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DEVELOPMENT AND OPTIMIZATION OF HYBRID POWERTRAINS AT THE X-IN-THE-LOOP ENGINE TESTBED

The development of hybrid powertrains is a challenging task for vehicle manufacturers. On the one hand there are requirements imposed by legislation and customers leading to different and in many cases concurrent development targets. On the other hand development engineers face a wide extent of degrees of freedom, which determine the vehicle's behavior and characteristics. An important tool to master the complexity of the development task consists in the integration of real drive units in the simulation. The TU Darmstadt has worked out a concept for this integration and is investigating the possibilities it presents for system tuning and the use of optimization methods.

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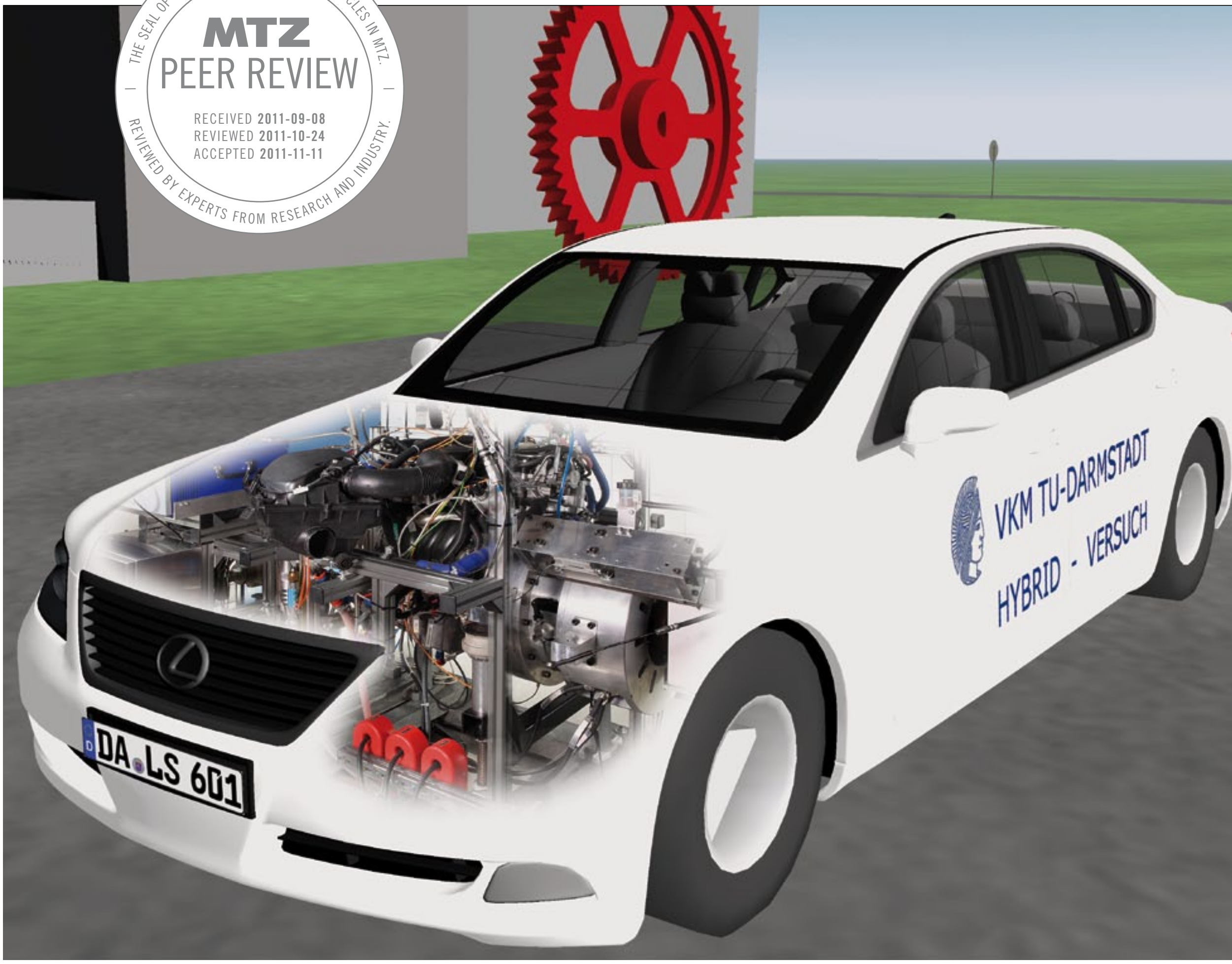


