Optimization of Hybrid Strategies with Heuristic Algorithms to Minimize Exhaust Emissions and Fuel Consumption

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Abstract The hybrid powertrain is a promising concept to contribute to achieve future CO_2-targets. This paper describes a method to improve future automotive powertrains efficiently in real world driving conditions. Beside the optimization of the internal combustion engine and the electric components, the operating strategy of the hybrid powertrain is of particular importance to minimize the vehicles fuel consumption. A combination of start/stop operation, downspeeding, load-point shifting and pure electric driving can provide substantial fuel savings compared to conventional powertrains. However, in addition to the fuel consumption the more and more stringent future emission legislation must be taken into the account when optimizing the operating strategy. A fast light-off of the catalytic converters and a control of the converter temperatures during pure electric driving must be achieved. Therefore, numerous parameters have to be optimized simultaneously to realize the best solution for the hybrid powertrain. A numerical optimization approach was used to define the operating strategies efficiently for the mentioned goals. The results of this optimization were compared to the fuel consumption and the exhaust emissions of the conventional powertrain. The potential of a further strategy optimisation could be evaluated. Generally, it could be shown that long phases of electric driving combined with aggressive load point shifting to balance the battery's state of charge are most favorable in terms of efficiency. The phases of electric driving are additionally limited by the temperature drop of the catalysts

F2012-B02-023

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SAE-China and FISITA (eds.), *Proceedings of the FISITA 2012 World Automotive Congress*, Lecture Notes in Electrical Engineering 191,
DOI: 10.1007/978-3-642-33777-2_25,

and the lack of pollutant conversion after restart. This is a new and innovative approach to develop electrified powertrains efficiently. Finally it can be stated, that the numerical optimization method proved to be a powerful tool to support the development process of hybrid powertrains with numerous degrees of freedom.

Keywords Hybrid vehicles · Fuel consumption · Emissions · Numerical optimization · Operation strategies · Hardware in the loop

1 Introduction

The future availability of fossil fuels and growing environmental concerns have increased the pressure on automakers to develop fuel efficient vehicles with low emissions. The hybrid electric vehicle (HEV) is a possible approach to meet these demands.

Unlike conventional vehicles, a HEV has two power sources for propulsion [1]. Therefore, main challenges of hybrid powertrain development are the multiple degrees of freedom and a large diversity of powertrain architectures. Due to that fact, an optimal operating strategy is of specific importance in order to reduce the fuel consumption. However, an efficient determination of the vehicle's possible operating modes can only be achieved with a combination of numerical simulation and test bench measurements (Engine in the Loop—EiL). With this approach, accurate investigations on different electrified powertrain architectures and operating strategies in combination with an existing combustion engine are possible without the demand of hardware prototypes.

The described approach will be illustrated for a parallel hybrid powertrain. In order to find an operating strategy in the New European Driving Cycle (NEDC) with lowest fuel consumption, a self-developed algorithm was used that allows a numerical optimisation of the numerous degrees of freedom involved in the problem.

2 Investigated Powertrain Topologies

The basic conventional powertrain consists of a 6-cylinder SI engine that is coupled to an automatic transmission with a torque converter including a lock-up-clutch (Fig. 1, left picture). All upcoming investigation results are referenced to the conventional powertrain with start/stop capability.

For the hybrid powertrain the electric motor/generator (MG) is placed between the SI engine and the automatic transmission. A clutch between the SI engine and the MG provides the capability of pure electric driving. In contrast to the

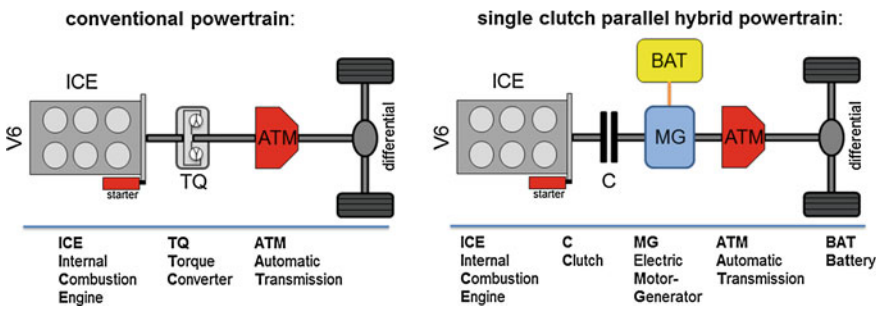


Fig. 1 Topology of the investigated powertrains

conventional powertrain, no torque converter is used because of a more efficient recuperation of brake energy and engine start-up [2].

