ABSTRACT. In this paper a method is proposed for determination of the design specifications regarding the energy exchange systems for different charge-sustaining hybrid vehicles of different vehicle classes. Hybrid drivetrains for vehicles combine multiple power sources in order to increase the driving functions. The function can enhance the fuel consumption, emissions, comfort, driving performance and safety. In this paper the focus is on fuel consumption reduction. The optimal energy management strategy is determined by using dynamic programming. Initially, the efficiencies of the energy exchange between the engine, vehicle road load and additional energy exchange system are assumed to be constant and independent of engine torque and speed. Therefore, the simulation results will be independent of the component technology and topology. The outcome of the simulations will be the required constant system component efficiencies, sizes and power specifications in order to achieve the required fuel consumption reduction, maintain state-of-charge and accomplish any power demand over a defined drive cycle. These design specifications will be used to chose system component technology. Finally, the chosen system component technologies will be used to determine optimal topologies and optimal energy management system control.

1. INTRODUCTION

A hybrid vehicle uses at least two different power sources to propel the vehicle of which one of them can generate power for energy storage in an accumulator, in order to increase the driving functions of the vehicle propulsion system. The driving functions can enhance the:

- Fuel consumption;
- Emissions;
- Comfort;
- Driveability (performance);
- Safety.

A secondary power source which consists of a bi-directional energy accumulator with energy conversion components (EC) is further mentioned in this paper as an energy exchange system (EES). Examples of EESs are battery combined with an electromotor or a flywheel combined with a continuously variable transmission and planet gear set. For example the fuel consumption and emissions can be reduced, because a smaller primary power source (engine or fuel cell) can be coupled with an EES during brief periods of high power demand. At other times, the primary power source operation is kept in high-efficiency region by using the EES to manage the
vehicle load. More fuel consumption and emission reduction with the application of an EES can be achieved by shutting off the primary power source at idle eliminating fuel waste when primary power source is not needed. Or by regenerative braking, which stores energy for later use. For example the comfort and driveability can be increased due to torque transients absorption of the engine and driveline by the EES. Or an EES masks deficiencies of conventional drivetrains such as pauses during shifts. Also an EES consisting of an electromotor provides high torque at low speed, which gives satisfying launch feel. The safety can be enhanced by the application of advanced electric braking systems or torque traction systems (all-wheel-drive confidence). In this case, a safety function could also be combined with the fuel consumption function regarding brake energy recovery due to the application of an EES.

1.1. Research Programme. The NWO\textsuperscript{1} research programme called “Impulse Drive” focusses on the design of a hybrid vehicle with significant reduction of fuel consumption (50% - 75%) and CO\textsubscript{2} emissions on a representative drive cycle. The design process is complex and therefore a design path is made. A schematic overview of the NWO design path is shown in figure 1.

\textsuperscript{1}The Netherlands Organization for Scientific Research
1.2. **Design specifications EES.** First, the required design specifications of EESs will be determined with help of an optimization tool, which consists of an energy management algorithm. In figure 1, this is depicted by an arrow with the label 1. Typically, the EES component specification requirements are

- storage power;
- energy storage level;
- energy storage - and energy converter efficiency.

Furthermore, the required design specifications of an EES depend on,

- the type of vehicle class;
- the type of engine;
- driving behavior;
- climate - and geographical influences;
- additional electrical (accessory) loads;
- functional constraints on the EES.

For example a multi-purpose vehicle (MPV) is a much bigger and heavier vehicle than a mini-compact vehicle. Between these type of vehicle classes is a significant difference in power request during vehicle launch or energy recovery gain during braking.

The function of a Diesel or a gasoline engine is the same i.e. by combustion of fuel achieve kinetic energy. The two types of engine differ in the type of combustion, compression ratios and energy density. Generally, the higher compression ratio results in a higher efficiency for the Diesel engine. However, as a drawback the Diesel engine produces, also depending on the energy management strategy to some extent, relative high NO\textsubscript{x} emissions and particulates [5].

The benefits or the obtained increase in driving functions of hybrid vehicles vary with the usage. For example the benefit may vary with driving behavior, climate and geography. The driving behavior, which is represented by the certified driving cycles (e.g. NEDC, HYZEM), show for example large differences in power requests. Regarding climate and geography at relative high environmental temperatures, the ‘Airco’ or ‘Climate Control’ may cancel some hybrid functions or fuel savings. ‘Climate Control’ may even cancel the Stop-and-Go function. However, benefits of regenerative braking (BER) and operating optimization (E-line) remain.

