Holistic Optimization of Energy Consumption of a Hybrid Powertrain with an "Equivalent Fuel Consumption Minimization Strategy" Algorithm

Master Thesis

Master Program Electromobility
of the
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Time Period: 06/19 –12/18/2020

Date:12/18/2020

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Stuttgart, December 18, 2020 Michael Zagun

Abstract

This master thesis shows a holistic approach for the optimization of the energy management task for a plug-in hybrid electric vehicle. The ‘Equivalent Consumption Minimization Strategy’ (‘ECMS’) as a local optimal approach is implemented into an embedded controller and applied to a system simulation model in ‘GT-SUITE’, which integrates a hybrid drivetrain and the associated control structure with a thermal management model. Two modifications and one extension to the basic ‘equivalent consumption’ cost function are proposed for the favor of an unambiguous interpretation of the penalty factor term, an enhanced applicability of the ‘ECMS’ close to the battery state of charge limit and an effective applicability of the ‘EMCS’ to the thermal management task. All proposed modifications and extensions prove their applicability in the virtual test environment and recommend themselves for the utilization in further application areas, like the integration of exhaust aftertreatment system, the holistic evaluation of a fuel cell drivetrain or the holistic evaluation of a hybrid ship propulsion system.

Zusammenfassung

Diese Masterarbeit zeigt einen ganzheitlichen Lösungsansatz zur Optimierung des Energiemanagements für ein Plug-in Hybridfahrzeug. Die ‚Equivalent Consumption Minimization Strategy‘ (‘ECMS’), der Klasse der lokal optimalen Steuerungsalgorithmen zugehörig, wird in einem eingebetteten Controller implementiert und auf ein Systemsimulationsmodell in der Software ‚GT-SUITE‘ angewendet, welches den hybriden Antriebstrang mit dem Thermomanagementsystem integriert. Es werden zwei Modifikationen und eine Erweiterung der zugrunde gelegten ‚äquivalenten Verbrauchs‘ Kostenfunktion vorgeschlagen zugunsten einer unmissverständlichen Interpretation des ‚Penalty Factor‘ Terms, einer verbesserten Anwendbarkeit der ‚ECMS‘ an der Kapazitätsgrenze der Batterie und einer effektiven Anwendbarkeit der ‚ECMS‘ für das Thermomanagement. Alle vorgeschlagenen Modifikationen und Erweiterungen erweisen sich in einer virtuellen Testumgebung als anwendbar und empfehlen sich für die Verwendung in weiteren Anwendungsbereichen, wie z.B. der Integration eines Abgasnachbehandlungssystems, der ganzheitlichen Bewertung eines Brennstoffzellenantriebs oder der ganzheitlichen Bewertung eines hybriden Schiffantriebsystems.

To my wife and my children

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1. Introduction

The commitment to the Paris Agreement stipulates a stepwise phase out of the GHG emissions from the automotive sector until 2050, which requires a monotonically increasing share of electrified vehicles to achieve the upcoming fleet emission targets which become effective from 2020. According to market monitoring, the next generation passenger car fleets will be a mix of downsized, highly efficient gasoline, diesel and biofuel internal combustion engines (ICE) combined with small and efficient electric traction motors before the transition to battery electric vehicles or fuel-cell electric vehicles will be inevitable.

The development of these hybrid vehicles means a complex enterprise, which general conditions are dominated by a mesh of relations and competing objectives. These are among other the expenses for new technologies, the increasing reliance on the supply chain, a disruptive evolution of the industry, increasing packaging efforts and pressure on functional integration, the compliance to upcoming emission regulations and fleet emission targets, the impending financial penalties, quota on passenger car registrations and low-emission zone restrictions and last but not least the changing customer expectations. Out of this the upstream conceptual development processes, which cover the specification of the drivetrain architecture are expected to consider the above given constraints, which in turn leads to the requirement for comprehensive and consistent development tool chains. System simulation is considered to add a huge value to the decision-making process, especially in the concept design process of a hybrid vehicle.

This master thesis focuses on the energy management task and its combination with the thermal management task as a crucial part of the concept finding process for a modern plug-in hybrid drive (‘PHEV’). The supervisory control concept is based on the ‘Equivalent Consumption Minimization Strategy’ (‘ECMS’), which means the selection of a locally optimal hybrid mode based on the variation of a set of admissible control input and the evaluation of a related cost function. The cost function relates the battery energy consumption and the fossil fuel consumption, by means of the efficiency chain of the hybrid drivetrain. Further, the supervisory control concept includes the interaction with the dynamics and the subordinate controls of the thermal management system and considers the instantaneous auxiliary power demand and foremost the internal combustion engine temperature.

The intention to combine the thermal management task with the supervisory control concept ‘ECMS’ requires a holistic and integrated modeling and solution approach of the vehicle thermal management system, the hybrid drivetrain system, the supervisory controls and the component-level controls of the hybrid vehicle.

The basic approach combines the system simulation software ‘GT-SUITE’ from Gamma Technologies, LLC with the modeling program ‘MATLAB/Simulink’ from The MathWorks, Inc. for the task of embedding an ‘ECMS’ controller prototype in a holistic dynamic hybrid vehicle system model.

The controller structure is derived following a modular design and the controller features are oriented on the concepts from literature [1]. The ‘ECMS’ controller includes a surrogate model of the underlying dynamic hybrid drivetrain for the purpose to evaluate the efficiency chain and the energy consumptions based on a backward-facing kinematic approach. Therefore, the kinematic surrogate model is based on ‘map-based’ component definitions, which allows an unconstrained modeling fidelity of the underlying dynamic hybrid drivetrain model in ‘GT-SUITE’. It may include mass and heat transport and combustion, which apply to the physical simulation of the internal combustion engine or the fuel cell. Further it may include chemistry and electro-chemistry which applies to the physical simulation of the exhaust aftertreatment and battery cells.

The created hybrid vehicle system model includes the drivetrain architecture, the relevant drivetrain components and the relevant thermal system components, which are specified inspired by the concept of the 2016 BMW 225xe [2]. The ‘ECMS’ controller is interconnected with the control structure of the hybrid vehicle system model and supplemented by additional system-level and component-level controllers for the handling of features like ‘Combustion Engine Cut-In during E-Drive’ and ‘Transmission Gear Shifting’

The functionality of the ‘ECMS’ controller is verified based on an isolated controller setup, using the stimulation with input signals and the comparison to reference results from the backward-facing vehicle simulation approach in ‘GT-SUITE’. Therefore, a kinematic and isothermal model version of the same hybrid drivetrain is created.

At all stages, drive cycle based maneuvers are conducted to the hybrid vehicle system model with the intent to evaluate the effectivity of the supervisory controls. For the purpose to derive a charge sustaining control stratetgy a calibration of the ‘ECMS’ controller, in terms of a constant equivalence ratio is conducted based on an iterative approach using the build in ‘Design Optimizer’ in ‘GT-SUITE’.

2. Basic principles

The following chapter covers the representative use cases and the basic theoretical and programmatical principles which are relevant for the realisation of this master thesis. The chapter is structured into three subchapters, which cover the priciples of the energy management task and the optimal control strategy (chapter 2.1), the reference hybrid vehicle drivertrain (chapter 2.2) and the tool chain which is applied to develop and evaluate the functions of the ‘ECMS’ controller prototype (chapter 2.3).

2.1. The energy management task and optimal controls

In the following the priciples of the energy management task and the optimal control strategy are covered. Starting with the basic scheme of the energy management task the integration of a supervisory controller into a hybrid vehicle control structure is shown and the principles of optimal controls are introduced and classified. Further a brief introduction is given to ‘Dynamic Programming’ as a ‘Global Optimization Strategy’ (chapter 2.1.1) and a focus is given to the class of ‘Local Optimization Strategy’ using the ‘Equivalent Consumption Minimization Strategy’ (chapter 2.1.2).

The operation strategy of a hybrid vehicle is embedded in a control structure of multitude subordinate subsystem- or component-level processes and a few supervisory system-level processes, which is illustrated in Figure 1.

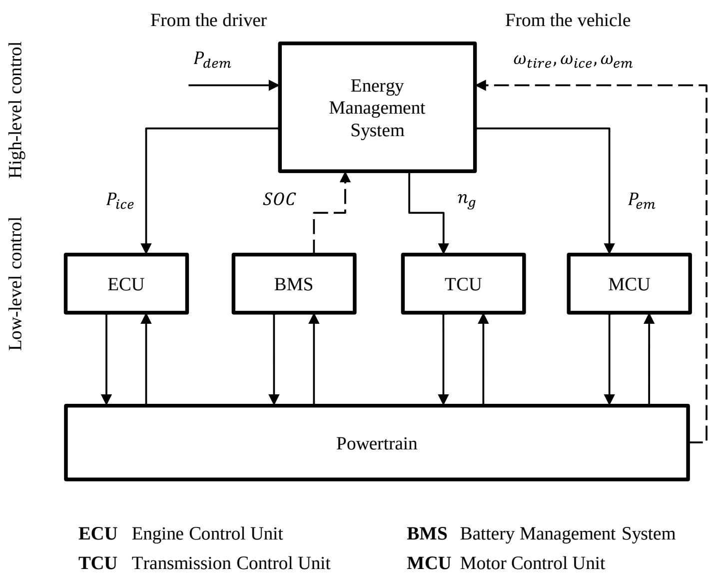


Figure 1: Two-layer control structure in a hybrid vehicle [1]

While the component-level control tasks, like controlling the engine air-to-fuel ratio or controlling the motor current angle utilize feedback control methods, the system-level tasks, like the optimization of the energy flow or maintaining the battery state of charge at a certain level requires a different approach. The energy management system processes available information from the vehicle and the driver and evaluates the optimal operating mode and the target values for the subordinate subsystem- or component-level processes. [1] Further it can be sensitive in respect to the upcoming maneuver such that the available information about the route (from the navigation system) and the expected vehicle speed (from the traffic information system) is considered in the decision making process [3], [4] and [5].

During the recent twenty years three major classes of energy management strategies have been thoroughly discussed throughout the industry, which are the ‘Global Optimization Strategy’, the ‘Local Optimization Strategy’ and the ‘Heuristic Strategy’. The ‘Heuristic Strategy’ is characterized by the set of rules, which are defined based on heuristics, correlations, intuition or from knowledge obtained from the optimization algorithms which are described in the following. The ‘Optimization Strategies’ are characterized by the minimization of an energy consumption related cost function, which is sensitive to the combination and interplay of a set of control inputs (e.g. target values for the component-level processes). [1]

2.1.1. Global Optimization Strategy

‘Dynamic Programming’ as a ‘Global Optimization Strategy’ goes back to the work and publications of Richard Bellman and constitutes a numerical method for the solution of a multi-stage decision making problem [6]. It considers the dynamic nature of the underlying system and derives the global optimal control policy for an a priori known maneuver by operating backwards in time according to Belman’s principle of optimality. The states of the system x and the control input u are discretized and consider the system constraints. In a first step each possible transition between the discrete system states is evaluated for its cost. In a second step all control policy variants are evaluated considering the cost J of the state they are originating from and the change of state they are causing. Finally, the control policy with the least cumulated cost is derived and regarded as the global optimal control policy.

$$\min_{u(t)} \int_0^{t_f} J(x(t), u(t), t)\, dt \tag{1}$$

In the context of the energy management task in a modern hybrid vehicle the battery state of charge represents the system state x and the power split between the combustion engine and the electric machine represents the control input u. The continuous cost function J is defined from two terms which address the terminal state cost G and the cost of applying the control input H.

$$J\big(u(t)\big) = G\left(x\big(t_f\big)\right) + \int_0^{t_f} H(x(t), u(t), t)\ dt \tag{2}$$

The continuous control problem is discretized as a discrete time model with the following definitions

$$x_{k+1} = f_k(x_k, u_k), \qquad k = 0, 1, \dots, N-1$$
$$u = u_0, u_1, \dots, u_{N-1} \tag{3}$$

so that the cost of the control policy u can be rewritten to

$$J_\pi(x_0) = g_N(x_N) + T_N(x_N) + \sum_{k=0}^{N-1} L_k\big(x_k, u_k(x_k)\big) + p_k(x_k) \tag{4}$$

Similar to equation (2) the first to terms $g_N(x_N) + T_N(x_N)$ relate to the final state x_N accounting for the cost of the final state and a penalty to enforce a partially constrained final state.

The last two terms relate to the cost of applying the control policy $u_k(x_k)$ accounting for the cost of the control input $L_k\big(x_k, u_k(x_k)\big)$ and the penalty $p_k(x_k)$ enforcing to keep the state constraints.

The global optimal control policy $J^*(x_0)$ is derived from the minimization of $J_\pi(x_0)$

$$J^*(x_0) = \min_{x \in \pi} J_\pi(x_0) \tag{5}$$

The ‘Dynamic Programming’ approach is expected to deliver superior fuel consumption savings and represents the benchmark for all other approaches. As it conducts a huge computational effort and requires the a priori knowledge of the maneuver it is exclusively used in the simulation environment.

2.1.2. Local Optimization Strategy

The ‘Equivalent Consumption Minimization Strategy’ (‘ECMS’) as a ‘Local Optimization Strategy’ goes back to the work of Paganelli. It considers the dynamic nature of the underlying system and reduces the global optimization problem to a local minimization problem, such that only the current system state x and the cost associated with the control input u is considered for the evaluation of the local optimal control policy.

$$\min_{u(t)} \int_0^{t_f} J(x(t), u(t), t)\, dt \;\; \rightarrow \;\; \int_0^{t_f} \min_{u(t)} J(x(t), u(t), t)\; dt \tag{6}$$

The control input is discretized and considers the system constraints. For each given time instance all control input variants are evaluated to calculate the resulting cost. The control input variant with the least cost is regarded as the local optimal control policy. [7] and [8]

In the context of the energy management task in a modern hybrid vehicle the power split between the combustion engine and the electric machine represents the control input. Following the notion that for a charge sustaining operating strategy the net sum of electrical power consumed from and replenished to the energy storage is zero and that finally all replenished electrical energy originates from the conversion of fossil fuel and the recuperation of kinetic energy, the internal battery power P_{bat} is transformed to an ‘electrical’ fuel consumption $\dot{m}_{bat}$ by means of the specific fuel consumption sfc_{eqv}. Consequently, the cost function is defined from these two objectives, the fossil fuel consumption $\dot{m}_{fuel}$ and the internal battery power and represents an equivalent fuel consumption $\dot{m}_{eqv}$. [1]

$$\begin{aligned} J(x(t), u(t), t) &= \dot{m}_{eqv}(x(t), u(t), t) = \dot{m}_{fuel}(u(t), t) + \dot{m}_{bat}(x(t), u(t), t) \\ &= \dot{m}_{fuel}(u(t), t) + sfc_{eq}(t) \cdot P_{bat}(x(t), u(t), t) \end{aligned} \tag{7}$$

In analogy to the internal combustion engine and the definition of combustion efficiency the specific fuel consumption sfc_{eqv} may be expressed by means of an equivalence factor s and the lower heating value of fossil fuel Q_{lhv}. [1]

$$sfc_{eqv}(t) = \frac{s(t)}{Q_{lhv}} \tag{8}$$

The equivalent factor represents the efficiency of the conversion chain between the chemical energy of the fossil fuel and the electro-chemical energy stored in the traction battery and as such it may be understood as a result from the actual operating conditions of the chain components. The original formulation of 'ECMS' considers a pair of time-averaged equivalence factors $s = [s_{dis}, s_{chg}]$, taking into account the efficiency chain during the discharge and charge of the traction battery. [1]

The system state constraints are considered by means of a multiplicative penalty function $p\big(x(t)\big)$, such that battery charging is favored at low battery state of charge and battery discharging is favored at high battery state of charge. [1]

$$\dot{m}_{eqv}(x(t), u(t), t) = \dot{m}_{fuel}(u(t), t) + \frac{s}{Q_{lhv}} \cdot P_{bat}(x(t), u(t), t) \cdot p\big(x(t)\big) \tag{9}$$

$$p\big(x(t)\big) = p\big(SOC(t)\big) = 1 - \left(\frac{SOC(t) - SOC_{target}}{(SOC_{max} - SOC_{min})/2}\right)^{a}, \qquad a = 1,3,5, \ldots \tag{10}$$

The penalty function accounts for the actual deviation of the battery charge $SOC(t)$ in respect to its anticipated target value SOC_{target} and scales it to an anticipated operating range defined by the expression $SOC_{max} - SOC_{min} = \Delta SOC$. It may be noted that this expression introduces a system state range ΔSOC rather than absolute system constraints and implies a symmetrical penalty function shape. The penalty term exponent a shifts the effect of the actual scaled deviation of the system state on to the penalty function value which is shown in Figure 2. In general, the penalty term exponent a is expected to be an uneven integer number.

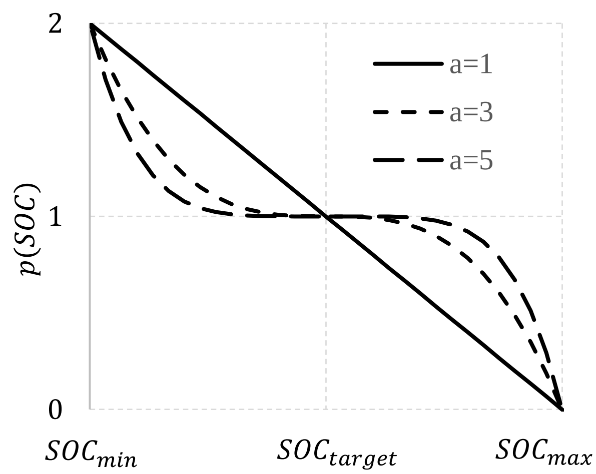


Figure 2: Penalty function used in ECMS. [1]

Compared to 'Dynamic Programming' the 'ECMS' approach is regarded to deliver slightly suboptimal fuel consumption savings if calibrated well for an a priori known maneuver or if being adapted in terms of the equivalence ratio either as a function of the battery power [5] or as function of the upcoming energy requirement and recuperation potential [3]. The 'ECMS' approach requires less computational effort and is regarded to fulfil the real time requirements in the context of online computation in a vehicle control unit. [1]

2.2. Hybrid Drivetrain

2.2.1. Reference Drivetrain (BMW 225xe)

In 2016 BMW introduced the 225xe iPerformance as a derivate of the 2 active tourer series. It was the third PHEV from BMW and the first with an electric all-wheel drive. The hybrid drivetrain combines a 1.5l three-cylinder turbocharged gasoline direct injection engine with an automatic six-speed transmission at the front axle and a 3-phase internal permanent magnet synchronous machine with a single-speed gearbox at the rear axle. Table 1 contains selected vehicle attributes.

