

Powerpack Design in S-HEV: Quantifying the Influence of Duty Cycles on Design and Fuel Economy

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ABSTRACT

Military vehicles experience a wide range of duty cycles depending on the place and purpose of their deployment. Vehicle fuel consumption directly depends on those use cases, which are ranging from patrolling during peace keeping operations to direct engagements in hostiles areas. Vehicle design should accommodate this wide range of operation modes to maximize the vehicle practicality during their service life. This paper aims to quantify the sensitivity of the powerpack design for a notional 15-ton series hybrid electric vehicle for two highly dynamic military drive cycles. The optimal design for a powerpack (engine coupled with a generator) will be separately determined for each of the use cases through a previously developed optimization routine that use the Genetic Algorithm. For each iteration of the Genetic Algorithm a design benchmarking was incorporated by using Dynamic Programming. Subsequently a comparison between the cycle-optimized designs will be performed to quantify the fuel consumption penalty of operating the vehicle with a cycle-tailored design on a different cycle. The results can help to understand the sensitivity of the vehicle fuel economy under various use conditions rather than designing around a single drive cycle.

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INTRODUCTION

In the military sector, the fuel consumption reduction effort is aiming to decrease the "tooth-to-tail" ratio [1]. In other words, the goal is to increase the ratio between the forces directly engaged in combat and the supporting forces. In order to develop more efficient military vehicles and to relieve their logistical burden, a detailed energy bill of deployed fleets needs to be evaluated. Based on the evaluation new vehicle designs can be developed, still capable of accomplishing the missions, but with much better fuel economy.

Determining the optimal powertrain design is a non-trivial task requiring a methodological approach which is beyond the ability of engineer's intuition [2, 3, 4, 5, 6, 7]. The high complexity of optimization inputs such as drive cycles, auxiliary loads and vehicle performance requirements, coupled with different hybrid vehicle topologies and components sizes, require modeling and simulation approaches able to capture all the interdependencies, tradeoffs and system limitations.

Understanding the duty cycles' power requirement is the key element in designing the optimized powertrain. However, in the literature most of the powertrain design optimization studies focus only on the regulatory drive cycles [8] which in many cases can misrepresent the reality [9]. The focus of this paper is to quantify the variability of the fuel consumption of the Series Hybrid Electric Vehicles (SHEV) on

different drive cycles. As the vehicle design is optimized on a particular drive cycle, the variation of fuel consumption by operating the vehicle on a different cycle can be significant, especially when the power requirements in both cycles are different. The contribution of this paper is twofold:

1. Evaluate the variation in a cycle-specific powertrain design.
2. Quantify the variability in fuel consumption when a cycle-optimized design is used on a significantly different cycle.

The paper is organized as follows. The introduction section presents the details on the vehicle model and drive cycles. The core part of the paper explains the cycle-specific design optimization framework. In the results part, the optimized design is found for each of the two different drive cycles. Next, a cycle-optimal design is selected and used on a different cycle, where the design was not optimized on, in order to evaluate the impact and variability of the fuel consumption. The paper concludes with the analysis of the powertrain operating points from the efficiency standpoint and discusses the directions for future work.

Vehicle Configuration

The vehicle configuration used in this study is a notional Series Hybrid Electric Vehicle (SHEV) with individual wheel motors, [Figure 1](#). This architecture brings several advantages. (i) There is no mechanical linkage between the powerpack (combustion engine

coupled with a generator) and the individual wheels, providing more flexibility in the vehicle hull design. (ii) All four in-wheel motors can be operated independently to achieve an unprecedented all-terrain maneuverability. (iii) A relatively larger battery pack enables a temporary silent operation of the vehicle. (iv) The powerpack can be used to export power.

The general advantage of the SHEV configuration is that the powerpack's power output can be operated independently of the immediate power demand on wheels. e.g. the powerpack can be completely shut down during the low power demands and the vehicle can be powered silently from the battery. Another advantage is that the powerpack does not need to be designed to satisfy the peak power demands, since the battery pack can provide additional power instantaneously. There is also an efficiency gain as the engine and the generator in the powerpack can be operated along its best combined efficiency line. Some of the disadvantages compared to a conventional configuration include additional cost, weight and system complexity. Therefore it is important to appropriately size the components, relative to each other and analyze the deployment scenarios from the power demand perspective to avoid any unnecessary cost.

