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# Concept Study of a 48V-Hybrid-Powertrain for L-Category Vehicles with Longitudinal Dynamic Simulation and Design of Experiments

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## Abstract

The demand for high efficiency powertrains in automotive engineering is further increasing, with hybrid powertrains being a feasible option to cope with new legislations. So far hybridization has only played a minor role for L-category vehicles. Focusing on an exemplary high-power L-category on-road vehicle, this research aims to show a new development approach, which combines longitudinal dynamic simulation (LDS) with "Design of Experiments" (DoE) in course of hybrid electric powertrain development. Furthermore, addressing the technological aspect, this paper points out how such a vehicle can benefit from 48V-hybridization of its already existing internal combustion powertrain. A fully parametric LDS model is built in Matlab/Simulink, with exchangeable powertrain components and an adaptable hybrid operation strategy. Beforehand, characterizing decisions as to focus on 48V and on parallel hybrid architecture are made. Simulative investigations in this paper focus on pure electric driving. First acceleration performance in electric mode is investigated and based on these findings further decisions regarding the powertrain are taken. However, even with additional limitations the number of possible variation parameters is still very high. With the method of "Design of Experiments" the number of simulation runs is reduced significantly by finding mathematical and statistical coherences between variation parameters and simulation results. Furthermore, this method allows to find local and global minima configurations within the variation space using software integrated solver functions (e.g., combinations of 2-speed gear ratios and E-motor speed dependent shifting points). DoE analysis findings of eDrive acceleration simulations are the basis for eDrive cycle analysis. WMTC simulations focus on average cycle efficiency, showing the possible advantages of different electric powertrain configurations for the considered vehicle.

## Introduction

This paper focuses on a methodical approach of how to efficiently dimension a hybrid powertrain for an L-category vehicle with the combination of longitudinal dynamic simulation and "Design of Experiments". After an introduction of the vehicle category and its legislation, the exemplary L-category research vehicle is presented. The proposed hybrid powertrain layout is explained and an overview of the LDS in Matlab/Simulink including its most important subsystems is given. Simulations and calculations in eMode are conducted, since pure electric driving during ICE cut-off phases is defined to be a crucial feature of the concept not only for the customer's driving experience, but also to reduce emission output [1]. With LDS results DoE models are built up and validated. DoE allows to handle and evaluate numerous different hybrid powertrain parameters and helps to understand their multidimensional interrelations on the simulation results. Two separate DoE models are created, one for the purpose of investigating pure electric acceleration performance and another one to study the vehicle transient cycle driving performance also in pure eMode.

The motivation and the goal of this research is to find an efficient approach of how to handle multifactorial problems with regard to the dimensioning of a hybrid powertrain. Furthermore, the described approach is not only intended to speed up the design process but also to detect and, thereby, not to miss optimal combinations of hybrid-system components. As the nature of hybrid systems in general is of relatively high complexity, the hypothetic hybrid system integrated into this exemplary vehicle includes a large number of characterizing parameters. In order to better assess the impact of different hybrid components and their variations on the configurations considered, but show drawbacks in terms of driving capabilities. These results indicate a tradeoff between efficiency and acceleration of the vehicle in eMode regarding gearbox layout.

It is important to note that both optimizations (acceleration and cycle) should not be considered absolute as they depend on multiple vehicle/ powertrain characteristics as well as the driving cycle. The following list gives some examples:

- Vehicle driving resistances and their composition (mass, air, roll)
- E-Motor characteristic (power, torque, speed, efficiency map)
- Battery size, type and efficiency
- Driving cycle (average speed, acceleration ramps, road gradient)
- …

## Summary & Conclusions

A new methodology of how to pre-design a new hybrid electric or pure electric powertrain for a powersport L-category vehicle is presented in this paper. The development of the hybrid system is focused on driving capabilities and efficiency, as these are decisive criteria for vehicles of that category. Pure electric driving is seen as a crucial feature of the concept, and hence first investigations in course of this research focus on pure eDrive only. Due to limited power and torque provided by the electric motor chosen for this concept, a 2-speed gear box is considered in course of the basic powertrain layout process. In order to make this development as efficient as possible, a parametric and fully changeable longitudinal dynamic simulation model of the vehicle including its powertrain is built up in Matlab/Simulink. This allows for a flexible development process, during which vehicle models and their characteristics as well as hypothetical powertrain components can be exchanged quickly.