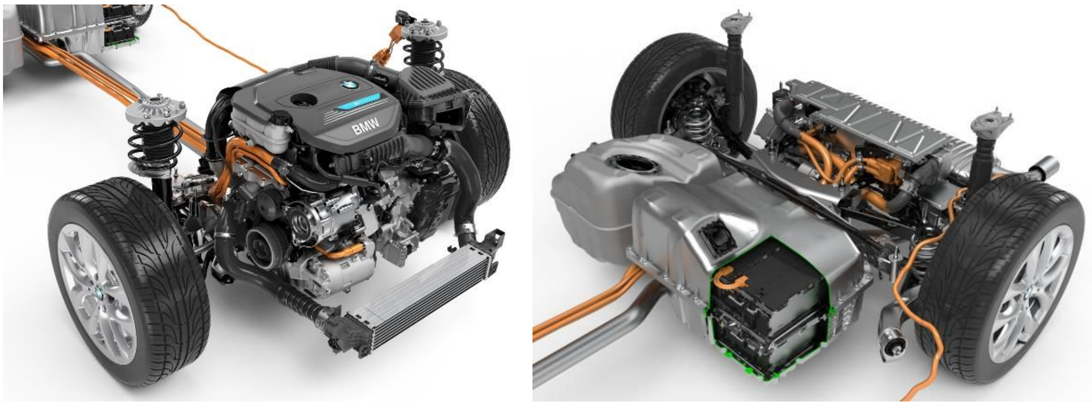


Figure 3: Drivetrain of the BMW 225xe iPerformance [9]

The operating strategy of the BMW 225xe iPerformance offers three different main operating modes. With the electric motor decoupled from the rear axle the vehicle is operated in conventional mode. With the combustion engine turned off and decoupled from the front axle the vehicle is operated in electric drive mode. When both the combustion engine and the electric motor are turned on the vehicle is operated in four-wheel drive mode. The driver torque demand is distributed fully electronically as the drivetrain is not connected mechanically between the front and rear axle. The supervisory controls switch between the main operating modes as a function of driving dynamics and efficiency requirements. Additionally, the driver is allowed to intervene the supervisory controls by applying specific driving modes, like *'Auto eDrive'*, *'Max eDrive'* and

‘Save Battery’ in combination with driving experience modes, like *‘Sport’*, *‘Comfort’* and *‘Eco Pro’*. To enable further operating modes, like ‘Combustion Engine Start-Stop’, ‘Combustion Engine Cut-In during E-Drive’, ‘Combustion Engine Load Shifting’, ‘Charging at Vehicle Stop’ the combustion engine is equipped with a high voltage belted starter generator. [2]

Table 1: Selected vehicle attributes published by BMW [2]

Attribute	Value	Unit	Remark
Max. Engine Power	100	kW	
Max. Motor Power	65	kW	
Acceleration 0-100 kph	6.7	s	
Maximum Speed	202	km/h	
Maximum Speed in E-Drive	125	km/h	
Vehicle Mass	1660 / 2105	kg	Min. / Max.
Fuel consumption	2.0	l/100km	Combined
CO_2 Emissions	46	g/km	Combined
HV Battery Capacity	7.7	kWh	
Electric Range	41	km	

2.3. Tool Chain

2.3.1. Drivetrain and Controls modeling in ‘GT-SUITE’

‘GT-SUITE’ is a 0D/1D/3D multi-physics CAE system simulation software developed, licensed and supported by Gamma Technologies, LLC. ‘GT-SUITE’ provides comprehensive component libraries for the simulation of fluid flow, thermal, mechanical, electrical, magnetic, chemistry, and controls. From those libraries accurate models of almost any engineering system are build, which are, among other vehicles and drivetrains, internal combustion engines and exhaust aftertreatment, batteries, power electronics and electric motors. For the purpose of controls design ‘GT-SUITE’ provides a versatile library of general mathematical and conditional blocks (‘primitives’) and a set of predefined model-based component-level controllers for specific applications, like among other internal combustion engine load control (compression or spark ignition) or the turbo charger control (wastegate or variable turbine geometry). [10]

Kinematic driving cycle analysis

For the preliminary evaluation of the fuel economy and energy management task ‘GT-SUITE’ provides a fast, kinematic solution approach, which is applicable to the mechanical domain and selected map-based vehicle components. Two solution conventions are applicable, according to the type of applied boundary conditions, which are the ‘forward’ and the ‘backward’ kinematic solution. The ‘forward’ kinematic solution imposes the load or actuator position on the power actuators and solves for the power transfer along the mechanical domain towards the tire. The ‘backward’ kinematic solution imposes the vehicle target speed onto the vehicle and solves for the power transfer along the mechanical domain towards the power actuators. The backward-facing vehicle solution approach builds the basis for the evaluation of the already implemented optimal control strategies, like ‘ECMS’ and Dynamic Programming. It allows to describe any kind of hybrid drivetrain structure from idealized rigid mechanical components by means of their inertias, speed transformation and power transfer efficiencies. One of its limitations is the combination of thermal with the energy management task, which is critical to fulfilling the basic objective of energy management. The backward kinematic solution approach is ‘local’ in time and only applicable to ‘map-based’ component definitions. It is not capable to solve the mass and the heat transport in the thermal management system.

Dynamic driving cycle analysis

Vehicle system simulation in ‘GT-SUITE’ is typically based on the dynamic driving cycle analysis. This implies that the maneuver is defined with the help of a target speed as a function of time or travelled distance and that a dynamic control structure is applied to actuate the drivetrain model, so it can closely follow the target speed. An integrated part of the vehicle control structure is the driver model. The driver model may be understood as a model-based speed controller. To fulfill this task, the driver model is equipped with corresponding controller states. The cruise control, which is the default state, actuates the accelerator pedal position and the brake pedal position. To estimate the required pedal positions and to precondition the corresponding PI controllers the driver model has a basic knowledge of the underlying drivetrain, like the vehicle mass, the actual retarding forces on the vehicle, the major drivetrain inertias, the actual engine speed, the engine power output map and the brake torque map. From these attributes the acceleration demand a_{Demand} is used to calculate for the required traction force F_z.

$$a_{Demand} = \frac{v_{actual} - v_{target}}{1s} \cdot P \tag{11}$$

$$F_Z = \left(m + \sum \frac{J_i}{r_{dyn}^2} \cdot \frac{\omega_i}{\omega_{Wheel}}\right) \cdot a_{Demand} + m \cdot g \cdot (sin\,\alpha + \mu \cdot cos\alpha) + c_W A \cdot \frac{\rho}{2} v^2 \tag{12}$$

Finally, the required engine power output in terms of the brake mean effective pressure for a 4-stroke combustion engine is calculated:

$$BMEP_{Demand} = \frac{4\pi}{V_h} \cdot T_{Demand} = \frac{4\pi}{V_h} \cdot F_Z \cdot r_{dyn} \cdot i^* \cdot \eta^* \tag{13}$$

Figure 4 shows the control structure of the default driver state. The drivetrain model is actuated with the accelerator pedal position "APP" and brake pedal position "BPP", which is appropriate for drivetrains with one power actuator (conventional or battery electric vehicle).

As hybrid drivetrains require a control unit which processes the driver pedal position signals to split up the driver torque demand on the appropriate drivetrain components, like internal combustion engine, mechanical brakes and electric machine, the driver model offers the 'driver torque demand' or the 'driver power demand' as alternative output signals to setup the power split control unit. Figure 5 opposes the alternative control structures for a generic hybrid drivetrain in GT-SUITE.

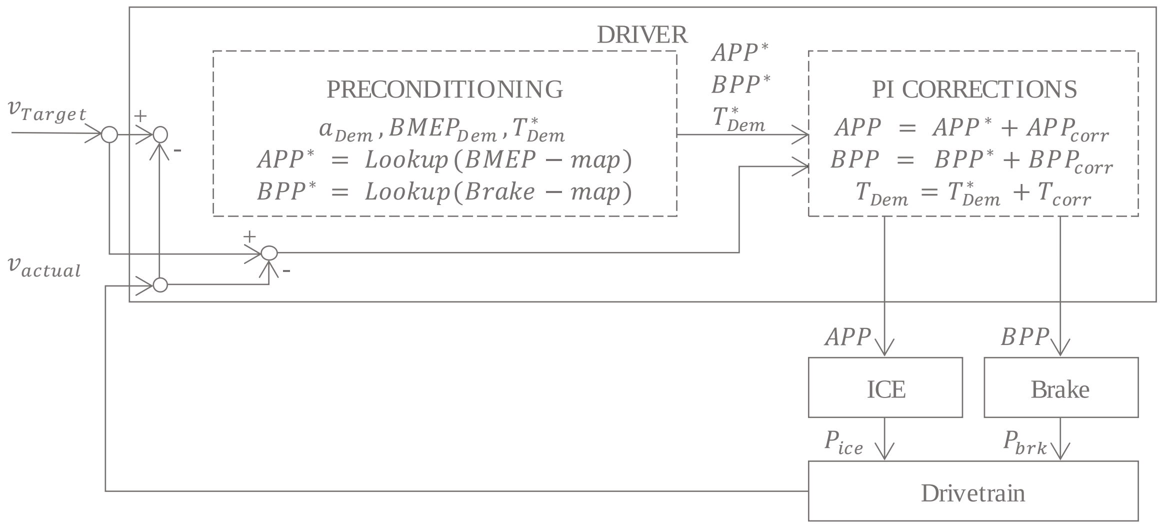


Figure 4:Control structure of driver model in GT-SUITE

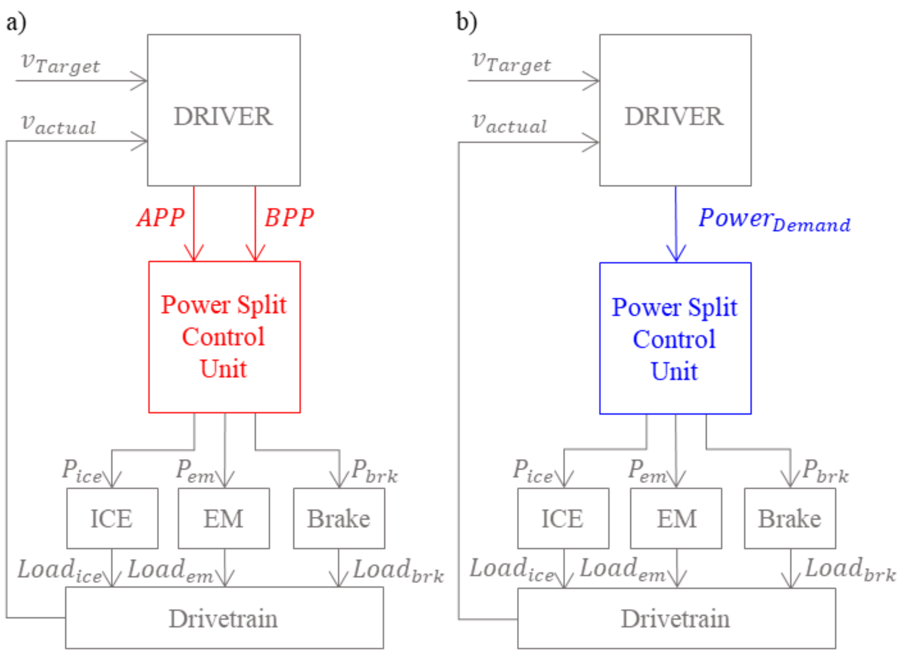


Figure 5: Alternative control structures for hybrid drivetrains in GT-SUITE, based on a) pedal signals, b) driver torque or power demand signal

The control structure is modeled hierarchically, based on a signal flow approach such that each signal represents a scalar value at a given time instance. In the context of the 'ECMS' controller development this characteristic of the control structure requires the supplement of a signal processing approach, which is capable to handle a multitude of values for each variable using a matrix-based solution approach. For the purpose of embedding such a specific controller 'GT-SUITE' provides a variety of options in the form of 'Multiple Input Multiple Output' ('MIMO') interfaces to the interpreter-based high-level programming language based Python functions, the Functional Mockup Unit and any dynamic libraries based on C or Fortran code which comply to the GT API convention. The 'ECMS' controller developed in this master thesis is embedded in 'GT-SUITE' using the interface to 'MATLAB/Simulink', which basically utilizes precompiled C code based dynamic libraries.

2.3.2. 'MATLAB/Simulink'

'MATLAB' is a commercial computational tool from The MathWorks, Inc. for the numerical solution of mathematical problems. The numerical solver is tailored for matrix calculation. It is widely used throughout the industry, in research and academia for numerical calculations and data analysis. It provides a graphical user interface, which allows to define the task or problem of interest from a proprietary high level language with a huge set of commands and functions. 'MATLAB' builds the basis for 'Simulink', which is a commercial computational tool from The

MathWorks, Inc.. Its graphical user interface is tailored for the hierarchical modeling of dynamic systems from a huge set of graphical blocks representing continous or time discrete functions or user code in the form of embedded ‘MATLAB’ functions or S-functions. Both ‘MATLAB’ and ‘Simulink’ can connect to third party tools using a tailored API for the linkage between the tools and the exchange of signals and messages. This co-simulation approach allows to solve complex multi-domain problems and suffers from the usage of tailored domain specific solvers. In the context of function development for embedded systems both ‘MATLAB’ and ‘Simulink’ allow to transform ‘MATLAB’ functions and ‘Simulink’ models into other programming languages like C and C++ unsing an integrated workflow called ‘MATLAB Coder’ or ‘Simulink Coder’. The approach consists of a formal transformation of the relevant functions and the problem description into the target language and a compilation of the generated target code into a dynamic library. [11], [12] and [13]

A common use case in the automotive industry is to define and model the vehicle control structure in ‘MATLAB’ and ‘Simulink’. In the context of an early-stage development of a control unit, when the target control unit hardware is still unavailable the co-simulation approach provides an adequate solution to verify the functionality of the developed code. From the moment the target control unit hardware is available the approach to embed the transformed code provides the verification of the code functionality in the target environment and the compliance to the real-time requirement. In case of a single control unit this test scenario requires the connection of the control unit to a PC, which mimics the behavior of the mechanical target hardware based on a real-time capable simulation model, the provided actuator signals and the feedback of synthesized sensor signals. In case of multiple and interconnected control units this test scenario may be set up from a variaty of setups including the partial integration of real sensors and hardware.

This master thesis represents an early-stage development scenario and utilizes ‘Simulink Coder’ to embed the ‘ECMS’ controller code in the CAE system simulation software ‘GT-SUITE’. The detailed approach is described in chapter 3.2

3. Experimental Procedure

The following chapter covers the applied approaches and the derived principles which are relevant for the realisation of this master thesis.

3.1. Hybrid Drivetrain Model Simulation using ‘GT-SUITE’

In the following sections the details of the elaborated simulation models are shown. A special focus is given to the preparation of the baseline results for the verification of the developed ‘ECMS’ controller utilizing the backward kinematic solution approach in ‘GT-SUITE’ and based on a kinematic variant of the hybrid vehicle system model (chapter 3.1.1). Further the embedding of the ‘ECMS’ controller in the dynamic hybrid vehicle system model is shown, covering the associated setup of the subordinate component-level controls (chapter 3.1.2). The drivetrain component specifications are listed in Appendix B.

3.1.1. Kinematic ‘ECMS’ using the Backward Kinematic Solution Approach

The created kinematic simulation model represents a P0/P4 PHEV drivetrain structure and utilizes the map-based modeling approach according to the convention of the backward kinematic solution approach in ‘GT-SUITE’. The energy storage (battery), the energy transformers (internal combustion engine, electric motor), the drivetrain (transmission, differential, shaft) and the vehicle (chassis, tires) are represented by phenomenological, data based, mechanically rigid component models. Figure 6 illustrates the basic build-up of the hybrid vehicle system model which includes the setup for the evaluation of ‘ECMS’ using the backward kinematic solution approach in ‘GT-SUITE’.

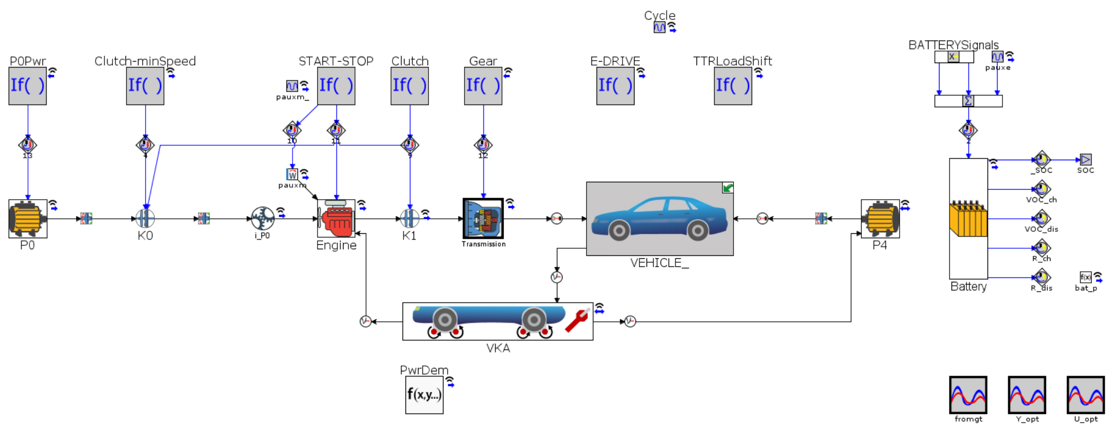


Figure 6: Setup of the hybrid vehicle system model for the evaluation of ‘ECMS’ using the Backward Kinematic Solution Approach in GT-SUITE

In the following the setup for the evaluation of ‘ECMS’ is described.

Control Input

According to the topology and the anticipated operating modes of the hybrid drivetrain a set of four control input variables and the according value ranges is defined, which are listed in Table 2. The below given discretization of the power request to the electric machines is regarded as a minimum resolution.

Table 2: Control Input variables and absolute constraints on control input for ‘ECMS’

Control Input	Value Range	Unit	Represents
‘Active Solution Power Source Port Number’ from part ‘VKA’ (Template ‘VehKinemAnalysis’)	2…3 $\in \mathbb{N}$	N/A	‘E-Drive’ mode
‘Requested Gear Number’ from part ‘Transmission’ (Template ‘Transmission’)	1…6 $\in \mathbb{N}$	N/A	Gear number
‘Requested Brake Power’ from part ‘P4’ (Template ‘MotorGeneratorMap’)	-80 …+80 Δ = 5%	kW	Traction motor
‘Requested Brake Power’ from part ‘P0’ (Template ‘MotorGeneratorMap’)	-15 …+15 Δ = 5%	kW	Starter-Generator

Constraints to Control Input

The solution approach of optimal controls, if unconstrained, may lead to an undesired operation because of a too frequent or too rapid change in control values. Therefore the following change rate and switching frequency constraints on control input are defined, which are listed in Table 3.

Table 3: Change rate and switching frequency constraints on control input for ‘ECMS’

Control Input	Switch	Time Delay	Purpose
‘Active Solution Power Source Port Number’	+	2 s	‘E-Drive’ mode allowed after 2 s
‘Active Solution Power Source Port Number’	-	5 s	‘Hybrid’ mode allowed after 5 s
‘Requested Gear Number’	+/-	1 s	Gear shift allowed after 1 s

Control Input	Change rate	Value	Purpose
‘Requested Gear Number’	+/-	1 s^{-1}	One gear per shift

Control Input	Switch	Fuel penalty	Purpose
‘Requested Gear Number’	+	0.1 g/s	Prevent upshifting during braking to stop

The following state constraints are defined in order to prevent undesired operating conditions by means of selected system states, which are listed in Table 4.

Table 4: Constraints on states for ‘kinematic’ ECMS

State variable	Condition	Purpose
Internal Combustion Engine speed	< 5000 rpm	Prevent inefficient high speeding
Traction motor brake torque	< max. Torque > min Torque	Prevent operation outside the efficiency map
Starter-generator brake torque	< max. Torque > min Torque	Prevent operation outside the efficiency map

Further conditional constraints are defined in order to prevent undesired operating modes by means of selected combinations of control input values or combinations of control inputs and hybrid vehicle system states, which are listed in Table 5.

Table 5: Conditional constraints on combination of control inputs and/or system states for ‘ECMS’

Condition		Purpose
If	Vehicle speed = 0	Reset gear number to 1 at vehicle stop
Then	‘Requested Gear Number’ = 1	
Else	‘Requested Gear Number’	
If	Vehicle speed = 0	Force ‘E-drive’ at vehicle stop
Then	‘Active Solution Power Source Port Number’ ≥ 3	
Else	‘Active Solution Power Source Port Number’ ≥ 2	
If	Power demand[1)] > 0 AND Traction motor brake power < 0	Prevent ‘through the road’ load shifting
Then	Skip scenario	
If	Power demand[1)] > 0 AND Traction motor brake power > Power demand	
Then	Skip scenario	
If	Power demand[1)] < 0 AND Traction motor brake power < Power demand	
Then	Skip scenario	
If	Power demand[1)] < 0 AND Traction motor brake power > 0	
Then	Skip scenario	
If	Power demand[1)] < 0 AND Starter-generator brake power > 0	
Then	Skip scenario	

<table>
<tr><td>If</td><td>‘Active Solution Power Source Port Number’ = 3</td><td rowspan="6">Force engine ignition off during ‘E-drive’ or vehicle stop
and
Prevent engine stall</td></tr>
<tr><td>Then</td><td>Clutch 1 open, Engine ignition off</td></tr>
<tr><td>Else</td><td>Clutch 1 closed, Engine ignition on</td></tr>
<tr><td>If</td><td>‘Active Solution Power Source Port Number’ = 3
OR Vehicle speed = 0</td></tr>
<tr><td>Then</td><td>Engine speed > 0</td></tr>
<tr><td>Else</td><td>Engine Speed > 850 rpm</td></tr>
<tr><td>If</td><td>Active Solution Power Source Port Number’ = 3</td><td rowspan="5">Force Starter-generator operation during ‘E-Drive’ or vehicle stop
and
Impel mechanical auxiliary</td></tr>
<tr><td>Then</td><td>Starter-generator clutch open,
Starter-generator brake power = 3 kW</td></tr>
<tr><td>Else</td><td>Starter-generator clutch closed</td></tr>
<tr><td>If</td><td>‘Active Solution Power Source Port Number’ = 3
OR Vehicle speed = 0</td></tr>
<tr><td>Then</td><td>Starter-generator speed = 2.500 rpm</td></tr>
</table>

The effective overall power demand to accelerate the vehicle and the hybrid drivetrain along the defined target speed profile is calculated by combining the applied brake power at the power actuators and by considering the associated efficency chains based on the following kinematic equation.

$$P_{Dem} = \left(P_{P0} \cdot \eta_{P0,m}^{sign(1,P_{P0})} + P_{ICE}\right) \cdot \eta_{TM} + P_{P4} \cdot \eta_{P4,m}^{sign(1,P_{P4})} \tag{14}$$

Penalties on control input

For the purpose to prevent shifting to higher gear numbers during the deceleration periods of the maneuver a constant fuel rate penalty of 0.1 g/s is applied.

