The new setup results in a reduced fuel consumption for both strategies which is expected since more energy can now be regenerated. It can also be noted that the SoC fluctuation is less for the ECMS strategy which is good since the upper SoC limit of 0.7 is now almost reached by the Constant SoC 50 strategy. By finetuning the equivalencefactors s_{dis}/s_{chg} and perhaps also changing the length of the prediction window p_w, this fluctuation can be made even smaller.

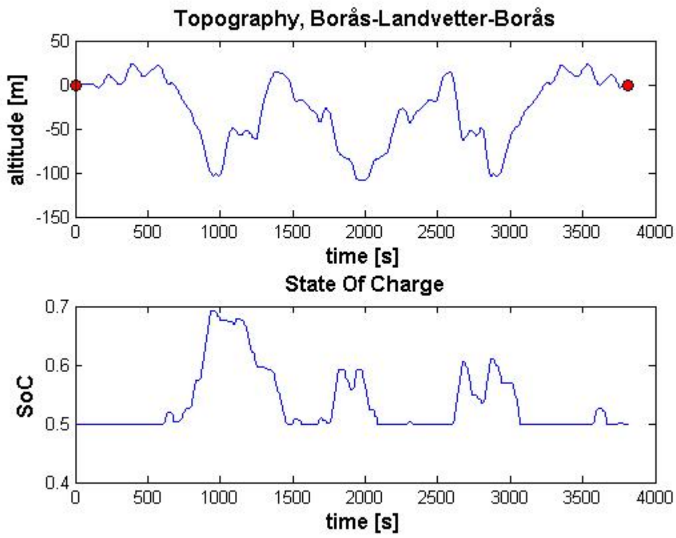

Figure C.1. Resulting SoC from simulation using the Constant SoC 50 strategy with resized EM and battery

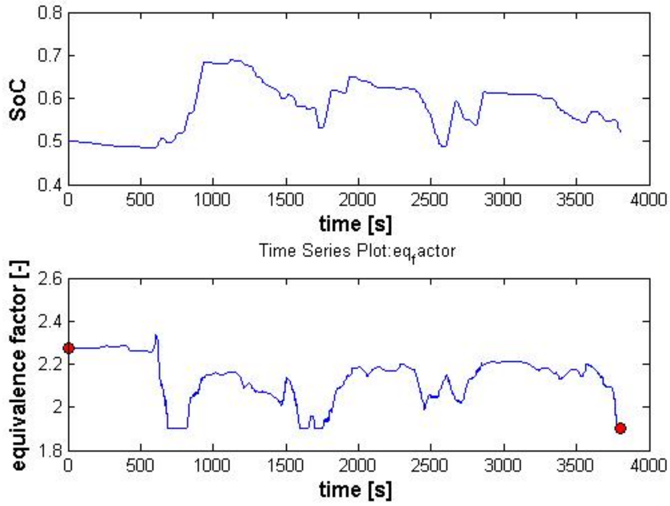

Figure C.2. Resulting SoC from simulation using the ECMS with resized EM and battery

Strategy	SFC [L]	SoC [-]	eSFC [L]
Conventional	25.53 (100%)	-	25.53 (100%)
Constant SoC 50	23.38 (92%)	0.50	23.38 (92%)
ECMS	24.30 (95%)	0.52	24.20 (95%)

Table C.1. Resulting fuel consumptions with resized EM and battery

Bibliography

[1] Daniel Ambühl and Lino Guzzella. Predictive reference signal generator for hybrid electric vehicles. *Vehicular Technology, IEEE Transactions on*, 58(9):4730–4740, 2009.

[2] J. Eklv. Real-time implementation of a vehicle motion coordinator for a single unit truck. Master's thesis, Chalmers University of Technology.

[3] Lino Guzzella and Antonio Sciarretta. *Vehicle propulsion systems*, volume 1. Springer, 2007.

[4] Ola Härkegård. Backstepping and control allocation with applications to flight control. 2003.

[5] Matthias Jönsson and Milen Kourtev. Predictive energy management for a mild hybrid long haul truck. Master's thesis, 2011.

[6] Leo Laine. *Reconfigurable motion control systems for over-actuated road vehicles*. Chalmers University of Technology,, 2007.

[7] Cristian Musardo, Giorgio Rizzoni, Yann Guezennec, and Benedetto Staccia. A-ecms: An adaptive algorithm for hybrid electric vehicle energy management. *European Journal of Control*, 11(4):509–524, 2005.

[8] P. Nyman and K. Uhlen. Coordination of actuators for long heavy vehicle combinations using control allocation. Master's thesis, 2014.

[9] Antonio Sciarretta, Michael Back, and Lino Guzzella. Optimal control of parallel hybrid electric vehicles. *Control Systems Technology, IEEE Transactions on*, 12(3):352–363, 2004.

[10] Kristoffer Tagesson, Peter Sundstrom, Leo Laine, and Nicolas Dela. Real-time performance of control allocation for actuator coordination in heavy vehicles. In *Intelligent Vehicles Symposium, 2009 IEEE*, pages 685–690. IEEE, 2009.

[11] Transformers. `http://www.transformers-project.eu/mainmenu/home/#.VnHHkbcveM8`, December 2015.

[12] K. Venkataraman and N. Acharya. Optimisation of distributed propulsion in long heavy vehicle combinations. Master's thesis, Chalmers University of Technology, Goteborg, Sweden, 2015.