All of the considered notional vehicle parameters are summarized in [Table 1](#). The optimum design of the in-wheel motors for this notional vehicle application was addressed previously in [10] by using a high-fidelity finite element e-machine model. The baseline engine and generator efficiency maps were selected based on their power output and public availability of their specification [11]. In order to demonstrate the cycle-specific design methodology, the Willans line component model scaling approach [12] is considered for the powerpack sizing. It offers an excellent balance between model fidelity and computation time while assuming that the engine and the electric machine losses linearly depend on speed and component physical dimensions. To generate the vehicle power demands, the fast-executable, backward facing, quasi-static, longitudinal vehicle model [13] is used to evaluate the fuel economy with the vehicle parameters from [Table 1](#).

Table 1. Notional vehicle parameters

Vehicle weight	15 ton
In wheel motor power	4x128 kW [10]
Powerpack output	~250 kW electrical
Battery pack	9 kWh
Baseline engine	255 kW, 10L V8 diesel engine
Baseline generator	Generic 143 kW e-machine
Frontal area	5.72 m ²
Drag coefficient	0.7
Rolling resistance	0.0136 N/kg
Tire radius	0.59m

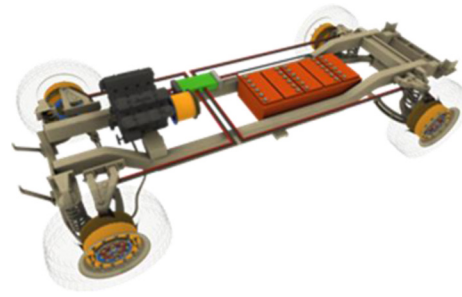


Figure 1. SHEV configuration

As the engine and the generator are coupled together to form the powerpack, their combined efficiency map is calculated. The mechanical work produced by the engine has to pass through the generator to produce electricity. Therefore, a combined quasi-static efficiency map is used where for each of the generator's electrical power output the engine's operation point with the minimum consumed fuel is selected. The power balance for SHEV is done on the electrical side, rather than on the mechanical side, which is commonly used for different hybrid vehicle topologies with a direct driveline connection between the engine and the wheels. The vehicle level controller requires electrical power which has to be satisfied and supplied by the powerpack, the battery or both combined together in different ratios, depending on the selected power management strategy.

Design Optimization Framework

The design optimization framework is depicted in [Figure 2](#), where on the left side the high-level steps of evaluating the drive cycle fuel economy are described. On the right side, more details are given for the actual nested design optimization for a particular drive cycle. The process ends with the result comparison. In the following sections each step will be described in more details.

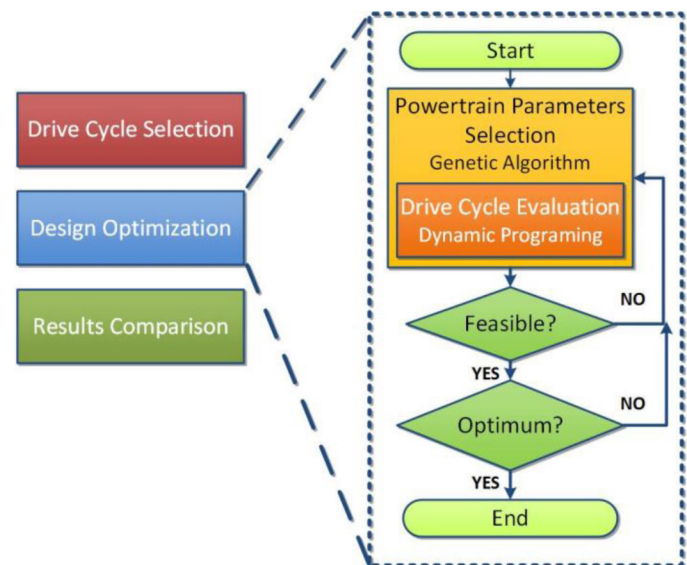


Figure 2. Design optimization framework