3 Hybrid Functions: Operation Modes

Hybrid powertrains have the capability to realise start/stop, braking energy recuperation, load point shifting and electric driving strategies. A reduction of the fuel consumption and lowest exhaust emissions can only be achieved with an optimised strategy. Therefore a numerical optimisation method based on several heuristic approaches was used to attain the mentioned goals.

4 Simulation Model

The numerical simulation model is a closed loop longitudinal vehicle dynamics model including the exhaust system that was built up in the GT-Suite^{TM}-software from Gamma Technologies. The vehicle including a 6-cylinder SI engine, electric components and the mechanical components of the powertrain, was modelled in accordance to a close-to-series powertrain. To provide fast simulation times, the battery, the electric motor, the SI-engine and the automatic transmission were characterised with performance and efficiency maps. For all investigations real time capability was achieved.

The up- and downshift commands for the automatic transmission model were set in dependency of the engine speed. In order of following a given driving cycle, the driver of the vehicle is represented by a PI-controller.

In accordance to that, the purpose of providing a fast light-off of the catalytic converters and a control of the converter temperatures during pure electric driving can be achieved.

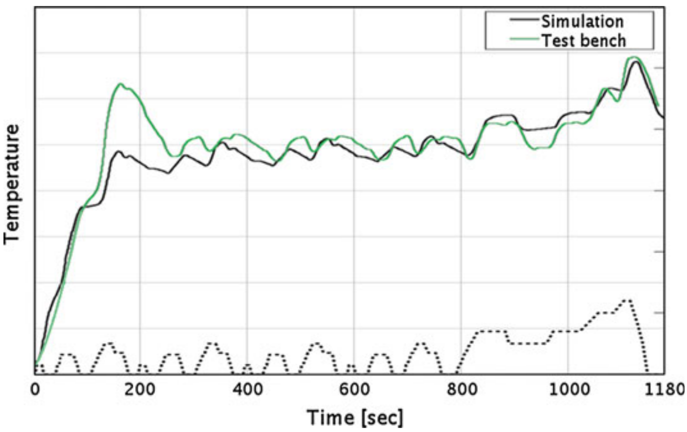


Fig. 2 Comparison of simulation and measurement

In addition to the dynamics simulation of the hybrid powertrain, a thermal model exhaust system was established and verified according to measurements from the test bed. The model consists of the thermal capacities and conductivities of the material. The enthalpy of the exhaust gas is the transferred from the engine model. Due to that, Fig. 2 shows the comparison of the temperature between simulation and measurement inside the catalytic converter in NEDC. The differences in the first time steps are because of special exhaust system heat up strategies from the ECU and exothermic reactions in the three-way catalytic converter which could not be integrated in the model. This will be done in a further step.

As already mentioned, the minimisation of the fuel consumption and exhaust emissions requires a purposeful choice of the best hybrid operation strategy for the instantaneous vehicle speed and acceleration. Therefore, a distinction of the different vehicle states in the NEDC was made, i.e. phases of constant speed, constant acceleration and deceleration and stand-still were evaluated and optimised separately (Fig. 3).

For example, downsizing and down speeding are well known effective measures in order to reduce the fuel consumption [3]. However, an appropriate choice must be made for the given powertrain [4, 5]. Previous investigations have shown potentials in order to minimise the fuel consumption by using load point shifting [6].

Therefore, a speed dependent upshift command and a pure electric driving velocity is combined with a load point shifting factor for all individual segments of the NEDC (Fig. 3) with constant vehicle speeds and constant acceleration in order to balance the battery's state of charge (SOC). With the purpose to sense and control the temperature of the catalytic converters, a parameter which coordinates the engine state was implemented. If the catalytic converter temperature reaches a defined lower limit, the internal combustion engine was started to heat up to provide exhaust enthalpy.

