

Management of Energy Flow in Complex Commercial Vehicle Powertrains

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ABSTRACT

After the realization of very low exhaust gas emissions and corresponding OBD requirements to fulfill Euro VI and Tier 4 legislation, the focus in heavy duty powertrain development is on the reduction of fuel consumption and thus CO₂ emissions again. Besides this, the total vehicle operation costs play another major role. A holistic view of the overall powertrain system including the combustion process, exhaust gas aftertreatment, energy recuperation and energy storage is necessary in order to obtain the best possible system for a given application. A management system coordinating the energy flow between the different subsystems while guaranteeing low exhaust emissions plays a major part in operating such complex architectures under optimal conditions. A heuristically Equivalent Consumption Minimization Strategy (ECMS) is presented which obtains the optimal settings of control signals to determine optimum engine efficiency and emissions behavior in addition to the desired exhaust gas temperature. In a second approach, a model-based predictive controller (MPC) concept based on a linear battery model and static operating maps of the vehicle and engine is applied. The benefit of this concept is the consideration of future information such as slope of the track. In this investigation, a long-haul hybrid truck has been chosen exemplarily to demonstrate the energy flow manager for commercial vehicles. The controller parameters are calibrated and the potential of the coordinator is assessed using a virtual development platform based on the longitudinal dynamics vehicle simulation environment VeLoDyn for ComApps.

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INTRODUCTION AND MOTIVATION

Pollutant emissions of modern Diesel engines used in commercial vehicle applications will be reduced to very low limits with enforcement of future emission legislations as e.g. Euro VI and Tier 4. In addition to the fulfillment of higher on-board diagnosis and in-use compliance demands, future development will be focused especially on the reduction of fuel consumptions and hence of CO₂ emissions. The total cost of ownership largely determines the economical success of a vehicle or mobile machine. With increasing crude oil prices, the fraction of fuel expenses on the total expenses will also increase. As a result, technologies formerly too expensive for a reasonable implementation can have a revival under the new boundary conditions.

Since Euro IV in heavy-duty truck and bus applications and Tier 4 in non-road applications, exhaust gas aftertreatment systems are an integral part of the powertrain

architecture. The exhaust gas temperature is a main parameter influencing the efficiency of exhaust gas aftertreatment systems. To achieve high conversion efficiencies, fast light-off has to be achieved at cold-start and light-out during low load points of operation has to be avoided. SCR systems operated with urea-water solutions require temperatures above approx. 200°C for dosing clearance. Particulate filters are best operated in temperature ranges between 250°C and 450°C for optimum continuous soot regeneration via O₂. With in-use compliance requirements, the engine management has to operate the aftertreatment system within a reasonable temperature range in order to guarantee low emissions during all driving conditions.

As discussed above, additional subsystems as e.g. thermal energy recuperation and alternative powertrain layouts, especially hybrids, are becoming serious options in all kinds of heavy-duty applications. A hybrid system offers the potential to improve the overall efficiency by mechanical

breaking energy recuperation. Furthermore, especially the mitigation of engine dynamic operation and engine operating-point shift are interesting aspects of this technology.

Different possibilities exist in the choice of the second storage and propulsion system. Possible alternatives to electric hybrids store energy kinetically, hydraulically or pneumatically. Kinetic hybrids usually use a flywheel for storage. These systems offer the advantage of high power densities and high efficiencies. It has been shown e.g. in modeling investigations of passenger car applications that flywheel hybrids can be superior to electric hybrids under certain driving patterns [1]. Pneumatic and hydraulic hybrids can also be attractive alternatives as, depending on the application, a basis for one of these systems is often already available on commercial vehicles. Regardless of the specific method of storage, the hybrid system can be viewed as an additional control variable in the energy flow management system.

Thermal energy recuperation systems can recover a certain part of the remaining exergy in the exhaust gas. A promising technology for recuperation is the Rankine process applied in the EGR loop and in the exhaust gas after the SCR catalyst. For vehicles operating highly dynamically, as e.g. city busses, thermoelectrics might be a viable future option in spite of its relatively low efficiency. A more in-depth overview of the different possible subsystems of modern commercial powertrains is given in [2].