Cost function

The cost function is defined according to (9) and (10) with the following setup:

Table 6: Coefficients for ‘ECMS’ cost function

Coefficient	Condition
SOC_{min}	0.4
SOC_{max}	0.6
SOC_{target}	0.5
Equivalence ratio s	2.77
Penalty term exponent a	1
Fossil fuel lower heating value Q_{lhv}	43.95 MJ/kg

Solver settings

The kinematic solution is solved using the ‘1 degree of freedom’ solution approach which effectively shrinks the mechanical model to a single equation of motion. The time step size of 1 s is kept constant for the entire simulation.

Calibration of equivalence ratio

The equivalence ratio is calibrated for the purpose of charge sustainannce ($SOC_{init} = SOC_{final} = SOC_{target}$) by means of the integrated design optimizer in GT-SUITE and based on the ‘discrete-grid’ search algorithm.

3.1.2. Dynamic System Model of the Hybrid Vehicle

The dynamic simulation model represents a P0/P4 PHEV drivetrain structure with an integrated thermal management model. Similar to the kinematic simulation model the energy storage, the energy transformers, the drivetrain and the vehicle are represented by phenomenological, data based, mechanically rigid component models. The thermal management model consists of multiple thermal circuits, which components are represented by phenomenological, data-based component models (heat exchangers, pumps, thermostats, compressors and blowers) and physical component models (pipes, flow splits, thermal masses).

Figure 7 shows the basic subassembly structure of the integrated thermal management model with the hybrid vehicle system model.

The electrical components are connected indirectly using a signal-based approach. The high-level and low-level controls of the hybrid drivetrain are contained in an internal subassembly. The signal flow from the sensors to the control subassembly and from the control subassembly to the actuators is transmitted ‘wirelessly’.

The drivetrain components are connected indirectly to the thermal management model using a signal-based approach. Therefore, the thermal losses of the energy transformer components are sensed and actuated onto the according thermal masses in the thermal management model.

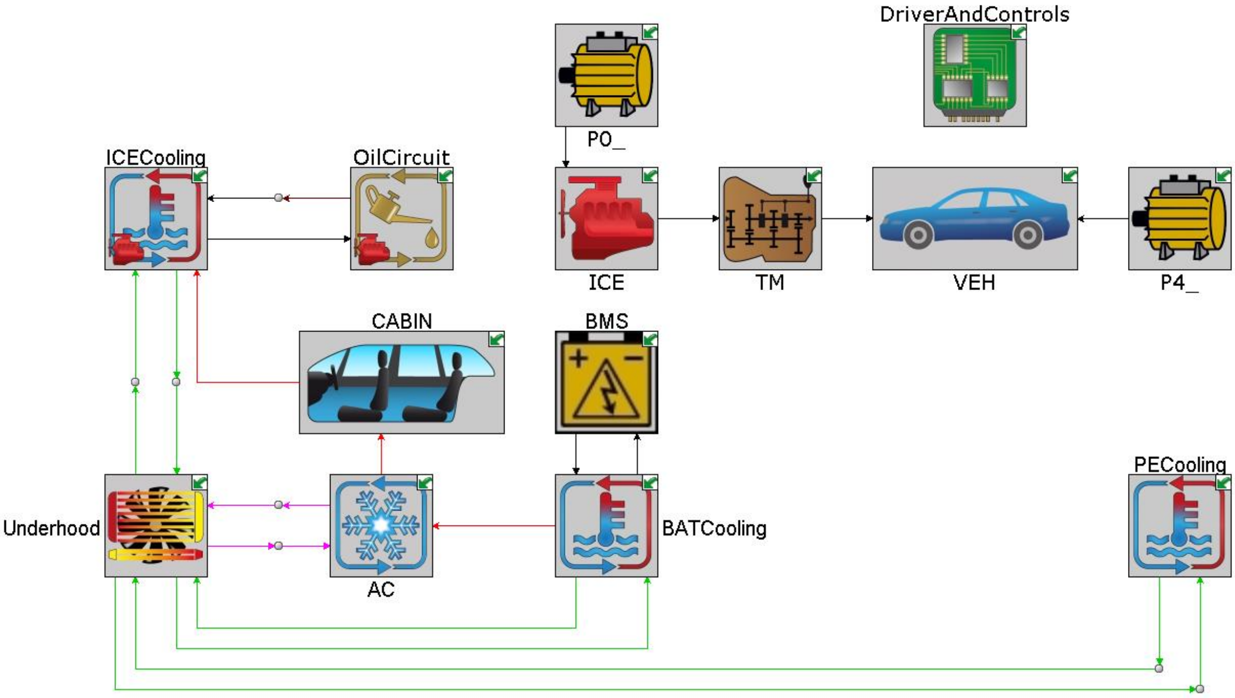


Figure 7: Simulation model of a P0/P4 hybrid drivetrain

The following section describes the setup of the relevant component models, like the battery pack and the internal combustion engine and the hybrid drivetrain control structure embedding the developed ECMS controller.

Battery Pack

The battery pack is structured from individual single cell models, based on the '*Battery'* template. The battery pack model is structured in seven electrically independent battery modules, each of them containing 15 serial busbar connected cells and is actuated in terms of a battery power request. In contrast to the reference vehicle the battery pack is scaled in terms of connected cells in series, with the target to provide a DC-link voltage of approximately 375 V and enough electrical power to supply the 80 kW rear traction motor. The electrical specifications of the cell are derived from electrochemical simulations using 'GT-Autolion', which are a result from an internal project and are listed in Appendix B. The effective open circuit voltage of each cell is sensed and summed up to evaluate the overall open circuit voltage of the battery module and the battery pack. The internal resistance of each cell and busbar is sensed and summed up to evaluate the overall internal resistance of each battery module and the battery pack.

The battery modules include direct cell cooling, by means of drilled 'single pass' cooling plates, which are positioned in between the cells. This arrangement is expected to deliver a superior heat exchange from and to the cell and consequently allows to represent each cell with a single thermal mass.

Internal Combustion Engine

The internal combustion engine is defined as a map-based model using the '*EngineMap*' template. The specifications represent a generic, turbo-charged, gasoline direct injection engine. The maps for the mechanical output, friction, fuel consumption, heat rejection and emissions are taken from the 'GT-SUITE' model library and are based on results from fast-running engine model simulations conducted in a previous internal project. These fast-running engine model simulations are based on a 'typical' coolant temperature set point of 100°C.

As the thermal state of the internal combustion engine structure and the engine coolant temperature as its observable is decisive for the quality of the combustion process, the internal friction loss and hence for the internal combustion engine efficiency and the fuel economy, a correction is applied to the nominal specifications based on an additive mean effective pressure term. The additive mean effective pressure correction term affects the lookup of the mapped engine specifications and is a function of the internal combustion engine speed and the engine coolant temperature. As no specifications for other temperature set points are available, the 'default' correlation from 'GT-SUITE' is used, which is illustrated in Figure 8.

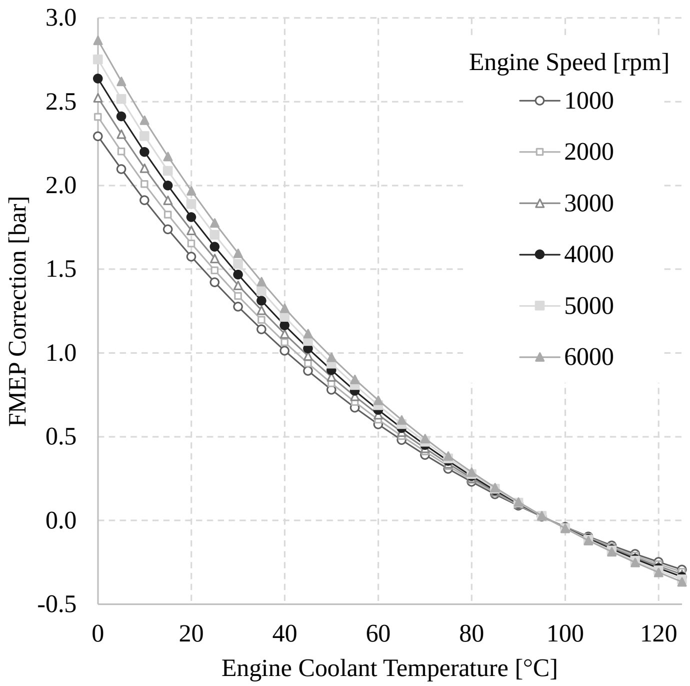


Figure 8: Additive mean effective pressure correction term as a function of internal combustion engine speed and engine coolant temperature

Vehicle Control Structure

The hybrid vehicle controls are structured into the driver model, the supervisory controller and the subordinate component-level controllers for the internal combustion engine, the clutch, the torque converter and the mechanical brakes. The driver model evaluates the power demand, which is required to follow the anticipated maneuver and provides it to the supervisory controller. The supervisory controller is based on the implemented 'ECMS' controller. Therefore it is provided with additional input signals regarding the hybrid vehicle system states. As a result the supervisory controller provides signals regarding the operating mode, the gear number and the power split between the combustion engine, the electric machines and the mechanical brakes.

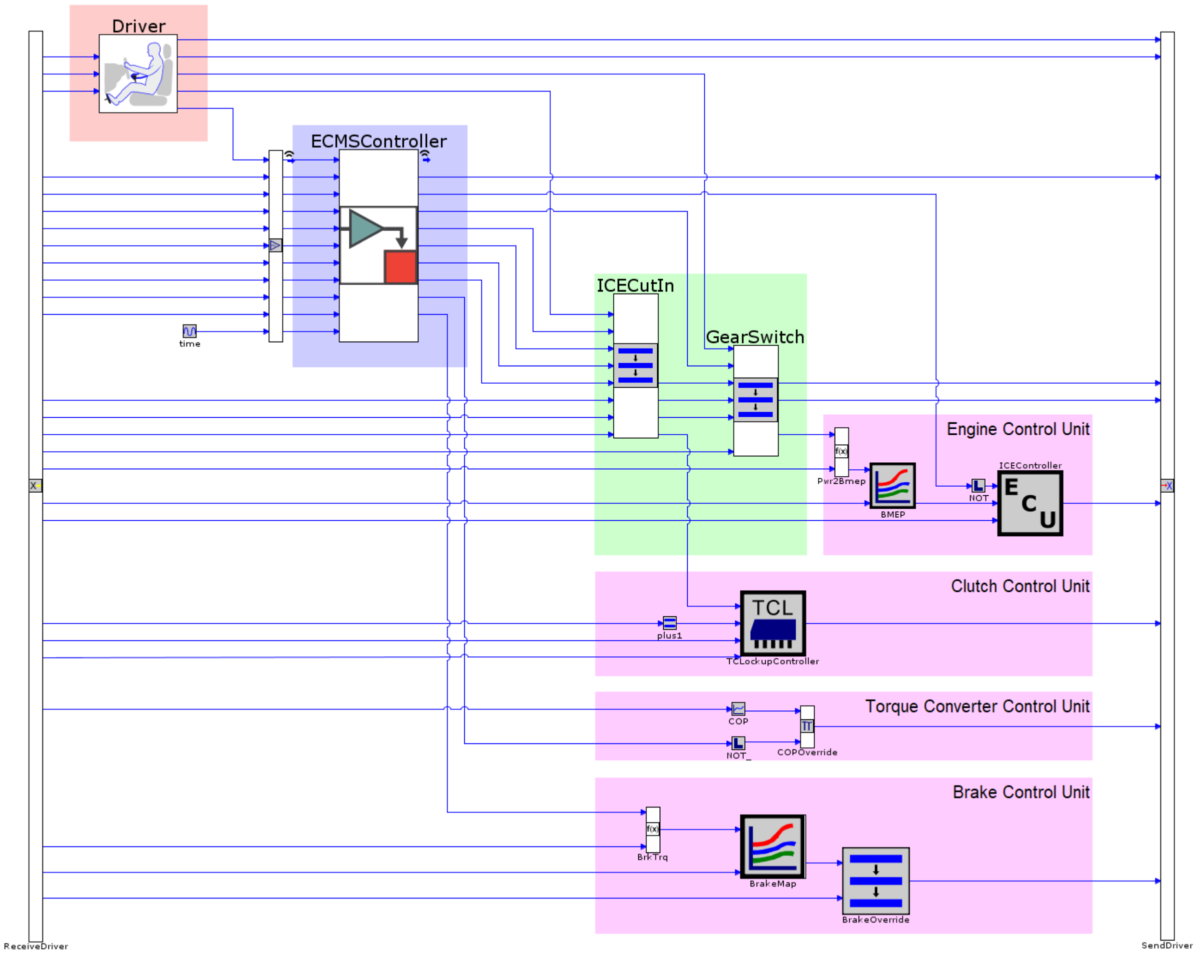


Figure 9: Hybrid vehicle control structure, contains driver model (red), supervisory controller (blue), high-level controls (green) and component-level controls (magenta)

The details regarding the power demand calculation are covered in chapter 2.3.1. The details regarding the developed 'ECMS' controller are covered in chapter 3.2. The following section contains the details regarding the introduced and applied high-level and component-level controls for the internal combustion engine, the clutch, the torque converter and the mechanical brakes.

For the application of the ‘ECMS’ controler the additional high-level controls are required to enable the functionality and refine the sequence of control states regarding the internal combustion engine cut-in during E-drive (‘ICE cut-in’) and the load shift between the internal combustion engine and the rear traction motor during gear switching (‘Load shift’).

The ‘ICE cut-in’ control considers three states ‘E-drive’, ‘ICE cut-in’ and ‘Hybrid drive’. It is provided with input signals regarding the operating mode, the vehicle speed, the slip of the lockup clutch, the component power requests and the driver power demand. It outputs signals regarding the component power requests and the transmission gear switching state. The ‘E-Drive’ state, which is the initial state, forces the transmission gear switching state to be active and passes through the power demand signals to the power actuators. The state switches to ‘ICE cut-in’ based on the operating mode signal provided from the supervisory controller. The ‘ICE cut-in’ state is applied as long as the engine speed is 10 rpm lower then the transmission input speed and the engine speed is greater then idle speed. For this period the component power requests from the supervisory controller are overwritten, such that the starter generator is requested with 10 kW (to speed up the internal combustion engine) and the rear traction motor is requested with the entire driver power demand. Further the transmission gear switching state is forced to be active. The ‘Hybrid drive’ state passes through the power demand signals to the power actuators and the shifting state of the transmission.

The ‘Load shift’ control condiders two states ‘Cruise’ and ‘Gear switch’. It is provided with input signals regarding the transmission gear switching state, the component power requests from the ‘ICE cut-in’ control, the driver power demand and a power request estimate to accelerate the free inertias of the internal combustion engine and the starter generator during the gear switching event, which is provided by the supervisory controller. It outputs the final component power requests. The ‘Cruise’ state, which is the initial state passes through all component power requests. The state changes to ‘Gear switch’ based on the gear switching state signal from the transmission. For this period the component power requests are overwritten, such that the starter generator is requested with zero power, the internal combustion is requested with the power request estimate to accelerate the free inertias and the rear traction motor is requested with the entire driver power demand.

Internal Combustion Engine Controls

The map-based internal combustion engine model is controlled by the predefined model specific controller template ‘ICEController’ from the ‘GT-SUITE’ template library. It is provided with input signals regarding the acceleration pedal request, the ignition state request and the engine speed. Therefore the power request from the supervisory controller is transformed firstly into a brake mean effective pressure request and secondly into an accelerator pedal position request using a reverse lookup of the brake mean effective pressure map.

Clutch Controls

The lockup clutch of the automatic transmission is controlled by the predefined model specific controller template ‘TCLockupControl’ from the ‘GT-SUITE’ template library. It is provided with input signals regarding the lockup state of the clutch, the gear number, the engine speed and the previously modified gear switching state. During the cruising state the position of the lockup clutch actuator is determined from a set of speed threshold values, such that a closed clutch is enforced at engine speeds higher then 1.150 min^{-1}. The built-in default function to keep the clutch unlocked during the first gear is disabled by masking the true gear number for the lockup clutch controller.

Torque Converter Controls

The torque converter hydrodynamic performance is specified by means of a coefficient of performance profile and a torque ratio profile, each as a function of the turbine to impeller speed ratio. The introduced ‘Torque Converter Control’ considers two states ‘E-drive’ and ‘Hybrid drive’. To prevent undesired motoring of the internal combustion engine (power transfer from turbine to impeller) after the state change from ‘E-drive’ to ‘Hybrid drive’ the torque converter contoller overwrites the coefficient of performance to zero during the ‘E-drive’ state.

Mechanical Brake Controls

The mechanical brakes performance is specified by means of a brake torque map as a function of wheel speed and actuator position. It is provided with input signals regarding the brake power request, the wheel speed and the vehicle target speed from the driver. The brake power request is firstly transformed into a brake torque request and secondly into an brake actuator position request using a reverse lookup of the brake torque map. The introduced ‘Brake Control’ considers three states ‘Cruise’, ‘Stop’ and ‘Launch’. The ‘Cruise’ state passes the brake actuator position. The state changes to ‘Stop’ after the wheel speed drops to zero. The ‘Stop’ state overwrites the brake actuator position to 100%, applying full brakes. The state changes to ‘Launch’ based on a non-zero vehicle target speed. The transition state ‘Launch’ overwrites the brake actuator position to 0%, preventing braking for the duration of one second.

3.2. ‘ECMS’ Controller

The following section covers the details about the implemented ‘ECMS’ Contoller. Starting with the basic controller structure and its functions the following chapters are referring to the corresponding functions. Regarding the basic controller functions, the controller design is inspired by the findings from the literature research and the documentation from the backward kinematic solution approach using ‘ECMS’ in ‘GT-SUITE’. The controller consists of individual functions which allow to include variants of features, which are related to the hybrid drivetrain topology, the constraint or penalty on control input and the cost function. The basic ‘MIMO’ functionality is provided from the ‘Simulink’ environment utilizing two options. Firstly by means of a tailored function block called ‘GT-SUITE Model (GT as Lead)’, which allows to set the appropriate number of incoming and outgoing scalar signals from and to the host environment, which is the ‘GT-SUITE’ hybrid vehicle system simulation model. The function block expects an array of incoming and provides an array of outgoing scalar signals. Secondly by means of ‘Tunable Parameters’, which may be modified from the host environment in the initial phase of the controller call, allowing to exchange scalar values, two-column arrays and two-diensional matrices. The signals are provided to a ‘MATLAB Function’ which includes the actual ‘ECMS’ controller functions. The ‘MATLAB Function’ block is capable to refer to ‘Tunable Parameters’, which allows a consistent signal flow between the ‘MATLAB Function’ and the host environment. For the purpose to memorize variable values from the last controller call an non-algebraic loop is applied using a ‘Memory’ block. This approach allows to keep the memorized signals in ‘Simulink’ and to reduce the number of signals being exchanged with the host environment. Figure 10 shows the ‘Simulink’ model with all required blocks.

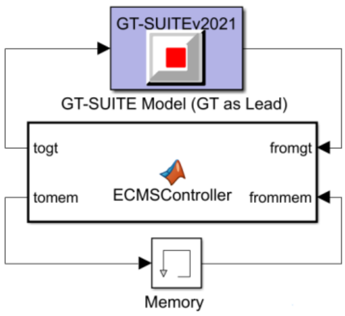


Figure 10: 'ECMS' Controller: basic ‘MIMO’ functionality using the Simulink environment.