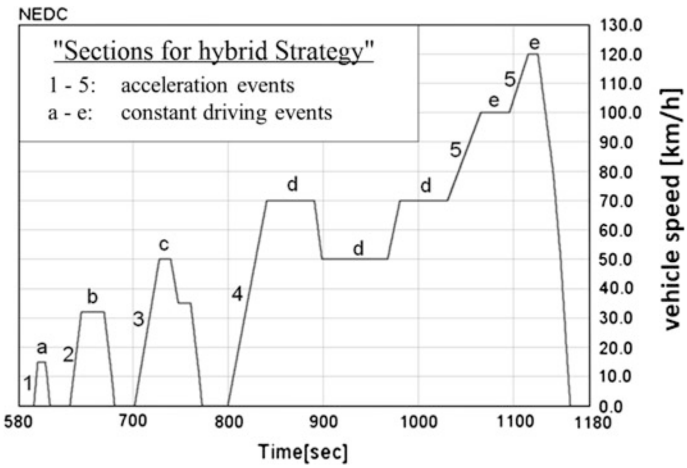


Fig. 3 NEDC-section separation

Table 1 Parameter definition

No.	Parameter
7	Variable speed dependant upshift-gear commands
10	Factor of load point shifting for all separated NEDC-segments
1	Maximum electric driving velocity

In order to find promising strategies to meet objectives a total of 18 parameters were taken to find their best combination (Table 1).

5 Optimisation Approach

The objective of the operation strategy is to minimise fuel consumption and exhaust emissions in the NEDC. To achieve the optimization of the hybrid powertrain with a large number of parameters in a reasonable time, a combination of meta-heuristic algorithms (see Fig. 4) was build up in order to handle the optimization. The advantage of this approach is that solutions will be continuously improved during the optimization process. Detailed information can be found in [7–10].

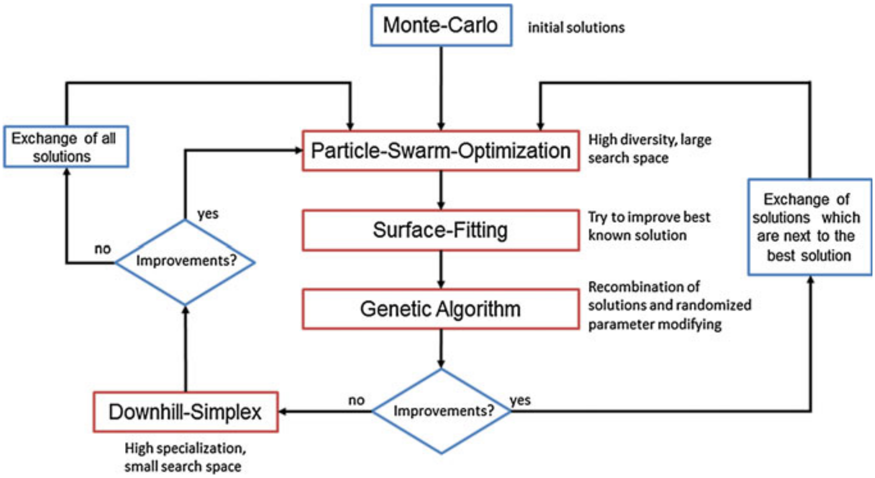
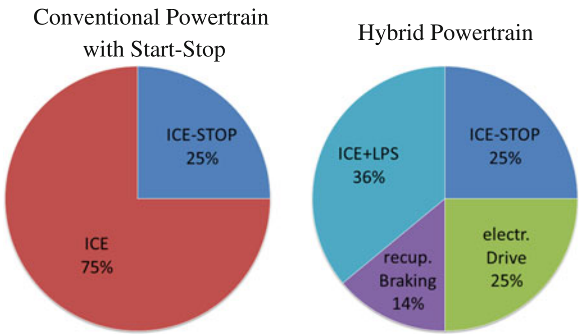


Fig. 4 Combination of meta-heuristic algorithms [13]

Fig. 5 Percentage of the operation modes in the NEDC



6 Results and Tendencies for the Operation Strategies

The best solution of parameter combination that could be found with the combined meta-heuristic algorithms was able to the reduce fuel consumption by 25.8 % compared to the conventional powertrain with start/stop capability.