For example additional electrical loads, which have affect on the specification of the EES are due to electric power assist steering or electric water pumps.

The functions of the EES are accumulate energy from the engine, the vehicle (i.e. BER) and supply energy to the vehicle. If one or two of these functions are not applied, this will lead to different specifications of the components and therefore also different system component technologies and topologies [4].

1.3. **EES Technology and Topology.** Initially, the efficiencies of the energy exchange between the engine, vehicle road load and EES are assumed to be constant and independent of engine torque and speed. Therefore, simulation results will be independent of the component technology and topology. The outcome of the simulations with the optimization tool will be the energy management strategy in accordance with the required constant system component efficiencies, sizes and power specifications. These design specifications will be a good benchmark in order to choose system component technology, which fulfill the required vehicle driving
functions (depicted by arrow with the label 2.). Finally, the optimization tool will be used to determine optimal and explore alternative vehicle topologies with optimal energy management control for different hybrid vehicles of different vehicle classes with the chosen EES technologies (depicted by the arrows with the label 3. and 4.). Then, the power dependant efficiency of the system components and kinematical constraints of the hybrid drivetrain will be incorporated during these simulations.

2. Simulation Model and Method

A generic energy flow scheme for a hybrid vehicle is shown in figure 2. The energy sources (accumulators) are $E_f$, $E_l$ and $E_a$. The energy flow paths are depicted by the arrows. $E_f$ represents the primary or chemical energy source, which could be for example fossil fuel or hydrogen fuel. $E_l$ represents the vehicle load which accumulates and dissipates energy over a certain drive cycle. $E_a$ represents an energy accumulator, which is able to store energy, but also to supply energy (e.g. battery or flywheel). $EC_1$, $EC_2$ and $EC_3$ represent energy converters, which convert chemical, electrical, mechanical or hydraulic energy.

2.1. Optimization criteria. The problem is to optimize the energy flow of the energy converters over a defined drive cycle in order to

- Minimize the fuel consumption and emissions.
- Maintain state-of-charge of the accumulator within a certain range.
- Accomplish any power drive demand.

The energy converters $EC_2$, $EC_3$ and energy accumulator $E_a$ are part of the EES. If the efficiencies of the energy converters and energy accumulator are 100%, the engine operates at its ‘sweet spot’ and delivers exactly the energy demand by driving the vehicle over the cycle. If the efficiencies are less than 100%, the

\[\text{lowest fuel consumption point}\]
energy delivered by the engine is higher than the required vehicle drive energy $E_l$ and depends on engine operating power over the cycle. This is determined by the energy management strategy.

2.2. **Energy management algorithms.** An approach called dynamic programming (DP) will be used to solve this problem [1]. With DP it is possible to find solutions for optimal energy flow control from the energy sources to achieve the overall control objectives. However, the control objectives or drive functions such as fuel consumption minimization or driveability are subjected to an integral constraint i.e. maintaining state-of-charge. This constraint requires for the DP solver to have foreknowledge of the drive cycle. So for real-time implementation other types of algorithms (quadratic programming (QP) and rule-based (RB) algorithm) will also be investigated [3], [6]. The optimization problem can be approximated by a QP problem, which has much less computational requirements. The RB energy management strategy is mainly based on engineering intuition and analysis of efficiency specifications of system components, while the DP algorithm is based to compute the optimal control strategy. Because with the DP technique it is possible to handle difficult constraint sets such as integer or discrete sets, it has a wider scope of applicability. Furthermore, DP leads to a globally optimal solution and is therefore useful as a benchmark for other optimization algorithms [2]. For example DP can be used to construct improved rules.

3. **Conclusions and Future work**

The proposed method for determination of the design specifications of the EES for different types of hybrid vehicles of different vehicle classes is discussed. The optimal energy management strategy is determined by using DP. The influence of the energy exchange efficiencies between the engine, vehicle load and the EES on the driving functions can be investigated. In order to determine the design specifications of the EES, these efficiencies are initially kept constant and independent of the engine torque and speed during the simulations. Therefore, the outcome of the simulations are independent of the topology and system component technology. As with DP, other optimizing algorithms QP and RB can be used to determine the performance of candidate power system combinations in order to determine the optimal topology. During this process the power dependant efficiency of the system components and kinematical constraints of the hybrid drivetrain will be incorporated.

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