3.2.1. Basic Structure of the ‘ECMS’ Controller

The basic structure of the ‘ECMS’ controller is embedded in the MATLAB function block and is defined from a set of functions for the definition of the control input, the combination of control inputs, the constraints on the control inputs, the evaluation of the energy consumption, the penalties on control inputs, the evaluation of the cost function and the selection of optimal scenario. Figure 11 illustrates the basic code structure as a signal flow diagram. Each block represents a function.

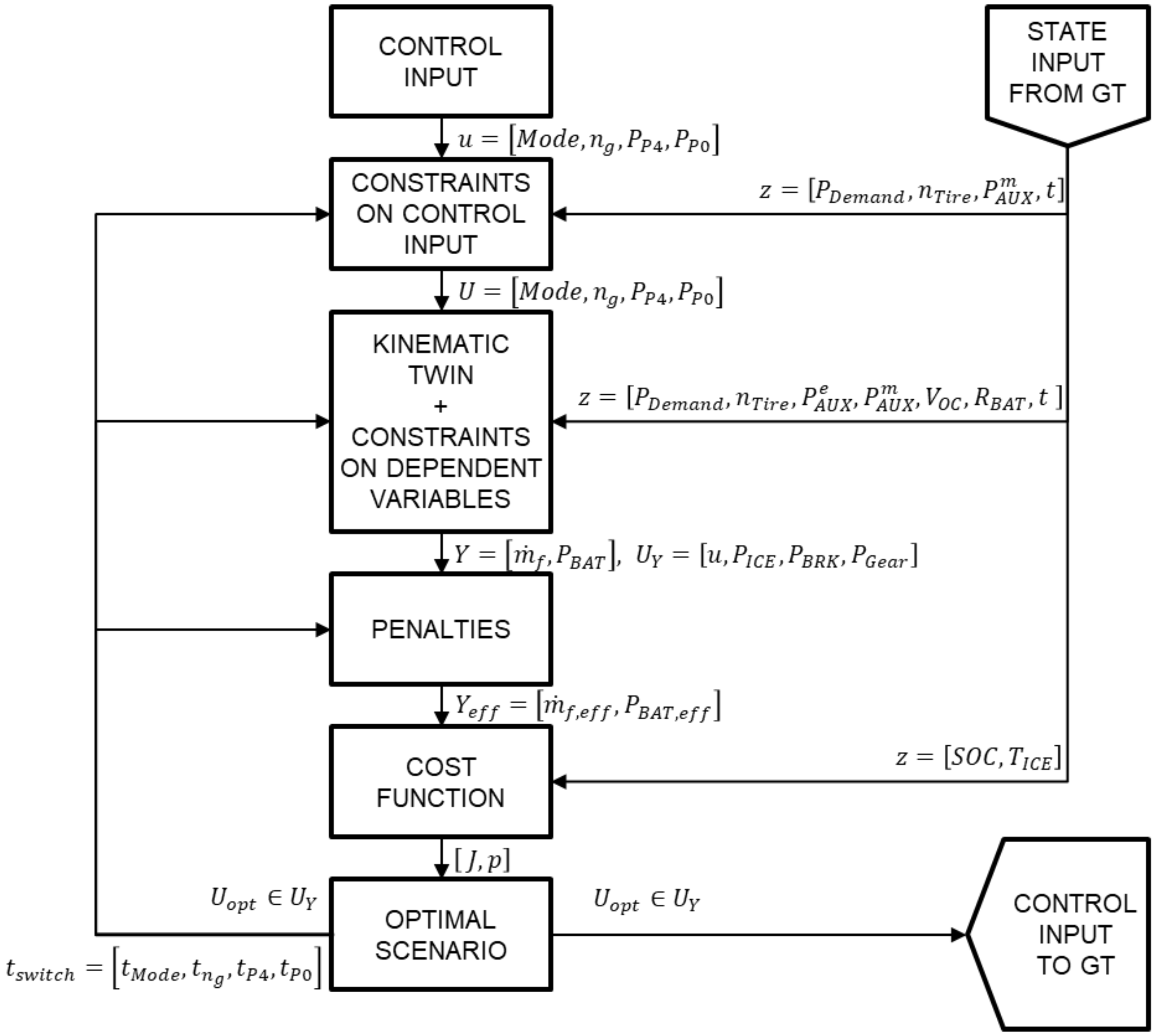


Figure 11: 'ECMS' Controller: basic code structure

3.2.2. Control Input

The control input function includes the declaration of each control input variable, their value range and their discretization. It provides the control input array u to the subsequent functions. For the anticipated P0/P4 hybrid drivetrain topology four control input variables are defined to cover the major operating modes of the hybrid vehicle. Table 7 contains all defined control input variables with their associated value range and discretization.

Table 7: 'ECMS' Controller: Control input variables, their value range and discretization

Control Input Variable	min	max	Δ	Unit	Remark
input1: 'Mode'	0	1	1	N/A	0: 'Hybrid' mode, 1: 'E-drive' mode
input2: 'ng'	1	6	1	N/A	Gear number
input3: 'PP4'	-80000	80000	8000	W	Power request to rear traction motor
Input4: 'PP0'	-15000	15000	1500	W	Power request to Starter-generator

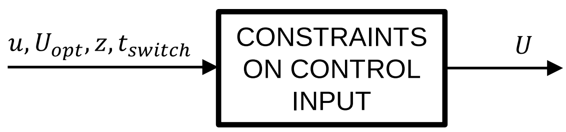
The control input variables are combined to the control array u using a full factorial approach, which results in

$$n_1 \cdot n_2 \cdot \ldots \cdot n_{m-1} \cdot n_m = \prod_{i=1}^{m} n_i \,, \qquad m = 4$$

5.292 combinations for the above given set of control input variables. The equidistant discretization of the control input variables is optional and may be alternatively defined from any value series. The above given discretization of the power request to the electric machines is regarded as a minimum resolution.

3.2.3. Constraints on Control Input

As not all combinations of the control array u are applicable to the hybrid drivetrain the task of conditional constraints to the control input is mandantory and described in the following section. The constraint on control input function expects the control array u, the state array z and the looped back optimal control U_{opt} from the previous controller sequence as input arguments. It provides the admissible control array U to the subsequent controller functions.



Constraints on Control Input based on operating modes

A set of checks is applied to the control input array u based on the expected operating modes of the hybrid vehicle, which are ‘E-Drive’ mode at vehicle stop, the Starter-generator powers the mechanical auxillaries during the ‘E-drive’ mode, internal combustion engine is truned off during ‘E-drive’ mode and no ‘Through the road’ load shifting allowed. These assumptions lead to the following set of checks, which are listed in Table 8.

Table 8: ‘ECMS’ Controller: Conditional constraints on control input array u

Condition (&: ‘and’, \: ‘or’, !: ‘not’, =: ‘equal’)		Purpose
If	Tire speed = 0 & Mode = 0	‘E-drive’ mode at car stop
Then	Exclusion	
If	Mode = 1 & (PP4 != 0 \ PP0 != 0)	‘E-drive’ mode disallows PP0 and PP4 variation
Then	Exclusion	
If	Power demand > 0 & PP4 < 0	Prevent ‘Through-the-road’ load shifting
Then	Exclusion	
If	Power demand < 0 & PP0 > 0	Prevent ‘E-assist’ during deceleration
Then	Exclusion	
If	Power demand < 0 & PP4 > 0	Prevent ‘E-assist’ during deceleration
Then	Exclusion	
If	Mode = 1	‘E-drive’ mode, power to the mech. auxiliaries
Then	PP4 = Power demand PP0 = mechanical auxiliary power demand	

Constraints on Control Input based on Change Rate

An excessively rapid change in control input values may lead to an undesired operation of the hybrid vehicle. Therefore the following change rate constraints on control input are defined, based on the looped back optimal control U_{opt} from the previous controller sequence and an change rate threshold. This approach is applied to allow gear shifting only by one gear number in ‘Hybrid’ mode. In addition to that the gear change is prevented during ‘E-drive’ mode and unrestricted when switching from ‘E-drive’ to ‘Hybrid’ mode. These assumptions lead to the following set of checks, which are listed in Table 9.

Table 9: ‘ECMS’ Controller: Change Rate constraints on control input array u

Condition (&: ‘and’, \: ‘or’, !: ‘not’, =: ‘equal’)		Purpose
If	mode = 1 & ng > ng_{opt}	Prevent gear upshift in ‘E-drive’ mode
Then	Exclusion	
If	mode = 1 & ng < ng_{opt}	Prevent gear downshift in ‘E-drive’ mode
Then	Exclusion	

If	mode = mode$_{opt}$ & ng > ng$_{opt}$ + 1	Limit gear upshift in 'E-drive' mode
Then	Exclusion	
If	mode = mode$_{opt}$ & ng < ng$_{opt}$ - 1	Limit gear downshift in 'E-drive' mode
Then	Exclusion	

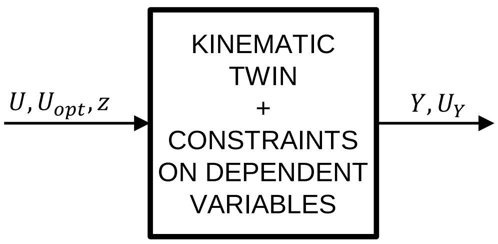
Constraints on Control Input based on switching frequency

In addition to a change rate, an excessively frequent change in control input values may lead to an undesired operation of the hybrid vehicle as well. Therefore the following change rate constraints on control input are defined, based on the looped back time stamp at which the last change to the according optimal control variable was applied. This approach is applied to allow gear shifting only after a time threshold of one second and to switch from 'E-drive' to 'Hybrid' after two seconds and from 'Hybrid' to 'E-drive' after five seconds. The other control input variables regarding the power request to the traction motor and starter generator are left unconstrained to ensure a good power distribution dynamic.

The exclusion of control input combinations has a significent effect on the size of the admissible control input array U. The size dynamically varies from one (during vehicle stop) to mutiple admissible combinations.

3.2.4. Kinematic Hybrid Drivetrain Function

The kinematic hybrid drivetrain function has the task of evaluating the relevant performance variables of the hybrid drivetrain Y resulting from the application of the admissible control input array U at the current system state z. Therefore the kinematic relations and the conversion efficiency chains of the hybrid drivetrain are defined. In general this approach has the advantage to define the relations independent from the dynamic hybrid drivetrain model, such that it can include a simplified version of a physics-based subsystem model (e.g. internal combustion engine, electric machine or battery), by means of a phenomenological set of equations. In particular for the prototyping of the 'ECMS' controller this approach is a necessity, because the kinematic mechanical solver can not be combined with the dynamic simulation approach in GT-SUITE, yet.



Further a sequence of conditional constraints on dependent variables is defined in the kinematic hybrid drivetrain function, ensuring that each relevant component operates within its expected range. The final admissible control input array U_Y represents the compliant subset of U. The following notations use superscripts which indicate whether the variable is expected to change based on the applied control input combination (→ k), to represent the variable value from the last controller sequence (→ opt) or to represent a system state (→ GT)

Angular Speed Relations

First the speeds of the rear traction motor, the internal combustion engine and the starter-generator is evaluated. The overall transmission ratio array i_{TM}, the constant gear ratio of the rear axle i_{P4} and the constant gear ratio of the starter-generator i_{P0} are provided as tunable parameters from the hybrid vehicle system model.

$$i_{TM}^{k} = Lookup\left(i_{TM}, n_g^k\right)$$

$$n_{ICE}^{k} = \begin{cases} mode = 0 & \rightarrow \quad i_{TM}^{k} \cdot n_{tire}^{GT} \\ mode = 1 & \rightarrow \quad 0 \end{cases}$$

$$n_{P0}^{k} = \begin{cases} mode = 0 & \rightarrow \quad i_{P0} \cdot n_{ICE}^{k} \\ mode = 1 & \rightarrow \quad 2500 \end{cases}$$

$$n_{P4} = i_{P4} \cdot n_{tire}^{GT}$$

The first conditional constraint on the resulting internal combustion engine speed is applied based on the provided tunable parameters n_{IDLE} and $n_{ICE,MAX}$.

$$n_{ICE}^{k} < n_{IDLE} \;\&\; n_{ICE}^{k} > n_{ICE,MAX}$$

All non compliant control input variable combinations excluded from further processing.

Gear changes affect the acceleration of the internal combustion engine and starter-generator inertias. The required power P_{gear} is evaluated from the change of the kinetic energy and the gear switching duration t_{dur}

$$P_{gear} = \begin{cases} mode = 0 & \rightarrow \quad \dfrac{J_{ICE} + J_{TM,in} + J_{P0} \cdot i_{P0}^2}{2 \cdot t_{dur}} \cdot {n_{tire}^{GT}}^2 \cdot \left({i_{TM}^{k}}^2 - {i_{TM}^{opt}}^2\right) \\ mode = 1 & \rightarrow \quad \dfrac{J_{TM,in}}{2 \cdot t_{dur}} \cdot {n_{tire}^{GT}}^2 \cdot \left({i_{TM}^{k}}^2 - {i_{TM}^{opt}}^2\right) \end{cases}$$

Electric Machines

For the evaluation of the electric machine performance the maximum battery power is evaluated first hand, based on the current states of open circuit voltage and the internal resistance of the battery pack

$$P_{BAT,MAX} = \frac{{V_{OC}^{GT}}^2}{4 \cdot R_0^{GT}}$$

It is set as a constraint on the sum of the requested electric machine powers, such that the rear traction motor is prioritized over the starter-generator.

The brake power constraint arrays $P_{P4,MIN}(n_{P4})$, $P_{P4,MAX}(n_{P4})$, $P_{P0,MIN}(n_{P0})$ and $P_{P0,MAX}(n_{P0})$ and the electro-mechanical conversion efficiency maps $\eta_{P4}(n_{P4}, T_{P4})$ and $\eta_{P0}(n_{P0}, T_{P0})$ of the electric machines are provided as tunable parameters from the hybrid vehicle system model.

$$P_{P4,MIN} = Lookup(P_{P4,MIN}(n_{P4}), n_{p4})$$

$$P_{P4,MAX} = Lookup(P_{P4,MAX}(n_{P4}), n_{p4})$$

$$P_{P0,MIN}^{k} = Lookup(P_{P0,MIN}(n_{P0}), n_{p0}^{k})$$

$$P_{P0,MAX}^{k} = Lookup(P_{P0,MAX}(n_{P0}), n_{p0}^{k})$$

The next conditional constraints on the requested electric machine power are applied

$$P_{P4}^{k} < P_{P4,MAX} \;\&\; P_{P4}^{k} > P_{P4,MIN}$$

$$P_{P0}^{k} < P_{P0,MAX}^{k} \;\&\; P_{P0}^{k} > P_{P0,MIN}^{k}$$

$$P_{P4}^{k} < \eta_{P4@BAT,\,MAX}^{k} \cdot P_{BAT,MAX}$$

$$P_{P0}^{k} > \eta_{P0@BAT,\,MAX} \cdot \left(P_{BAT,MAX} - P_{P4,DC}^{k}\right)$$

with

$$\eta_{P4,BAT,\,MAX}^{k} = Lookup\left(\eta_{P4}(n_{P4}, T_{P4}), \max(n_{P4}, 1), T_{P4}^{k}\right)$$

$$\eta_{P0@BAT,\,MAX}^{k} = Lookup\left(\eta_{P0}(n_{P0}, T_{P0}), n_{P0}^{k}, T_{P0}^{k}\right)$$

and

$$T_{P4}^{k} = \frac{\min\left(P_{P4}^{k}, P_{BAT,MAX}\right)}{\max(\omega_{P4}, 1)}$$

$$T_{P0}^{k} = \frac{\min\left(P_{P0}^{k}, P_{BAT,MAX} - P_{P4,DC}^{k}\right)}{\omega_{P0}^{k}}$$

and all non compliant control input variable combinations excluded from further processing.

The electro-mechanical conversion efficiency lookup is defined as follows,

$$\eta_{P4}^{k} = Lookup\left(\eta_{P4}(n_{P4}, T_{P4}), \max(n_{P4}, 1), T_{P4}^{k}\right)$$

$$\eta_{P0}^{k} = Lookup\left(\eta_{P0}(n_{P0}, T_{P0}), n_{P0}^{k}, T_{P0}^{k}\right)$$

with

$$T_{P4}^{k} = \begin{cases} mode = 0 & \rightarrow & \dfrac{P_{P4}^{k}}{\max(\omega_{P4}, 1)} \\ mode = 1 & \rightarrow & \dfrac{\left(P_{P4} + P_{gear}\right)}{\max(\omega_{P4}, 1)} \end{cases}$$

$$T_{P0}^{k} = \frac{P_{P0}^{k}}{\omega_{P0}^{k}}$$

which finally allows to evaluate the DC power demand based on

$$P_{P4,DC}^{k} = \eta^{k\,-sign\left(1, P_{P4}^{k}\right)}_{\;P4} \cdot P_{P4}^{k}$$

$$P_{P0,DC}^{k} = \eta^{k\,-sign\left(1, P_{P0}^{k}\right)}_{\;P0} \cdot P_{P0}^{k}$$

Internal Combustion Engine

In ‘Hybrid’ mode the residual positive power demand, which results from the net sum of the driver power demand and the power requests combinations to the electric machines, is applied to the internal combustion engine. The power demand to the internal combustion engine is constraint by the operating range of its brake mean effective pressure map $bmep(n_{ICE}, app)$ which is provided as a tunable parameter from the hybrid vehicle system model.

$$P_{ICE,DEM}^{k} = \eta_{TM}^{-sign\left(1,P_{Demand}^{GT}\right)} \cdot \left(P_{Demand}^{GT} - \eta^{k}{}_{P4,m}^{sign\left(1,P_{P4}^{k}\right)} \cdot P_{P4}^{k}\right)$$

$$-\eta^{k}{}_{P0,m}^{sign\left(1,P_{P0}^{k}\right)} \cdot P_{P0}^{k} + P_{AUX,m}^{GT} + P_{gear}^{k}$$

The mechanical efficiencies of the drivetrain η_{TM}, the rear traction motor $\eta_{P4,m}$ and the starter-generator $\eta_{P0,m}$ are provided as constant tunable parameters from the hybrid vehicle system model.

The next conditional constraint on the requested internal combustion engine power is applied

$$P_{ICE,DEM}^{k} > P_{ICE,MAX}^{k}$$

and all non compliant control input variable combinations excluded from further processing.

The fossil fuel consumption is evaluated from the sequential lookup of the brake mean effective pressure map and the fuel consumption map $fc(n_{ICE}, APP)$, which is provided as a tunable parameter from the hybrid vehicle system model. This two step approach is required as 'Simulink Coder' does not allow to interpolate on a non-rectangular or staggered map data, which does not allow to provide the fuel consumption map as a function of brake mean effective pressure.

$$app^{k} = Lookup\left(bmep(n_{ICE}, APP), n_{ICE}^{k}, bmep^{k}\right)$$

$$m_{fuel}^{k} = Lookup\left(fc(n_{ICE}, APP), n_{ICE}^{k}, app^{k}\right)$$

Mechanical Brakes

The residual negative power demand, which results in 'Hybrid' mode from the net sum of the driver power demand and the power requests combinations to the electric machines and in 'E-drive' mode from the net sum of the driver power demand and the power constraint of the rear traction motor, is applied to the mechanical brakes.