In order to get an impression of impact of operating strategies, Fig. 5 shows the percentage of the different operation modes (Table 2) within the NEDC.

The left pie chart shows that the conventional powertrain with start-stop capability is propelled by the internal combustion engine for 75 % of the cycle time. The internal combustion engine is shut off during the remaining time. The resulting strategy from the optimization approach, shown in the right pie chart, pursues the objective of a fast light-off of the catalytic converters including a minimisation of the fuel consumption and combines increased engine stand-still events with pure electric driving and load point shifting.

Table 2 Operation modes

ICE:	Conventional operation of the combustion engine
ICE-STOP:	Engine-stop events
ICE + LPS:	Operating the combustion engine with load point shifting/boosting
Electric drive:	Pure electric driving
Recup. Braking:	Recuperating energy while braking

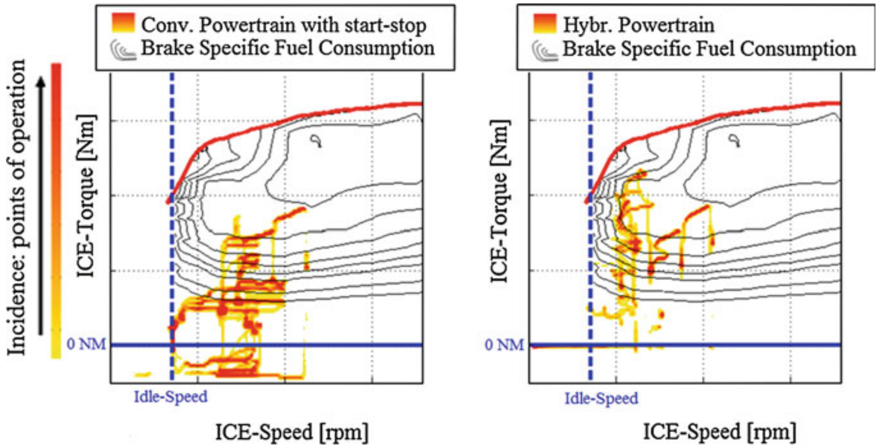


Fig. 6 Load spectrum

As shown in Fig. 5 the events of conventional engine operation are replaced by long electric driving and long engine stop events. The internal combustion engine is only used in combination with the capability of load point shifting to provide energy for pure electric driving and in order to balance the battery's state of charge.

The tendency of long phases of electric driving combined with aggressive load point shifting in order to accomplish a higher efficiency can be clearly derived from the results. Figure 6 illustrates this trend.

Due to the fact of down speeding, the optimized hybrid strategy shifts operating points with a constant optimised factor in regions with higher efficiency. It becomes obvious from Fig. 6 that the operating points are shifted to a region of high fuel efficiency. The generated energy is stored in the battery and used for pure, highly efficient electric driving.

Due to this fact, the usage of a multiple-parameter optimisation approach has shown the enhanced optimization possibilities by means of an enhanced number of parameters. There are still reveals considerable further potentials for the fuel efficiency.