In spite of increasing complexity of the overall powertrain, the engine combustion system still plays a crucial role in the overall system optimization. On the one hand, there is still some potential in the general optimization of the trade-off between engine-out emissions, fuel consumption and system cost. On the other hand, the engine has to provide well-defined amounts of energy to the aftertreatment and the heat recuperation system. This can either be achieved by altering the combustion parameters at constant load with minimized effect on raw emissions and fuel consumption. Alternatively, the energy demand might be satisfied best by an operating point shift of the combustion engine in conjunction with increasing the energy level of the hybrid storage systems. The optimal operation strategy will depend for example on the current energy level of the storage system. It might also include a forecast on energy levels within a certain time horizon based on an anticipated driving profile. As a result, the engine management has to evolve to an energy flow management, distributing the mechanical and thermal energy fluxes on demand in order to achieve the maximal possible overall efficiency while guaranteeing low emissions and smooth torque supply.

In this study, two potential approaches to realize an energy flow management system are discussed. The focus is on such models that can be implemented real-time capable on current or near-future series production control system hardware. For demonstration purposes, a purely model-based design process is performed utilizing a longitudinal vehicle

dynamics simulation software which will be introduced in the next section.

VIRTUAL DEVELOPMENT PLATFORM

The Matlab/Simulink® based vehicle simulation environment Velodyn for ComApps is used in this study as a virtual development platform for controller design. Velodyn for ComApps is a specialized version of the forward longitudinal vehicle simulation Velodyn for heavy-duty trucks and mobile working machinery [3, 4]. It is characterized by a flexible modular modeling structure, allowing individual powertrain and vehicle components to be modeled in varying level of detail while guaranteeing maximum reusability during the development process.

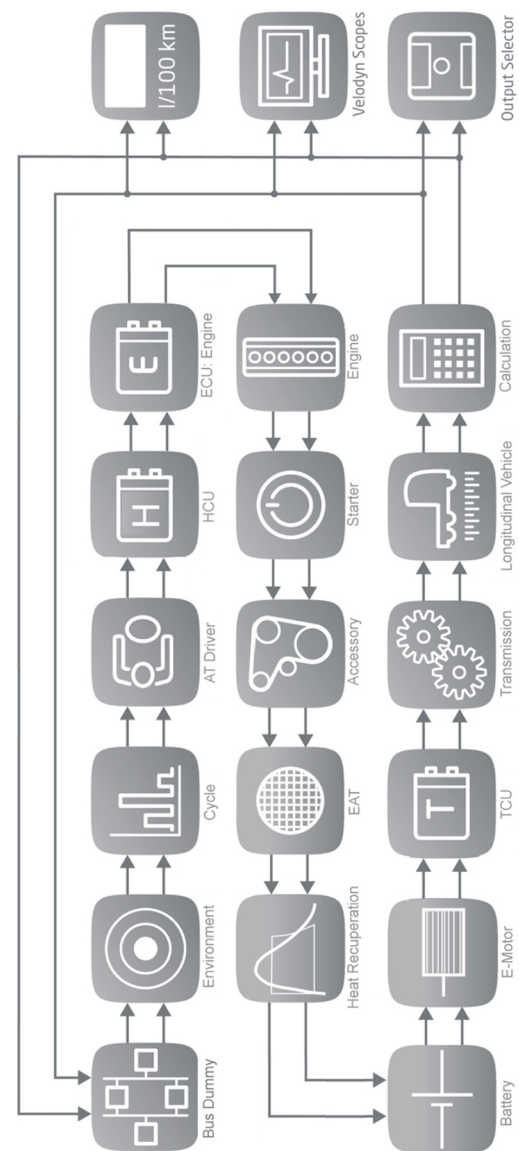


Figure 1. Model structure of the electric hybrid truck

Fig. 1 shows the structure of the heavy-duty truck used to test the energy flow controller proposed in this study. The exemplary long-haul truck under investigation is equipped with a six-cylinder EGR-engine with oxidation catalyst, coated particulate filter and SCR catalyst. A classic parallel electric-hybrid structure is investigated in this work.