Battery

The battery terminal power demand is evaluated by summing up the DC power demands from the electric machines and the electric auxiliaries

$$P_{terminal}^{k} = P_{P4,DC}^{k} + P_{P0,DC}^{k} + P_{AUX,e}^{GT}$$

which allows to eveluate the battery current I_{bat}^{k} to

$$I_{bat}^{k} = \begin{cases} P_{terminal}^{k} > 0 \quad \rightarrow \quad \dfrac{V_{OC,dis}^{GT} - \sqrt{{V_{OC,dis}^{GT}}^{2} - 4 \cdot R_{bat,dis}^{GT} \cdot P_{terminal}^{k}}}{2 \cdot R_{bat,dis}^{GT}} \\ P_{terminal}^{k} < 0 \quad \rightarrow \quad \dfrac{V_{OC,chg}^{GT} - \sqrt{{V_{OC,chg}^{GT}}^{2} - 4 \cdot R_{bat,chg}^{GT} \cdot P_{terminal}^{k}}}{2 \cdot R_{bat,chg}^{GT}} \end{cases}$$

and the internal battery efficiency η_{bat}^{k} to

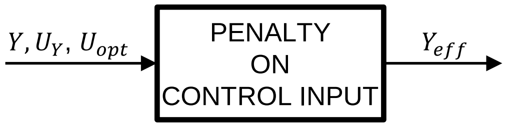
$$\eta_{bat}^{k} = \begin{cases} P_{terminal}^{k} > 0 \quad \rightarrow \quad 1 - \dfrac{R_{bat,dis}^{GT} \cdot I_{bat}^{k}}{V_{OC,dis}^{GT}} \\ P_{terminal}^{k} < 0 \quad \rightarrow \quad 1 + \dfrac{R_{bat,chg}^{GT} \cdot {I_{bat}^{k}}^{2}}{P_{terminal}^{k}} \end{cases}$$

and finally the internal battery power P_{bat}^{k} to

$$P_{bat}^{k} = \begin{cases} P_{terminal}^{k} > 0 \quad \rightarrow \quad P_{terminal}^{k} \cdot \dfrac{1}{\eta_{bat}^{k}} \\ P_{terminal}^{k} < 0 \quad \rightarrow \quad P_{terminal}^{k} \cdot \eta_{bat}^{k} \end{cases}$$

3.2.5. Penalty on Control Input

The penalty on control input is originally a measure to account for the additional energy consumption which occurs due to control input change by means of a penalization of the fossil fuel or the battery energy consumption and by means of an increment or a rate. Furthermore, it can be utilized to tune the evaluation of the optimal control strategy by imposing penalty on specific control input change.



In the context of gear number selection the penalization of gear upshifts is an effective measure to prevent upshifting during the deceleration phases of the vehicle, which may be unexpected from a driver comfort perspective or undesired from the vehicle dynamics perspective. Therefore, a fuel rate penalty is specified to penalize upshifts with a constant fuel rate of 0.1 g/s.

3.2.6. Cost Function

The cost function is defined according to equation (9), by invoking the penalized fuel consumption $m_{fuel,eff}$, the battery power consumption.

$$m_{eqv}^{k} = m_{fuel,eff}^{k} + \frac{s}{Q_{lhv}} \cdot P_{bat}^{k} \cdot p(SOC_{bat}^{GT}) \tag{15}$$

The penalty factor is an effective measure to tune the evaluation of the cost function for the derivation of a charge sustaining optimal control strategy. The penalty factor equation found from literature (10) has the characteristics to force a symmetrical operating range of the battery state of charge, though it creates the contrary impression, by means of the two constraints soc_{min} and soc_{max}. This characteristic gets notably evident for $soc_{target} \neq (soc_{max} + soc_{min})/2$.

$$p\left(SOC^{GT}\right) = 1 - \left(\frac{SOC^{GT} - SOC_{target}}{(SOC_{max} - SOC_{min})/2}\right)^{a} \tag{16}$$

Based on this finding the following penalty factor terms are proposed and discussed, which are namely the ‘Relative Battery SOC Constraint’ penalty factor and the ‘Absolute Battery SOC Constraints’ penalty factor.

‘Relative Battery SOC Constraint’ Penalty Factor

The penalty factor term (10) or (16) can be simplified to the following expression without changing the characteristic of the penalty factor term as a function of the current battery state of charge deviation. Furthermore, it allows to reduce the number of setup coefficients from four to three and an unambiguous interpretation.

$$p\left(SOC^{GT}\right) = 1 - \left(\frac{SOC^{GT} - SOC_{target}}{\Delta SOC}\right)^{a} \tag{17}$$

This proposed modification to the penalty factor term allows to define a symmetrical definition of the target and constraints values with $SOC_{target} = (SOC_{max} + SOC_{min})/2$, which is shown in Figure 12 with an exemplary set of coefficients.

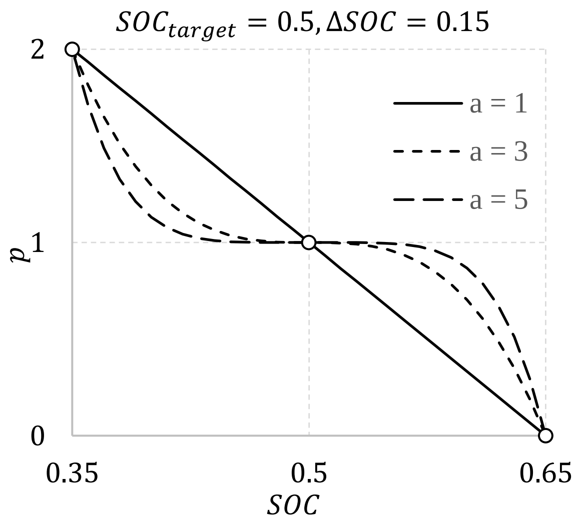


Figure 12: 'ECMS' Controller: 'Relative Battery SOC constraints' penalty factor, with an exemplary setup coefficients: SOC_{target} = 0.5, ΔSOC = 0.15 and variation of penalty term exponent a

‘Absolute Battery SOC Constraints’ Penalty Factor

The penalty factor term (10) or (16) can be extended to the following expression, changing the characteristic of the penalty factor term as a function of the current battery state of charge deviation. It requires the definition of the battery state of charge target and the upper and lower constraints as absolute values and distinguishes between two operating ranges, according to whether the current battery state of charge SOC^{GT} is above or below the target value SOC_{target}.

$$p = 1 - \left(\frac{max\left(SOC^{GT} - SOC_{target}, 0\right)}{SOC_{max} - SOC_{target}} + \frac{min\left(SOC^{GT} - SOC_{target}, 0\right)}{SOC_{target} - SOC_{min}} \right)^{\alpha} \tag{18}$$

This proposed modification to the penalty factor term allows to define an asymmetrical definition of the target and constraints values with $SOC_{target} \neq (SOC_{max} + SOC_{min})/2$, which is shown in Figure 13 with an exemplary set of coefficients.

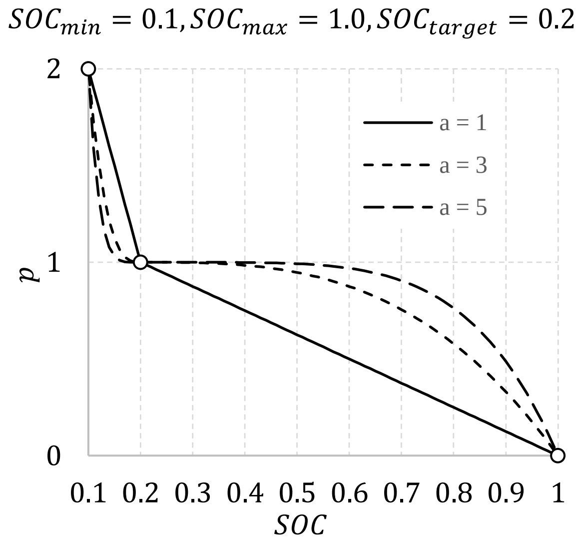


Figure 13: 'ECMS' Controller: 'Absolute constraints' penalty factor, with an exemplary asymmetric setup coefficients: $SOC_{min} = 0.1$, $SOC_{max} = 1.0$, $SOC_{target} = 0.2$ and variation of penalty term exponent a

‘Engine Temperature’ Cost Function and ‘Absolute Engine Temperature Constraint’ Penalty Factor

For the purpose to enhance the warm up of the internal combustion engine during cold start, by means of a favorization of the ‘Hybrid’ mode, an additional multiplicative penalty term to the cost function is proposed. It is inspired by the multiplicative penalty factor term (18) and is defined with the target to lower the equivalent cost for fossil fuel consumption during low engine temperature.

$$m_{eqv}^{k} = m_{fuel,eff}^{k} \cdot p(T_{ICE}) + \frac{s}{Q_{lhv}} \cdot P_{bat}^{k} \cdot p\left(SOC^{GT}\right) \tag{19}$$

$$p(T_{ICE}) = 1 - \left(\frac{max\left(T_{ICE} - T_{ICE,target}, 0\right)}{T_{ICE,target} - T_{ICE,max}} + \frac{min\left(T_{ICE} - T_{ICE,target}, 0\right)}{T_{ICE,min} - T_{ICE,target}}\right)^{a} \tag{20}$$

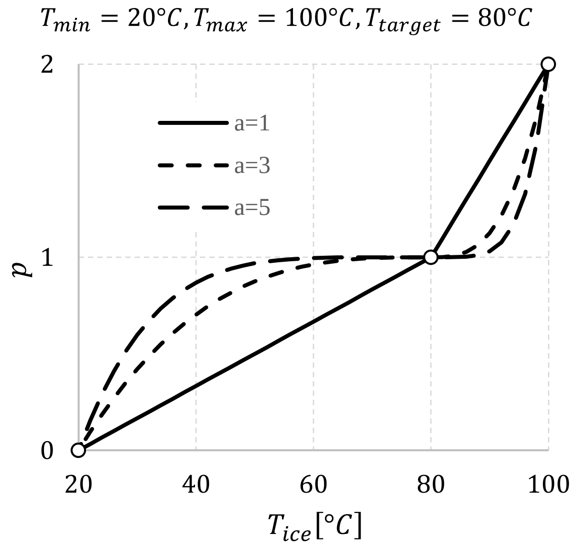
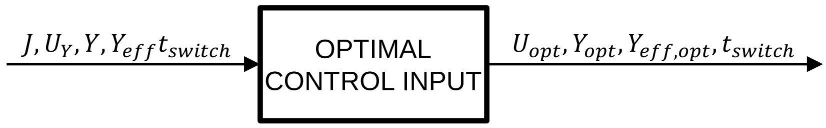


Figure 14: 'ECMS' Controller: 'Absolute Engine Temperature Constraint' penalty factor as a function of engine coolant temperature, with an exemplary asymmetric setup coefficients: T_{min} = 20°C, T_{max} = 100°C, T_{target} = 80°C and variation of penalty term exponent a

3.2.7. Selection of the Optimal Control Input

The selection of the optimal control input is based on the according cost function value. In the case that multiple control input combinations result in the same minimum cost function value the first control input combination is selected.



For the case that the optimal control input changes compared to the previous controller sequence a new time stamp is assigned to the according variable, such that it can be considered in the switching constraints on control input during the upcoming controller sequence.

3.2.8. Calibration of Equivalence Ratio

For the purpose to derive a local optimal and charge sustaining control strategy ($SOC_{init} = SOC_{final} = SOC_{target}$) for the given hybrid vehicle setup and the given maneuver, the equivalence ratio is calibrated by means of the integrated design optimizer in GT-SUITE and based on the 'discrete-grid' search algorithm. Therefore the equivalence ratio is repeatadly modified with constant values and the vehicle maneuver is reevaluated until the final battery state of charge is within the defined tolerance of 0.1%.

Based on a constant equivalence ratio it is expected that the charge sustainance calibration procedure has to be reconducted as soon as the setup of the hybrid vehicle or the maneuver is modified.

3.2.9. Verification based on an Isolated 'ECMS' Controller Setup

During the development of the 'ECMS' controller an isolated setup is preferred. Dependent on the degree of maturity of the controller and the task various setups are used. The conceptual phase is conducted in the 'MATLAB' environment, which allows to simultaneously develop and inspect the controller operation. Each function is passed to the 'MATLAB Coder' to verify the compliance to the conventions and limitations which apply for code generation. The connection of the controller to the host environment 'GT-SUITE' is verified based on the succesful compilation by the 'Simulink Coder' and the succesful call to the embedded controller from the host environment.

The controller operation is finally verified based on the call from the host environment and the stimulation with the according input signals. These input signals are derived from the evaluation of the kinematic 'ECMS' using the backward kinematic solution approach (chapter 3.1.1), which are shown in chapter 4.1 and discussed in chapter 5.1. The input signals consist of the time series for the effective overall power demand (14), the tire speed and constant values for the auxiliary power demands and the component temperature. The battery state of charge and the according circuit parameters are evaluated individually based on the controller decisions and the resulting battery current or battery power and looped back as state signals to the 'ECMS' controller.

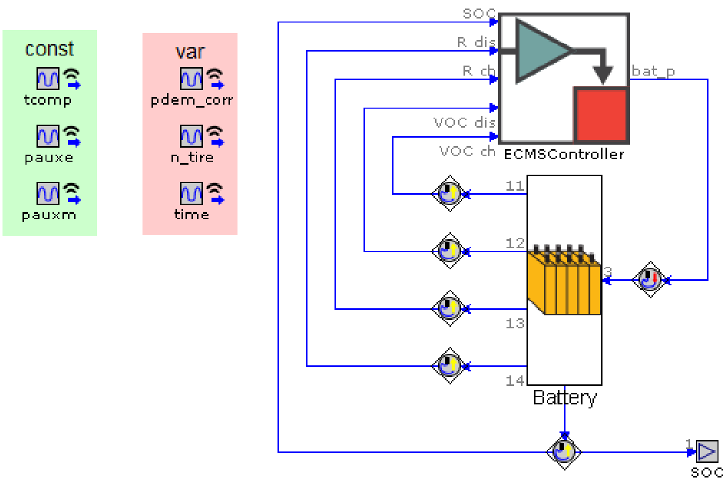


Figure 15: 'ECMS' controller verification using an isolated setup in 'GT-SUITE'

4. Results

The following chapter covers the results which are derived from the developed ‘ECMS’ controller and the applied procedures during this master thesis. The chapter is structured into two subchapters, which cover the verification of the isolated ‘ECMS’ controller operation based on the comparison to the backward kinematic solution approach (chapter 4.1) and the simulation results of the embedded ‘ECMS’ controller in the hybrid vehicle system model based on the alternative cost function formulations (chapter 4.2).

4.1. Verification of the isolated ECMS Controller

The verification includes the comparison of the resulting time series of the optimal control variables and the major result variables including the internal combustion engine power, the fossil fuel consumption, the internal battery power, the penalty factor and the cost function. The verification is shown for the NEDC and the WLTC (class 3) drive cycles.

Regarding the comparability of results, two potential sources of error are identified. The first is related to the introduced two step interpolation approach for the evaluation of fossil fuel consumption in the ‘ECMS’ controller (see also chapter 3.2.4, section ‘Internal Combustion Engine’).

Figure 16 shows the fossil fuel consumption rates evaluated from the backward kinematic solution approach in GT-SUITE and from the re-evaluation using the introduced two-step interpolation approach in ‘MATLAB’. For the WLTC (Class 3) drive cycle the deviation in fuel consumption is -0.02 … +0.07 g/s or -0.7 and +19.5% depending on the operating point. For fossil fuel consumption rates > 1.5g/s the deviation reduces to ±0.02 g/s or ±1%.

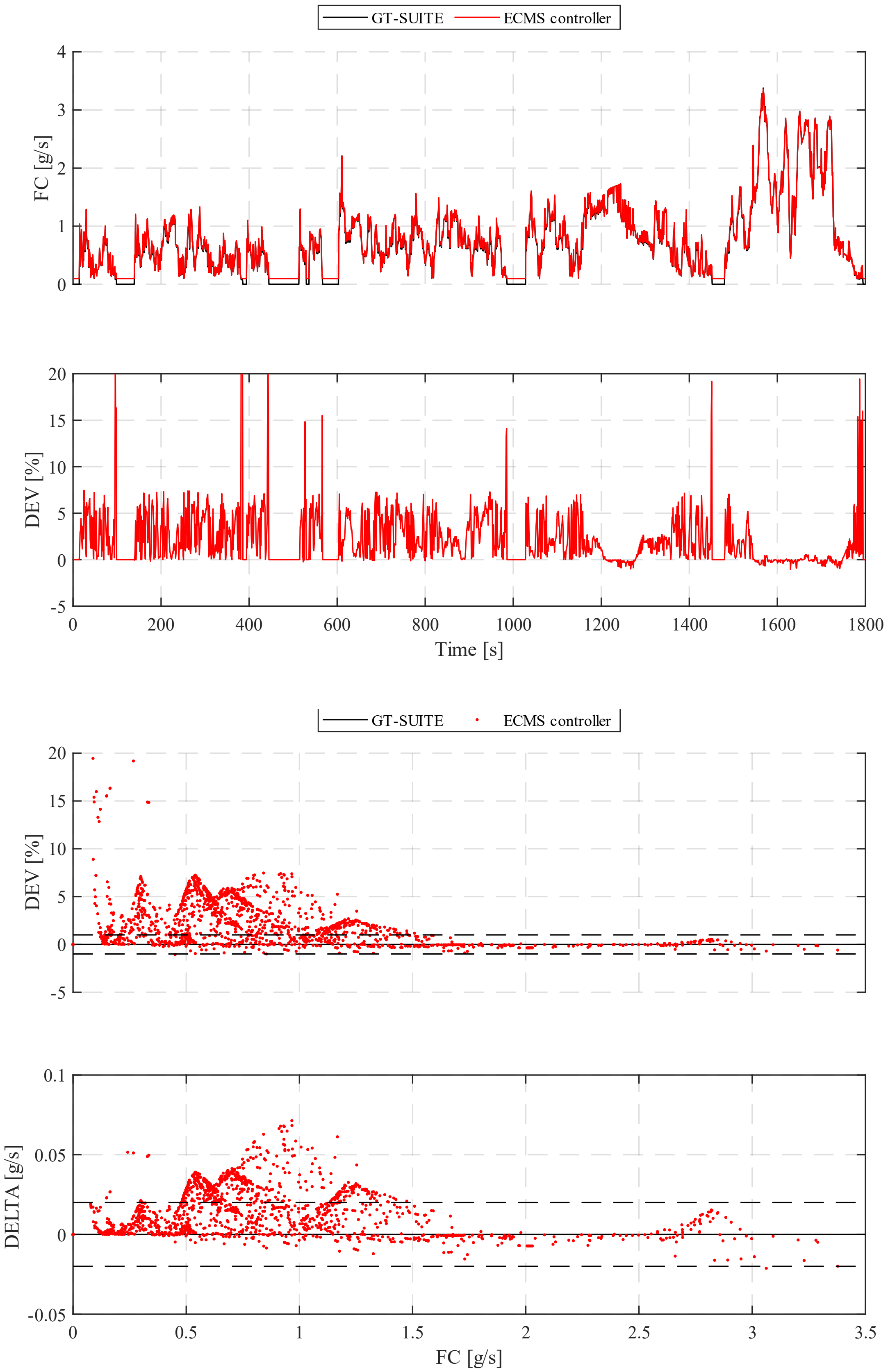
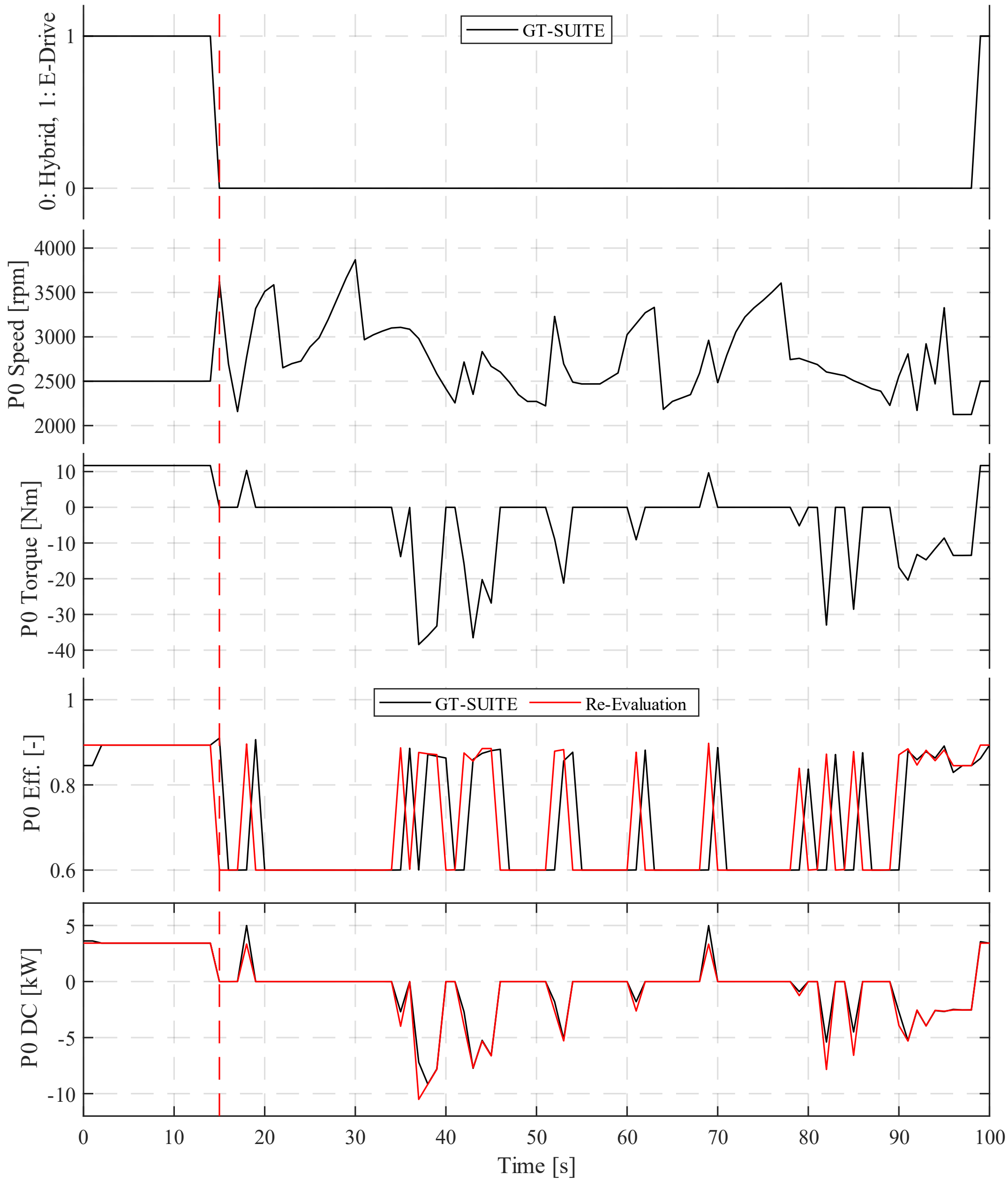


Figure 16: 'ECMS' controller: Fuel consumption deviation resulting from two-step interpolation approach, WLTC (Class 3) drive cycle

The second potential source of error is related to a convention in the backward kinematic solution approach during the evaluation of all admissible control input combinations in ‘GT-SUITE’, regarding the evaluation of the electro-mechanical conversion efficiency inside the map-based electric machine template ‘MotorGeneratorMap’. When in ‘Hybrid’ mode, the electro-mechanical conversion efficiency is not evaluated for each control input combination individually, but it is set constant and based on the last evaluated control input combination from the previous time step. This convention has the consequence, that the DC power request from the electric machines to the battery is distorted, which leads to a deviation in the penalty factor (Figure 18 and Figure 19) and cost function evaluation, which finally contributes to the selection of the optimal control input combination. In contrast to this the ‘ECMS’ controller evaluates the electro-mechanical conversion efficiency for each control input combination individually.