This leads to a large number of configuration variants for the hybrid system, which come into consideration. In order to overcome this challenge and keep an overview of the numerous possible configuration variables and their relation to each other, "Design of Experiment" models in the software tool AVL CAMEO are built up. Starting with a DoE model, which investigates driving capabilities and acceleration performance, first conclusions can be made. The model is validated with actual LDS simulation results and further used to conduct optimization runs. The target functions of this optimization (vehicle acceleration and top speed) are aimed to be minimized or maximized respectively by combining EM gear ratios and shift speeds as optimally as possible. The 2-speed EM gearbox variants shows performance benefits over a single-speed variant, its advantage decreases with greater EM or hybrid power of the vehicle powertrain.

Similar investigations are conducted with cycle simulation results. In this case WMTC part 1 with a top speed of around 60kph is used for pure e-Drive analysis. The driving cycle duration in this case is ten times longer than the short acceleration ramps of the acceleration analysis. Together with the larger number of variation parameters, including battery parameters and EM type, this leads to considerable higher computational effort. In order to cope with this, a DoE model with a significantly reduced number of variations is used to optimize the vehicle's pure electric transient driving cycle performance.

The vehicle and powertrain configurations used in this paper are exemplarily used to show the methodology of combining LDS with DoE. The DoE models are validated with actual single simulation LDS results. Both the acceleration model as well as the cycle DoE show good fit and high accuracy, while reducing the computational effort significantly. The graphical user interface of AVL CAMEO including its intersection plots helps to keep an overview of the numerous variables and their interrelation to each other. The methodology and approach of this paper proves to be a useful and efficient tool for pre-designing and -dimensioning of such hybrid powertrain systems.

## Future Work

In the next steps, the method explained in this paper will be applied on hybrid driving modes in order to further specify the vehicle hybrid powertrain configuration. After defining a hybrid strategy, the vehicle will be tested on a chassis dyno test bench with the hybrid system being simulated by the test bench brake. In this phase of the research the goal will be to validate the simulative results with actual measurement devices at facilities of IVT at TU Graz in collaboration with RC-LowCap project partners.

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## Definitions & Abbreviations

**ASM** - Asynchronous Electric Motor (=IM)
**AT0-40** - Acceleration Time from 0 to 40kph
**BSFC** - Brake Specific Fuel Consumption
**BSG** - Belt-Driven Starter Generator
**CC** - Centrifugal Clutch
**conti** - Continuous
**CVT** - Continuous Variable Transmission
**DoE** - Design of Experiments
**EM** - Electric Motor
**eMode** - Electric Driving Mode
**ESS** - Energy Storage System
**FF** - Full-Factorial
**FPM** - Free Polynomial Models
**GR** - Gear Ratio
**HCU** - Hybrid Control Unit
**i1st** - Gear Ratio First EM Gear
**i2nd** - Gear Ratio Second EM Gear
**ICE** - Internal Combustion Engine
$i_{EM}$ - Gear Ratio from Electric Motor to Rear Wheel(s)
$i_{EM\_GB}$ - Gear Ratio of the Electric Motor Gearbox
$i_{final}$ - Gear Ratio of the Final Drive
**IM** - Induction Motor
$i_{sec}$ - Gear Ratio of the Secondary Drive
**LDS** - Longitudinal Dynamic Simulation
**Li-Ion** - Lithium-Ion
**OFAT** - One-Factor-at-a-Time