The main components of the depicted truck model are the vehicle, the powertrain including the engine, aftertreatment, heat recuperation and hybrid systems, the driver and the system environment. For mobile machinery as e.g. mining or farming vehicles, additional components to model the hydraulics and working equipment can be added. Within the overall model, each individual component can either be described by models set-up in Simulink and provided by the Velodyn library as well as by integration of a dedicated external simulation tool (compare [5]). In this simulation for example, the engine is modeled using GT-Power while the exhaust gas aftertreatment is modeled with KatSim [6].

The component models are complemented with controller structures, commonly referred to as “soft-XCUs”. Depending on the target of the simulation, these control algorithms might be simplified compared to the algorithms used in real life.

ENERGY FLOW MANAGEMENT

This section describes the basics of the used energy flow management strategies ECMS (Equivalent Consumption Minimization Strategy) and MPC (Model Predictive Control). All functions are included in the HCU of the virtual development platform shown in Fig. 1. Furthermore the simulation results are discussed and summarized.

The total required power of a parallel hybrid powertrain is calculated by

$$P_{req} = P_{ICE} + P_{EMG} \quad (1)$$

with the power of the internal combustion engine P_{ICE} and the power of the electric motor generator P_{EMG} . The goal of the energy flow management is to apply an optimized use of the electric motor for an efficient operation of the engine.

EQUIVALENT CONSUMPTION MINIMIZATION STRATEGY

The idea of ECMS is to reduce the global optimization problem which solves for the total minimum of the whole cycle with an offline optimization (Dynamic Programming), to a local problem in which only the current operation point is considered [8]. This allows a real time optimization with moderate computational effort. The approach also takes into account various constraints such as the maximum torques of the engine and electric motor, and the state of the battery. In order not to shorten the batteries lifetime, the state of charge (SOC) is allowed to vary only within 30% and 90%. A schematic of the implementation is given in Fig. 2. In order to ensure a high NO_x conversion efficiency when the engine is

running, the monolith temperature of the SCR catalyst is also taken into account.

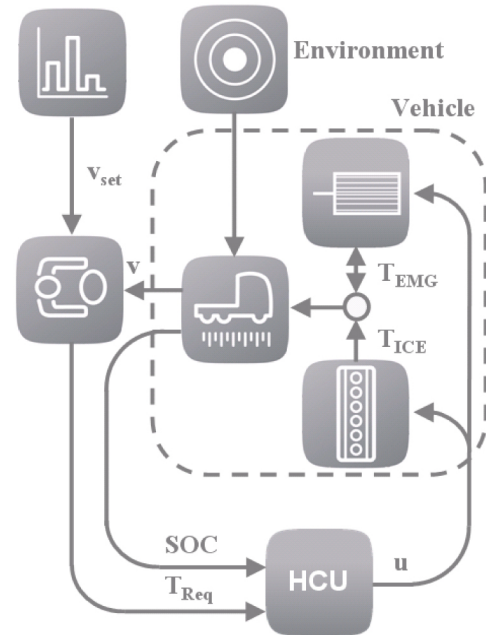


Figure 2. Schematic of the ECMS strategy and its implementation

An actuating variable u is introduced to split up the required power between the engine and the motor

$$P_{ICE} = P_{req} \cdot (1 - u) \quad (2)$$

$$P_{EMG} = P_{req} \cdot u \quad (3)$$

According to Eq. (3), a positive u leads to a discharge of the battery and hence a decreasing SOC. With $u = 1$, the maximum value of the actuation variable, all the power is generated by the electric motor (E-Drive). At $0 < u < 1$ the motor supports the engine (Boost). On the other hand, a negative u charges the battery (Charge), while the combustion engine performs a load shift (see Eq. (2)).

Dependent on the torque required, not every setting of u is reasonable to use. In Fig. 3 typical characteristics such as maximum, optimal and an artificially defined non optimal (nopt) torque and the maximum torque of the electric motor are shown. The curves divide the map into different sections. For example, the torque of section 1 can only be reached with electric support (Boost). Section 2 includes torque above the optimum efficiency curve where it is less advantageous to charge the battery. All meaningful modes for the defined sections are listed in Tab. 1.