Figure 17 shows the electro-mechanical conversion efficiency of the electric machines evaluated from the backward kinematic solution approach in GT-SUITE and from the subsequent re-evaluation using the bi-linear interpolation approach based on the template ‘Lookup2D’ in ‘GT-SUITE’. For the WLTC (Class 3) drive cycle the deviation of the electro-mechanical conversion efficiency is observed in each ‘Hybrid’ mode period (e.g. $15\ s \leq t \leq 99\ s$) but not in ‘E-Drive’ mode (e.g. $12\ s \leq t \leq 14\ s$). The deviation depends on the last control input combination from the previous time step and the actual control input combination of the current time step.



GT-SUITE
0: Hybrid, 1: E-Drive
1
0
P0 Speed [rpm]
4000
3500
3000
2500
2000
P0 Torque [Nm]
10
0
-10
-20
-30
-40
GT-SUITE
Re-Evaluation
P0 Eff. [-]
1
0.8
0.6
P0 DC [kW]
5
0
-5
-10
0
10
20
30
40
50
60
70
80
90
100
Time [s]

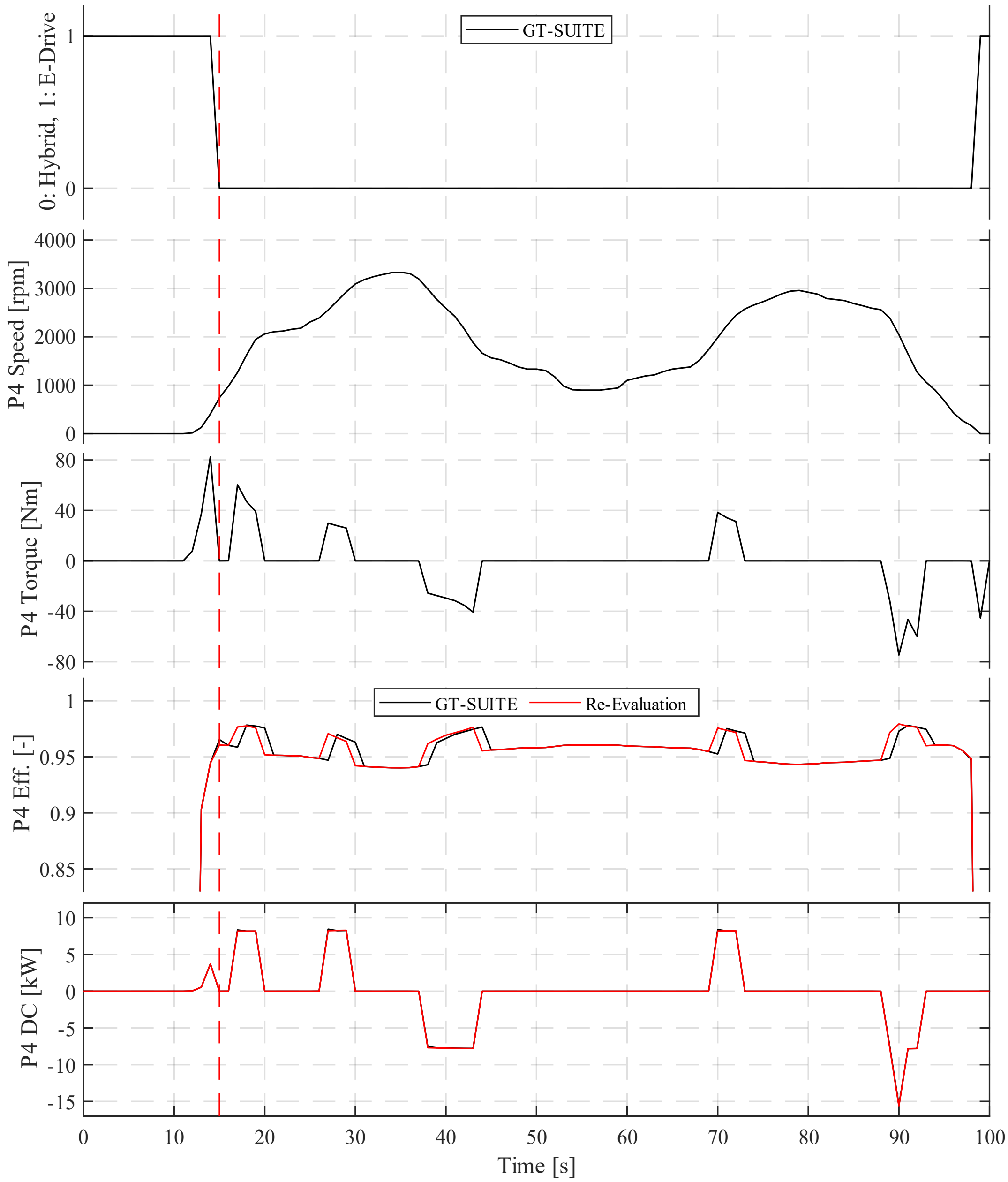


Figure 17: 'ECMS' controller: Electro-mechanical conversion efficiency deviation resulting from differing evaluation convnetions in ‘GT-SUITE’ and the ‘ECMS’ controller

NEDC

The NEDC drive cycle offers a sequence of constant acceleration and constant speed periods, which is of use especially during the initial development phase of the 'ECMS' controller. Figure 18 shows the time series of the control input and the main result variables.

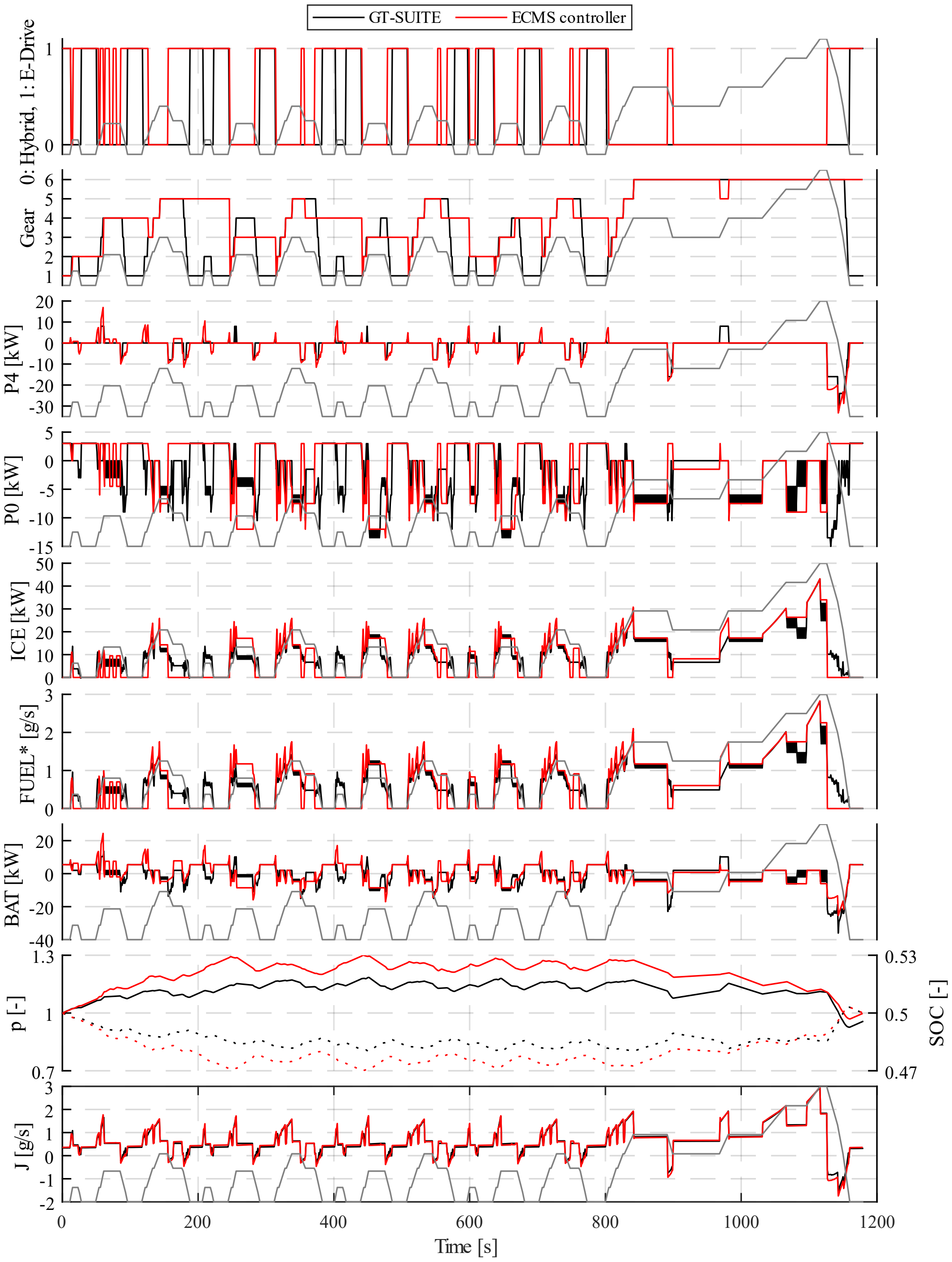


Figure 18: Verification of isolated 'ECMS' controller, by means of a stimulation with backward kinematic solution results (power demand, battery state of charge) based on NEDC drive cycle.

WLTC

The WLTC (Class 3) drive cycle, being a comparatively more dynamic maneuver, is of use during all develoment phases of the 'ECMS' controller. Figure 19 shows the time series of the control input and the main result variables.

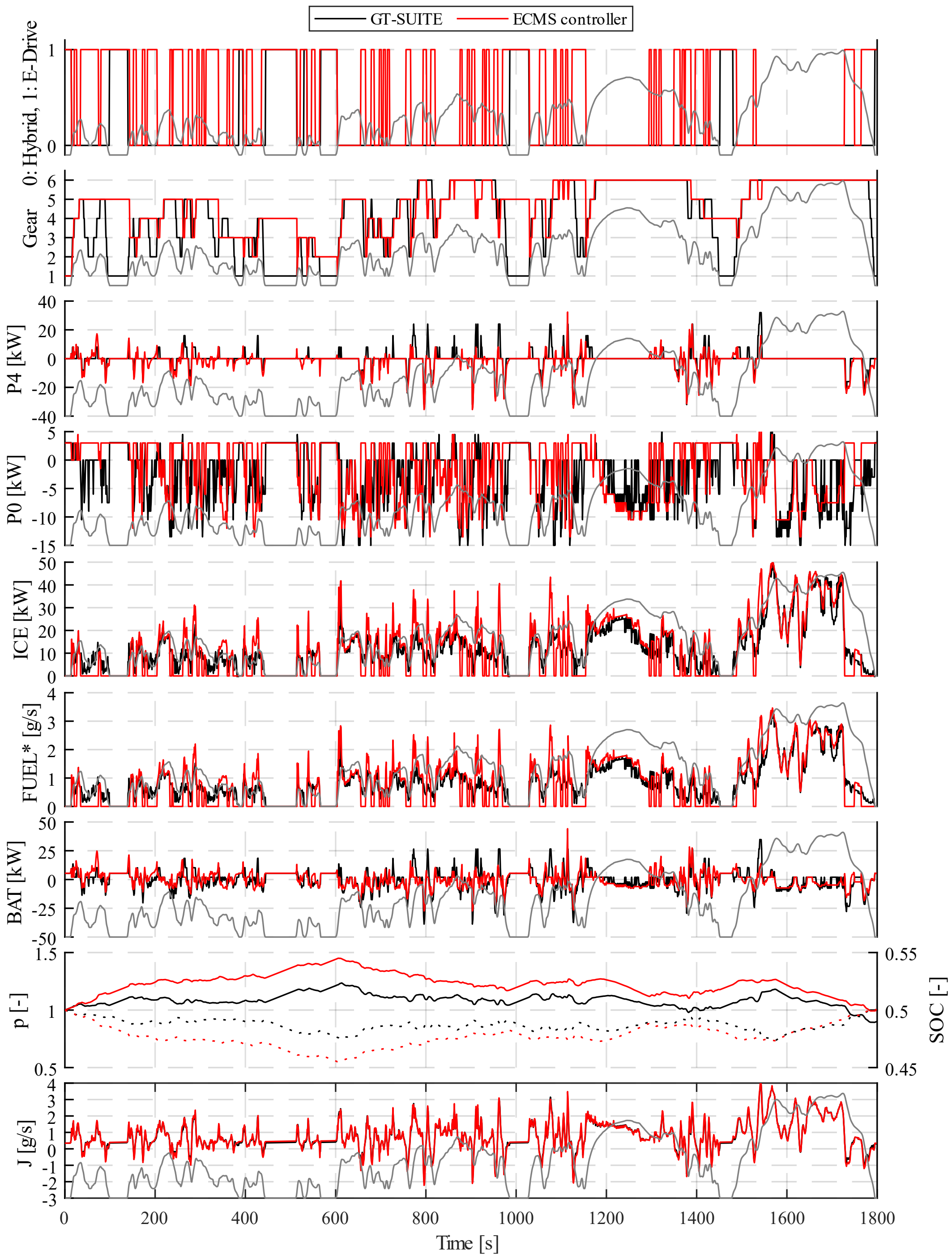


Figure 19:Verification of isolated 'ECMS' controller, by means of a stimulation with backward kinematic solution results (power demand, battery state of charge) based on WLTC (class 3) drive cycle.

4.2. Dynamic ECMS Controller

In the following the results of the embedded 'ECMS' controller are shown, which are based on the dynamic operation within the control structure of the hybrid vehicle system model in 'GT-SUITE'. Three different cost functions are opposed for the WLTC (Class 3) drive cycle, which refer to the variations of the multiplicative penalty factor terms (chapter 3.2.6).

4.2.1. 'Relative Battery SOC Constraint' Penalty Factor

The 'Relative Battery SOC Constraint' Penalty Factor (17) is evaluated using the attribute values listed in Table 10. The relative battery state of charge constraint ΔSOC is set high enough to prevent an undershoot of the lower constraint SOC_{min} and to keep the penalty factor positive. The equivalence ratio s is calibrated in order to provide a charge sustaining control policy.

Table 10: Coefficients for 'ECMS' controller with 'Relative Battery SOC Constraint' Penalty Factor

Coefficient	Condition
ΔSOC	0.1
SOC_{target}	0.5
Equivalence ratio s	2.7
Penalty function exponent a	1
Fossil fuel lower heating value Q_{lhv}	43.95 MJ/kg

Figure 20 shows the time series of the control input and the main result variables.

The fossil fuel consumption is evaluated to 6.41 l/100km with a fuel-equivalent CO2 emission of 153 g/km.

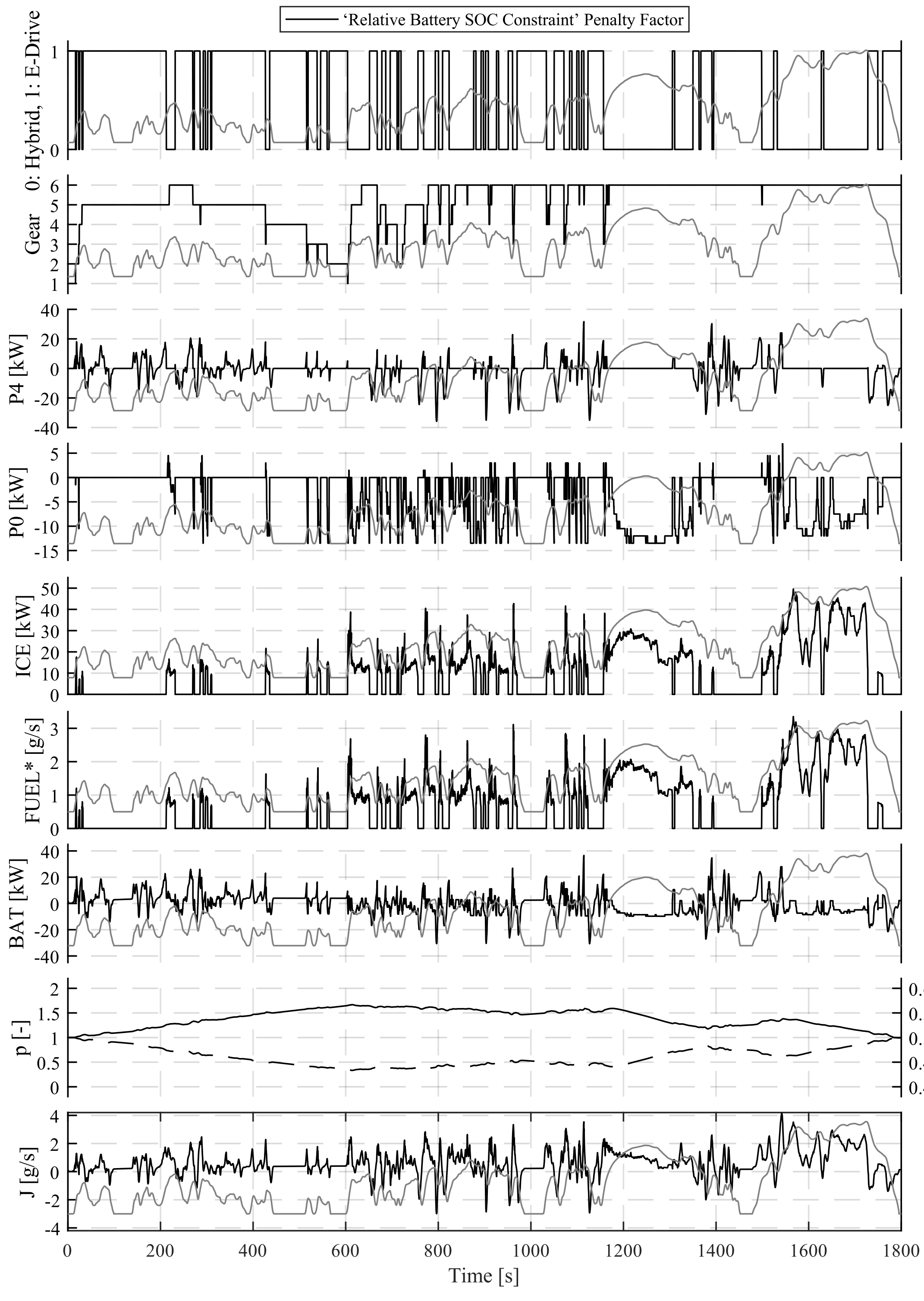


Figure 20: 'ECMS' controller with 'Relative Battery SOC Constraint' penalty factor based on WLTC (class 3) drive cycle.