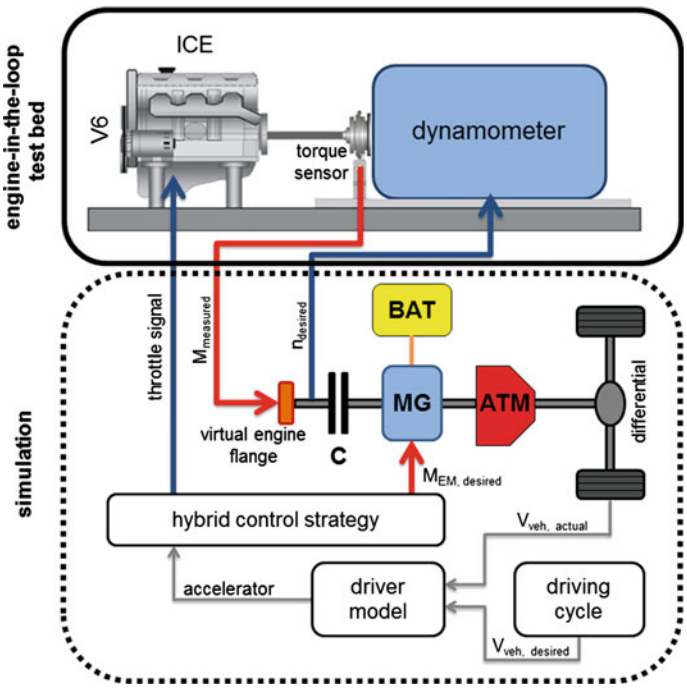


Fig. 7 Control of the engine in the loop test bed

7 Validation and Verification

For the verification and validation process, the investigated engine was operated on an Engine-in-the-Loop test bench. For this purpose, the model of the combustion engine within the simulation was replaced by measured signals from the hardware [11].

The EiL-test bench was controlled using the LABCAR-software from ETAS. The closed loop control principle, which consists of hardware and software components, is shown in Fig. 7.

On the mechanical level, an interface is defined between the crankshaft of the real combustion engine and a virtual clutch. The connection between the test bed and the simulation is done by feeding the measured torque at the flange on the test bed into the virtual engine flange. Simultaneously, the calculated speed of the virtual engine flange is transmitted to the test bed dynamometer. In order to transfer the calculated throttle signal to the engine's control unit, the model's virtual bus system has to be connected to the real CAN bus system. [12]

The conventional powertrain with and without start/stop capability and the optimised single clutch parallel hybrid powertrain strategy were verified at the EiL-test bench. Figure 8 shows a good correlation between the simulation results and the measured fuel consumption at the test bench. Dynamic and cold-start

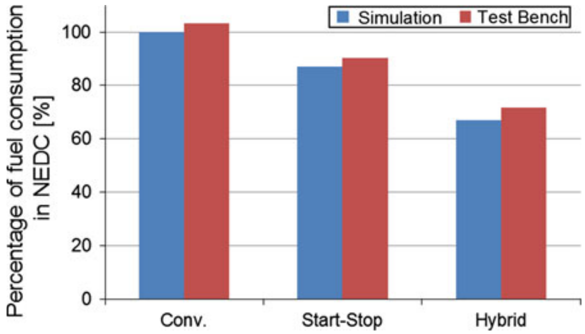


Fig. 8 Simulation vs. Test bench

effects are not considered within the stationary engine maps. Thus, slight differences between simulation and test bed results can be observed. However, the good agreement between simulation and experiment clearly shows that the numerical method is able to predict the potentials of the different strategies correctly.

8 Summary and Conclusion

The hybrid powertrain is a promising concept to contribute to the future CO_2-targets.

Besides the dimensioning of the internal combustion engine and the electric components, the operating strategy of the hybrid powertrain is of particular importance to optimise the vehicles fuel consumption. However, in addition to the fuel consumption the more and more stringent future emission legislation must be taken into the account when optimizing the operating strategy. A fast light-off of the catalytic converters and a control of the converter temperatures during pure electric driving must be achieved

A combination of start/stop operation, down speeding, load-point shifting and pure electric driving can provide substantial fuel savings compared to conventional powertrains including compliance with formalities. Due to the fact that numerous parameters have to be optimised, a numerical approach is useful to define the operating strategies efficiently.

Therefore a new and sophisticated approach with a numerical optimiser based on several heuristic methods was developed. The results of this optimization were compared to the fuel consumption of the conventional powertrain with start-stop capability. Generally, it became obvious that long phases of electric driving combined with aggressive load point shifting to balance the battery's state of charge are most favourable in terms of efficiency after reaching the light-off temperature of the catalytic converters. The strategies were verified on an Engine-in-the-Loop test bench.

In order to obtain a strategy for arbitrary driving cycles and real-life cycles, a more general formulation of the driving parameters and criteria has to be provided for optimisation what will be a future target.

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