4.2.2. ‘Absolute Battery SOC Constraint’ Penalty Factor

The ‘Absolute Battery SOC Constraint’ Penalty Factor (18) is evaluated for a charge depleting maneuver using the attribute values listed in Table 11. The upper battery state of charge constraint SOC_{max} is set equal to the initial value SOC_{init} for the purpose to keep the penalty factor value positive. The equivalence ratio s is calibrated in order to provide a charge sustaining control policy once the actual battery state of charge falls below the target level SOC_{target}.

Table 11: Coefficients for ‘ECMS’ controller with ‘Absolute Battery SOC Constraint’ Penalty Factor

Coefficient	Condition
SOC_{init}	1.0
SOC_{min}	0.15
SOC_{max}	1.0
SOC_{target}	0.2
Equivalence ratio s	2.375
Penalty function exponent a	1
Fossil fuel lower heating value Q_{lhv}	43.95 MJ/kg

Figure 21 shows the time series of the control input and the main result variables. The maneuver represents the repeated sequence of the WLTC (Class 3) drive cycle. The charge sustaining period where $SOC_{min} \leq SOC \leq SOC_{target}$ starts at 3,345s during the high speed section of the second sequence of the WLTC (Class 3) drive cycle.

For the ‘charge depleting’ maneuver of three consecutive WLTC drive cycles the fossil fuel consumption is evaluated to 2.69 l/100km with a fuel-equivalent CO2 emission of 64 g/km and a electric energy consumption of 11.89 kWh/100km.

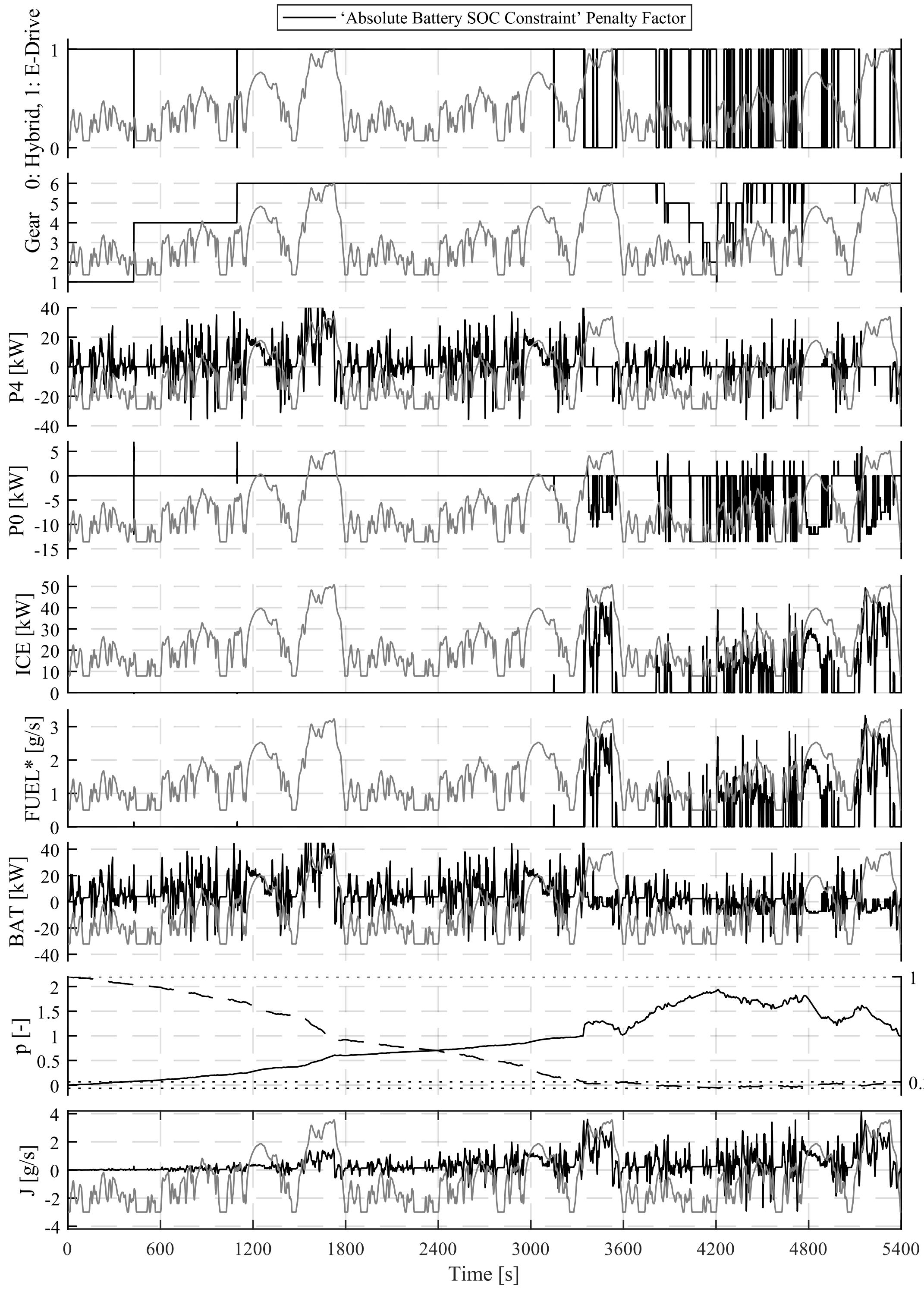


Figure 21: 'ECMS' controller with 'Absolute Battery SOC Constraint' penalty factor based on three consecutive WLTC (class 3) drive cycles

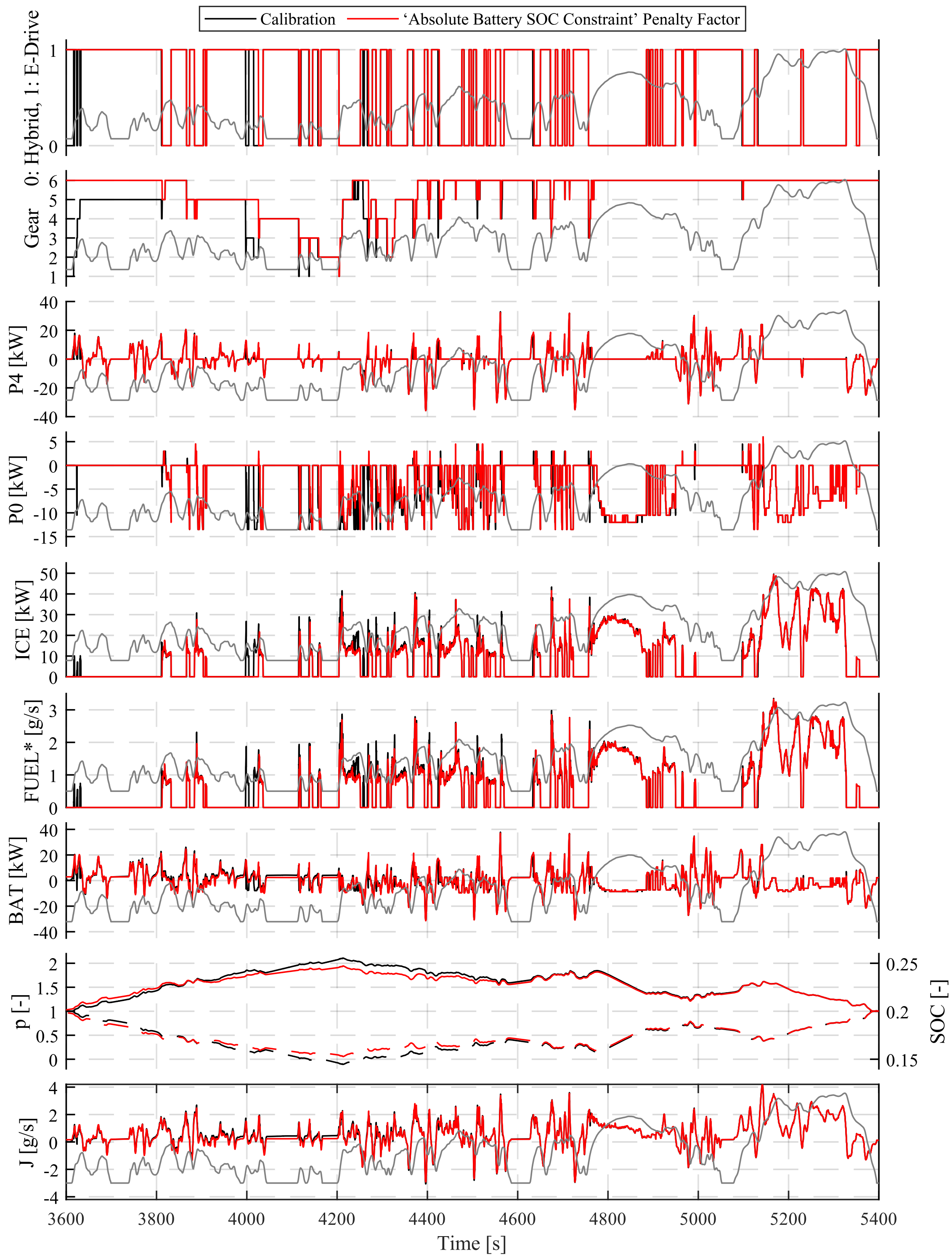


Figure 22: 'ECMS' controller with 'Absolute Battery SOC Constraint' penalty factor, comparison between 'calibration' run and the 'charge sustaining' period of the 'charge depleting' maneuver

4.2.3. ‘Engine Temperature’ Cost Function

The ‘Engine Temperature’ Cost Function (19) and (20) is evaluated for a charge sustaining maneuver using the attribute values listed in Table 12. The engine coolant temperature constraints T_{min} and T_{max} are set asymmetrically in respect to the target temperature T_{target} such that the cost of fossil fuel consumption becomes zero for engine coolant temperatures $T = T_{min}$, which deliberately leads to the favorization of control input combinations with high battery charging values. The battery state of charge constraints SOC_{min} and SOC_{max} are set symmetrically in respect to the target value SOC_{target}. The equivalence ratio s is calibrated in order to provide a charge sustaining control policy.

Table 12: Coefficients for ‘ECMS’ controller with ‘Engine Temperature’ Cost Function

Coefficient	Condition
T_{min}	20°C
T_{max}	100°C
T_{target}	80°C
Penalty function exponent	1
SOC_{min}	0.4
SOC_{max}	0.6
SOC_{target}	0.5
Penalty function exponent a	1
Equivalence ratio s	2.95
Fossil fuel lower heating value Q_{lhv}	43.95 MJ/kg

Figure 23 shows the comparison of the ‘Engine Temperature’ cost function with the ‘baseline’ cost function and the ‘Relative Battery SOC Constraint’ penalty factor, based on the time series of the control input and the main result variables. The second subplot from bottom shows the engine coolant temperature and the associated ‘Absolute Engine Temperature Constraint’ penalty factor. The time to warmup the engine from 20°C to 60°C is reduced from 626s to 210s and from 20°C to 80°C (which is the engine coolant thermostat opening set point) from 750 s to 640 s.

The fossil fuel consumption is evaluated to 6.18 l/100km with a fuel-equivalent CO2 emission of 148 g/km.

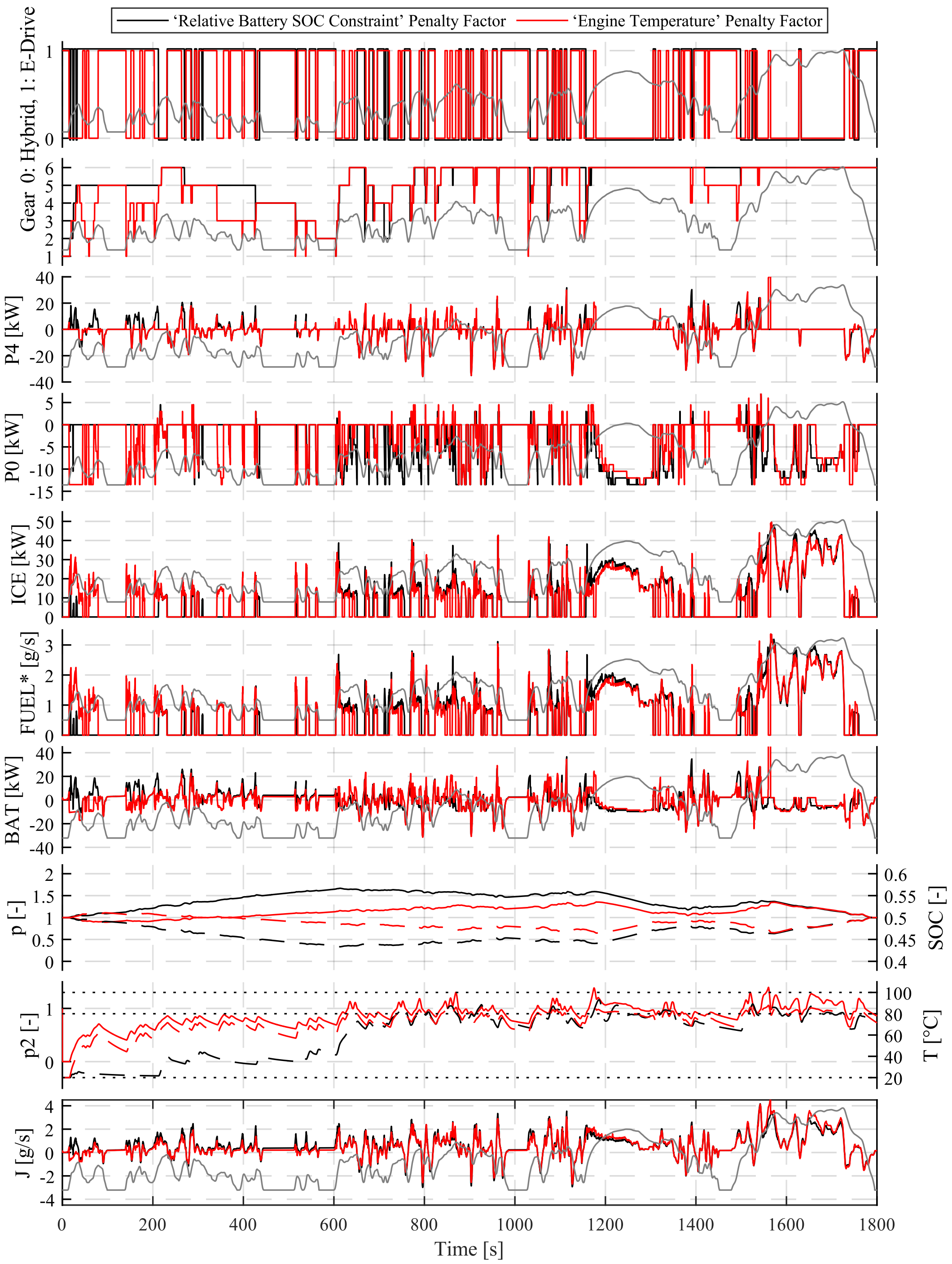


Figure 23: 'ECMS' controller with ‘Engine Temperature’ cost function

5. Discussion

The following chapter summarizes the findings obtained during the master thesis. The chapter is structured into two subchapters, which cover the verification of the developed 'ECMS' controller (chapter 5.1) and the evaluations of the introduced cost functions (chapter 5.2).

5.1. Verification of the 'ECMS' Controller

Based on the isolated setup of the 'ECMS' controller and considering the known differences in the evaluation approaches of the fossil fuel cosumption and of the electric machine efficiency, the verification focuses on the recognition of similarities in the optimal control input switching patterns. For the periods of equal operating modes (both 'E-Drive' or 'Hybrid'), the comparison of result variables, like fossil fuel consumption or battery power is taken into account as well.

The 'E-Drive' mode is activated during each vehicle stop and vehicle launch period, which is expected from the definition of the constraint on control input.

For both maneuvers (NEDC and WLTC) the 'ECMS' controller applies the 'E-Drive' mode to all 'regenerative braking' periods. This is not observed from the backward kinematic solution approach in 'GT-SUITE', which in contrast applies the 'Hybrid' mode to all vehicle cruise periods including the 'regenerative braking'. During the 'regenerative braking' periods similar power requests to the rear traction motor are observed.

During the acceleration periods and for the 'ECMS' contoller being in 'Hybrid' mode, similar gear number requests (in terms of value and timing) are observed. During the deceleration or 'regenerative braking' periods the gear number requests do not match because of the activated 'E-Drive' mode in the 'ECMS' controller and the associated prevention of shifting, which is defined as constraint on control input in the 'ECMS' controller only.

During the acceleration periods and for the 'ECMS' contoller being in 'Hybrid' mode, no load shifting to the internal combustion engine is applied. During the higher constant speed periods in the NEDC drive cycle ($v \geq 50$ km/h) similar (negative) power requests to the starter generator are observed. During the lower constant speed periods in the NEDC drive cycle ($v = 32$ km/h) the load shifting to the internal combustion engine is significantly higher.

The backward kinematic solution approach in 'GT-SUITE' results in 'chattering' power requests from the starter generator with frequent changes of more than one control input discretization step, which is attributed to the previously remarked convention regarding electric machine efficiency evaluation in ‘GT-SUITE’. The ‘ECMS’ controller doesn’t show any ‘chattering’ for the power request.

5.2. Influence of the Cost Functions on the Optimal Control Strategy

5.2.1. ‘Absolute Battery SOC Constraint’ penalty factor

The ‘Absolute Battery SOC Constraint’ penalty factor proves to be applicable to the selected charge depleting maneuver by means of an accordingly set upper battery state of charge constraint. The ‘ECMS’ controller decision for applying almost exclusively the ‘E-Drive’ mode during the first 3.345 s is dominated by the battery state of charge being higher than its target value and its contribution to the cost function by means of the ‘Absolute Battery SOC Constraint’ penalty factor. During the initial high battery state of charge the ‘Absolute Battery SOC Constraint’ penalty factor is approximately zero, which results in a very low cost for battery power consumption and the preference of the ‘E-drive’ mode. The equivalence ratio is calibrated beforehand based on a single sequence of the WLTC (Class 3) drive cycle and is reused for the charge depleting maneuver. This calibration approach is admissible because the battery state of charge falls below its target value during the entire WLTC (Class 3) drive cycle.

After the battery state of charge falls below its target value the ‘ECMS’ controller returns to a comparably similar optimal control policy, as is observed during the calibration run. The few deviations in the optimal control policy are attributed to the small ‘initial’ deviation in battery state of charge of 0.0014 at the begin of the third WLTC sequence.

5.2.2. ‘Engine Temperature’ Cost Function

The ‘Engine Temperature’ cost function proves to be applicable to the selected charge sustaining maneuver by means of an accordingly set lower temperature constraint. The ‘ECMS’ controller decision for applying almost exclusively the ‘Hybrid’ mode during the initial 78 s of the maneuver is dominated by the initially low engine coolant temperature and its contribution to the cost function by means of a low ‘Engine Temperature’ penalty factor value. This results in the application of a maximum load shifting to the internal combustion engine due to the low cost of fuel consumption and the associated negative cost for battery charging. The application of the ‘Engine Temperature’ cost function leads to a comparably alternating optimal control policy which is characterized by short sequences of ‘Hybrid’ mode with high internal combustion engine load shifting. These sequences are triggered by a decay of the engine coolant temperature below approximately 65°C and amplified by the linear correlation of the thermal penalty factor. Figure 24 shows the operating point distribution of the internal combustion engine during the initial period of 0-650 s. The effect of the ‘Engine Temperature’ cost function on the internal combustion engine load leads to the occurance of full load operation and less agglomaration around the operating point 1,250 rpm / 95Nm.

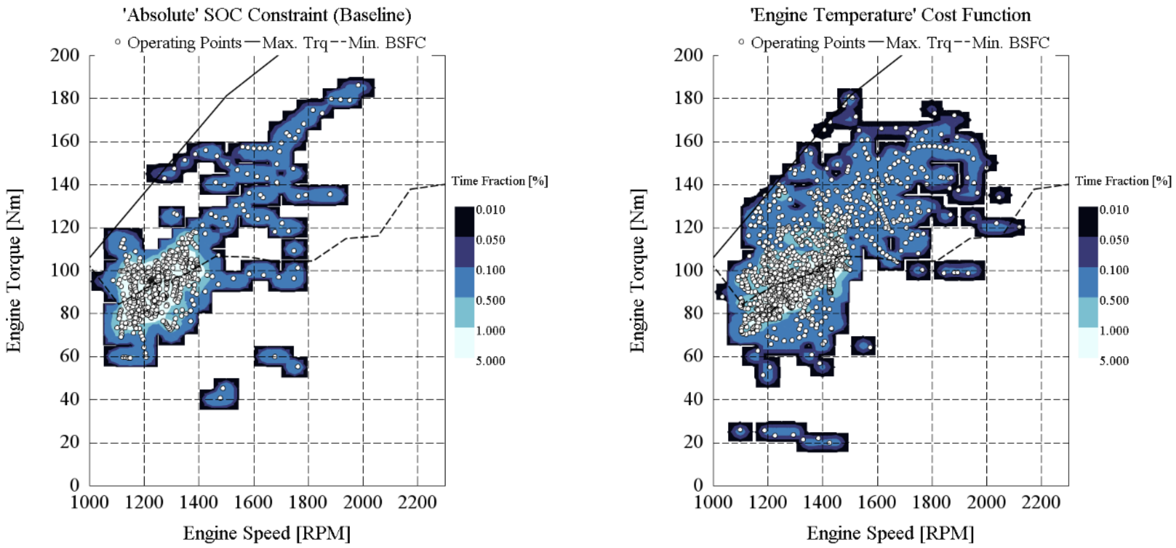


Figure 24: Operating point distribution of the internal combustion engine resulting from the ‘Relative Battery SOC Constraint’ cost function (left) and the ‘Engine Temperature’ cost function (right)

6. Conclusions

This master thesis focuses on the energy management task and its combination with the thermal management task as a crucial part of the concept finding process for a modern plug-in hybrid drivetrain.

A supervisory control concept based on the ‘Equivalent Consumption Minimization Strategy’ is successfully realized by means of an embedded ‘ECMS’ controller in the system simulation software ‘GT-SUITE’. The introduced approach combines the thermal management task with the supervisory control concept of ‘ECMS’, which results in a holistic and integrated modeling and solution approach of the vehicle thermal management system, the hybrid drivetrain system, the supervisory controls and the component-level controls of the hybrid vehicle.

The controller structure is derived following a modular concept and the controller features are oriented on the concepts from literature sources. The programmatical implementation of the ‘ECMS’ controller is realized using ‘MATLAB/Simulink’ and ‘Simulink Coder’. The ‘ECMS’ controller functions and operation is verified based on the comparison to the backward kinematic solution approach in ‘GT-SUITE’ and using input stimulation in an isolated controller setup.

Three modifications to the ‘ECMS’ cost function are proposed. The ‘Relative Battery SOC Constraint’ penalty factor allows to reduce the number of setup coefficients of the penalty factor term known from literature and contributes to its unambiguous interpretation. The ‘Absolute Battery SOC Constraint’ penalty factor allows a broader applicability of the ‘ECMS’ to the operation close to a battery state of charge limit or to the combined evaluation of a preceding charge depleting period and a subsequent charge sustaining period in a single maneuver. The ‘Absolute Engine Temperature Constraint’ penalty factor allows to modify the cost for fossil fuel consumption as a function of the engine coolant temperature and contributes to the combination of the thermal management task. It enhances the warm-up procedure of the internal combustion engine by applying the ‘Hybrid’ mode with maximum load shifting of the internal combustion engine.

A crucial part of the current solution approach and the derivation of a charge sustaining optimal control policy is the calibration of a constant equivalence ratio. The usage of a constant equivalence ratio effectively necessitates the a-priori knowledge of the vehicle speed and the power demand by running repeatedly the same maneuver during the calibration process.

7. Outlook

Based on the findings from literature research further improvement potential is already identified in favor of a continuous or sequential calibration of the equivalence ratio. The potential techniques apply a calibration strategy based on a look-ahead horizon, making use of the available information from the navigation system (elevation, distance, speed limits, emission control areas along the given route) and the traffic information system (expected traffic speed). The introduced design of the 'ECMS' controller allows to remain major parts of the controller structure and code with the intention to include it as a crucial subsystem. The following figure shows the envisioned high-level controller structure, which is inspired by the 'A-ECMS' approach [5]. The functions are adapted to the integrated toolset in 'GT-SUITE'.

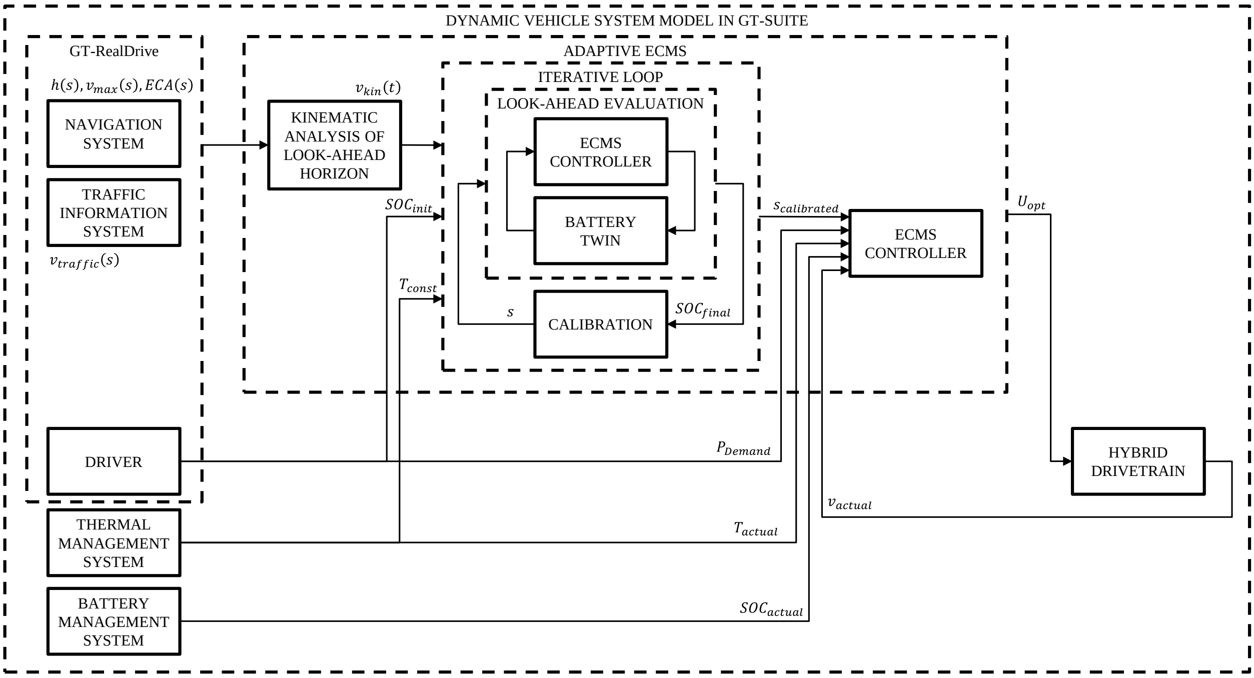


Figure 25: Envisioned high-level controller structure based on 'A-ECMS' approach

The findings from this master thesis provide valuable input for the development and the template design of the anticipated 'Dynamic ECMS Controller'. The elaborated solution approach states a proof of concept regarding the applicability of an integrated 'ECMS' controller with a dynamic vehicle system model. Further the elaborated solution approach will be used as a test environment for the pre-development and assessment of potential upcoming controller features.

The introduced 'ECMS' controller is expected to be adjusted and tested in the context of further applications areas, like the integration of the exhaust aftertreatment system, the holistic evaluation of a fuel cell drivetrain or the holistic evaluation of a hybrid ship propulsion system.

Glossary of symbols

Abbreviations

APP	Accelerator Pedal Position
BMEP	Brake Mean Effective Pressure
BPP	Brake Pedal Position
CAE	Computer-Aided Engineering
CD	Charge depleting
CS	Charge sustaining
DC	Direct current
ECMS	Equivalent Consumption Minimization Strategy
GHG	Green house gas
ICE	internal combustion engines
MIMO	Multi Input Multi Output
PHEV	Plug-in Hybrid Electric Vehicle
SOC	Battery state-of-charge
WLTC (Class 3)	Worldwide harmonized Light vehicles Test Cycle, ‘Class 3’ refers to ‘high power’ vehicle class with a max. power to kerb weight ratio of $> 34\ W/kg$

Variables

A	Vehicle Reference Area
a	Penalty term exponent, Acceleration
c_W	Aerodynamic Drag Coefficient
fc	Fossil fuel consumption
F_Z	Tractional Force
G, g	Terminal Cost continous / discrete, gravitaional constant
H	Cost of applying control input u, ‘Hamiltonian’
I, i	Current
i	Gear Ratio
J	Cost Function, Inertia
L	Cost of applying control input u
m	Mass
$\dot{m}$	Mass Flow Rate
n	Angular Velocity
n_{IDLE}	Internal combustion engine idle speed
P	Power, Preconditioning Factor
p	Penalty

Q_{lhv}	Lower Heating Value
R_0	Battery Internal Resistance
r_{dyn}	Dynamic Tire Radius
s	Equivalence Factor
sfc	Specific fuel consumption
T	Torque
T_{ICE}	Engine coolant temperature
T_N	Terminal Penalty
t	Time
t_{dur}	Duration to switch transmission gear
t_{switch}	Time stamp
u	Control Input
U	Admissible Control Input
U_Y	Finel Admissible Control Input
U_{opt}	Optimal Control Input
V_h	Displacement Volume
V_{OC}	Open circuit voltage
v	Velocity
x	System State
Y	Dependent variable
z	System state

Greek variables

α	Road Elevation
Δ	Difference
η	Energy Conversion Efficiency
μ	Tire rolling resistance coefficient
π	The Number pi
ρ	Air Density
ω	Angular Velocity

Subscripts

$actual$	Actual value
AUX	Auxiliary related value
bat	Battery related variable
brk	Mechanical Brake
chg	Battery Charge
$corr$	Correction
$Dem, Demand$	Demand
dis	Battery Discharge
e	electrical
eff	Effective value
em	Electric Machine
eqv	Equivalent value
$fuel$	Fossil fuel related value
$f, final$	Final state
$gear$	
ice, ICE	Internal Combustion Engine
$init$	Initial value
k	Time index,
m	mechanical
max	Maximum value
min	Minimum value
N	Final time index
opt	optimal
$P0$	Starter-Generator related value
$P4$	Rear traction motor related value
$target$	Target value
$terminal$	Battery terminal related value
$tire$	Tire related value
TM	Transmission
$Wheel$	Wheel value
0	Initial State

Superscripts

GT	Signal from GT-SUITE
k	Index of control input combination
opt	Optimal control input from previous controller sequence

Appendix A

The following section contains component specifications for the reference hybrid vehicle [2], which are used for the setup of the hybrid vehicle system model.

Table 13: Selected vehicle attributes published by BMW [2]

Attribute	Value	Unit	Remark
Vehicle Mass Curb	1,660	kg	
Cargo Mass Max.	445	kg	
Wheelbase	2,670	mm	
Drag Coefficient	0.29		
Projected frontal Area	2.4	m^2	
Tires	205/55R17		

Table 14: Selected transmission attributes published by automobile catalog [14]

Attribute	Value	Unit	Remark
Gear ratio 1	4.459		
Gear ratio 2	2.508		
Gear ratio 3	1.556		
Gear ratio 4	1.142		
Gear ratio 5	0.851		
Gear ratio 6	0.672		
Final Drive Ratio	3.944		

Appendix B

The following section contains component specifications for the hybrid vehicle system model, which are based on empirical assumptions and findings from other internal projects.

Table 15: Additional vehicle model attributes

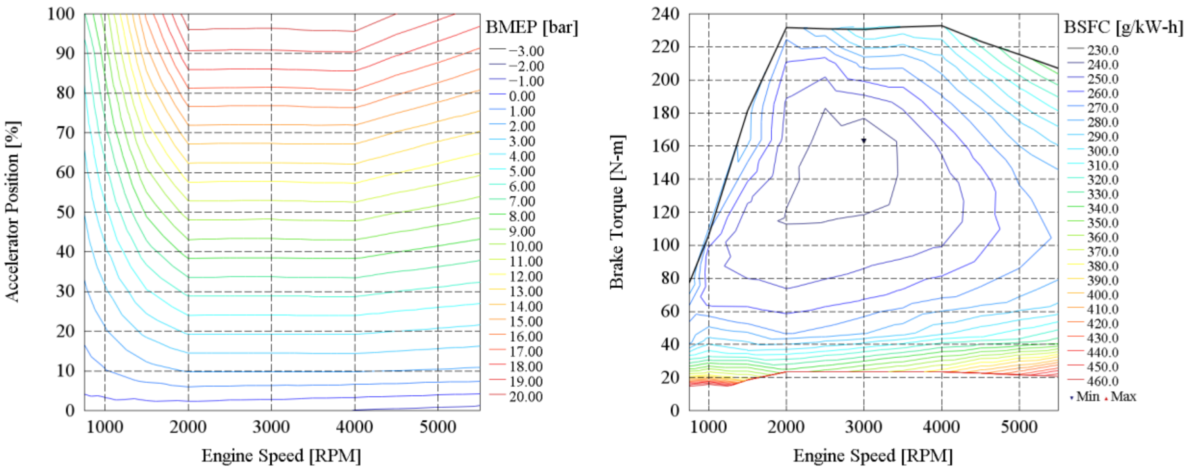
Attribute	Value	Unit	Remark
Weight distribution	52/48	%	
Rolling Radius Correction	0.97	-	
Tire Rolling Resistance Factor	0.01		
Wheel inertia	1.25	kg m²	

Table 16: Additional transmission model attributes

Attribute	Value	Unit	Remark
In-Gear Efficiency	0.96	-	
Input shaft inertia	0.05	kg m²	
Output shaft inertia	0.05	kg m²	
Gear Ratio Transition Time	0.5	s	

Table 17: Additional internal combustion engine model attributes [15]

Attribute	Value	Unit	Remark
Displacement volume	1,400	cm³	
Engine inertia	0.15	kg m²	
Maximum BMEP	20.7	bar	→ Figure 26
Min. brake specific fuel consumption	233	g/kWh	



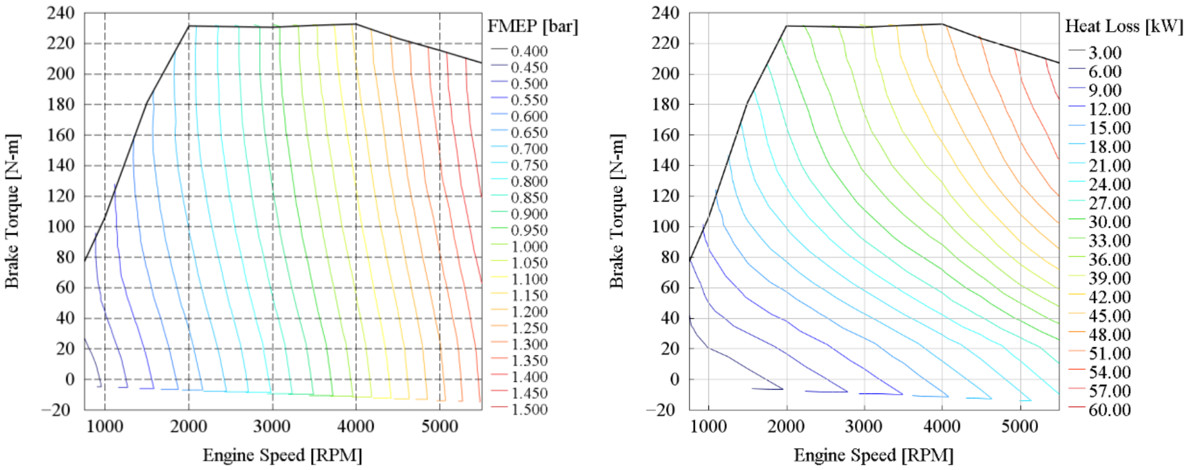


Figure 26: Map-based internal combustion engine model represented by maps of BMEP, BSFC, FMEP and Heat Loss as function of Engine Speed and Load

Starter-Generator

Table 18: Selected attributes defined in the starter generator model

Attribute	Value	Unit	Remark
Max. Power / Torque	15 / 60	kW / Nm	Motor and Generator → Figure 27
Corner / max. speed	2,387 / 13,500	rpm	
Max. Efficiency	0.915	-	
Inertia	0.031	kg m²	
Gear ratio / mech efficiency	2.5 / 0.98	-/-	

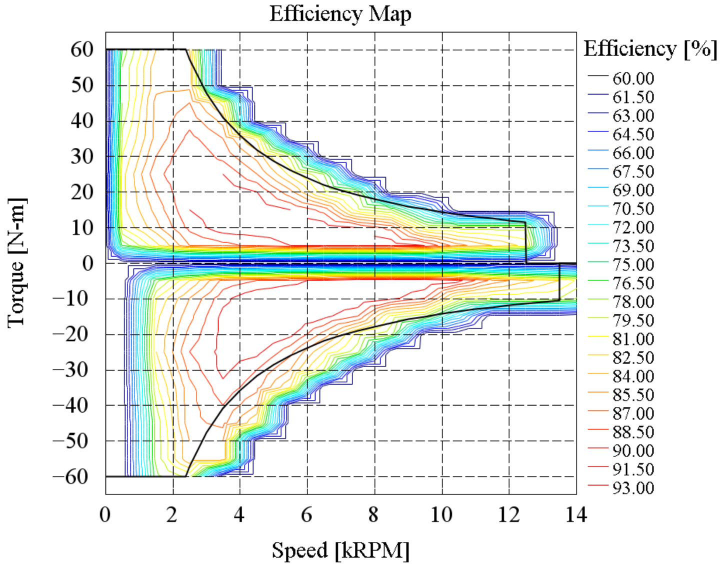


Figure 27: Torque constraints of the starter generator

Traction Motor

Table 19: Selected attributes defined in the traction motor model [16]

Attribute	Value	Unit	Remark
Max. Power / Torque	80 / 280	kW / Nm	Motor and Generator → Figure 28
Corner / max. speed	2,700 / 10,400	rpm	
Max. Efficiency	0.982	-	
Inertia	0.02	kg m²	
Gear ratio / mech efficiency	9 / 0.97	-/-	

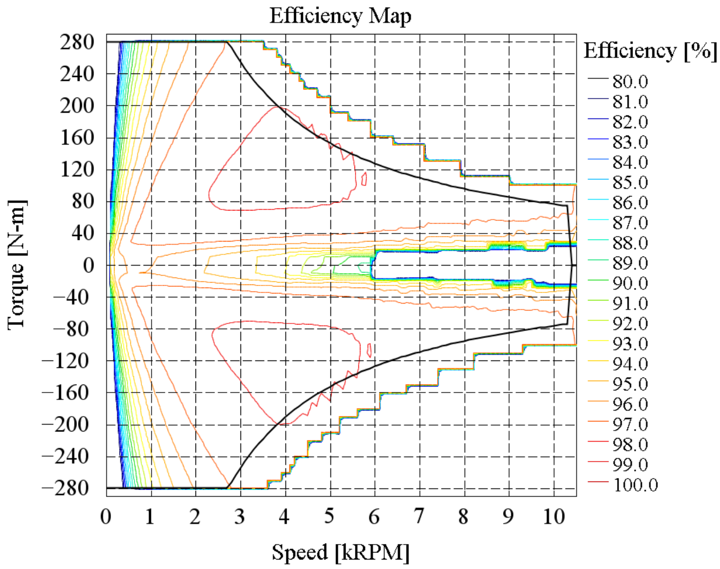


Figure 28: Torque constraints and conversion efficiency map of the traction motor

Battery

Table 20: Selected attributes defined in the battery model

Attribute	Value	Unit	Remark
Cell Capacity	26	Ah	
Number of Series / Parallel Cells	105/1		Scaled
Open Circuit Voltage (Voc), Charge	3.8	V	constant
Open Circuit Voltage (Voc), Discharge	3.6	V	constant
Internal Resistance (R0), Charge	2	mΩ	constant
Internal Resistance (R0), Discharge	2	mΩ	constant

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