1 MOTIVATION

The targets for hybrid vehicle development are derived from the demand for high vehicle efficiency, durability and drivability as well as low pollutant emissions and vehicle costs. The scope of possibilities for system tuning ranges from the components' dimensions and adjustments to their mechanics and application to functions and parameters of the hybrid operating strategy.

The partially adverse effect of these measures on the different development targets can be illustrated by an example: In a vehicle with a power split or a parallel powertrain configuration low driving power demand can be supplied permanently by the internal combustion engine (ICE) or alternately and in different combinations by the ICE and the electric motor (EM). Using the ICE exclusively it is set to run mainly in low load points and consequently generally with low efficiency. Sharp increases in the power demand can only be met with limited dynamics and may lead to increased emissions, depending on the type of ICE. However, installing sufficiently dimensioned electric components und using them with a corresponding strategy the powertrain's response to load steps can be improved and emissions due to transient ICE operation can be reduced. These improvements in drivability and emissions are accompanied by increased costs or strain of the electric components, which may result in reduced durability. Furthermore, the high usage of electric components can result in reduced efficiency. If the necessary electric energy has to be provided by charging the battery with the ICE, additional effort will be generated due to losses in the EM and the battery. To which extend this additional effort can be compensated by a higher ICE efficiency (load point shifting) depends strongly on the driving profile, which is mainly influenced by the driver input.

The interaction between the different possibilities of intervention and the development targets and the thereby ensuing complexity of the system tuning is aggravated in the example given before when pure electric driving is permitted. More electric power is needed and the problems related with turning off the ICE – the cooling down of the exhaust gas system and elevated input of oxygen to a three-way catalytic converter – require adequate measures [1]. These concerns and additionally drivability requirements have to be met in the design and application of all powertrain systems.

Due to the complexity of the development task the possibilities of purely analytical approaches are limited. Driving simulations present the flexibility needed to test numerous variants. However, in the advanced phases of the development process one cannot rely on pure simulation, as current simulation model quality does not allow an accurate evaluation of the quality of a powertrain configuration, especially when considering the development targets emissions and drivability. It is recommended that, for the advanced development of drive units as well as the function development and application of the hybrid operating strategy, the drive units are set up on an engine testbed and integrated into an in-the-loop vehicle simulation (XiL), which operates in realtime. This integration of the real components into the vehicle simulation should be applicable as easily as possible and usable in current testbed systems.

2 INTEGRATION OF REAL DRIVE UNITS INTO THE VEHICLE SIMULATION

Generally, there are two ways to combine simulation and test on an engine testbed. On the one hand, pure simulation can be used to create load profiles and provide these profiles as input for the testbed controllers, on the other hand simulations can be set up to run in realtime at a testbed. The first method implies that the simulated drive unit's response to the input variable and its dynamics correspond to the real system with its current application, for example a ICE. The testbed dynamometer can set the speed according to a calculated speed profile and the load can be applied in an open loop control, for example setting the load input for an ICE. If no precautions like a precontrol logic are taken, a closed loop torque control to set the engine load leads to deviations between the actual and the set load points, as the two controllers for speed and torque are applied to control systems with different response times [2].

As the model accuracy necessary for the open loop control of a ICE cannot be obtained with acceptable effort, and possible changes to the unit under test should be investigated as well, the Institute for Internal Combustion Engines and Powertrain Systems, together with AVL, worked out a concept to upgrade existing engine testbeds and to equip them with a realtime vehicle simulation [3, 4]. The idea to use vehicle simulation at a testbed had been realized before, as testbed automation systems facilitate running certification cycles with a vehicle simulation. Yet the need to test hybrid powertrains brings about new requirements, especially due to the start-stop operation and the demand for high flexibility of the simulation models and flexibly customizable test scenarios with a simulated environment. Furthermore, the realtime simulation should be able to interact with enhanced units under test and their control units [5].

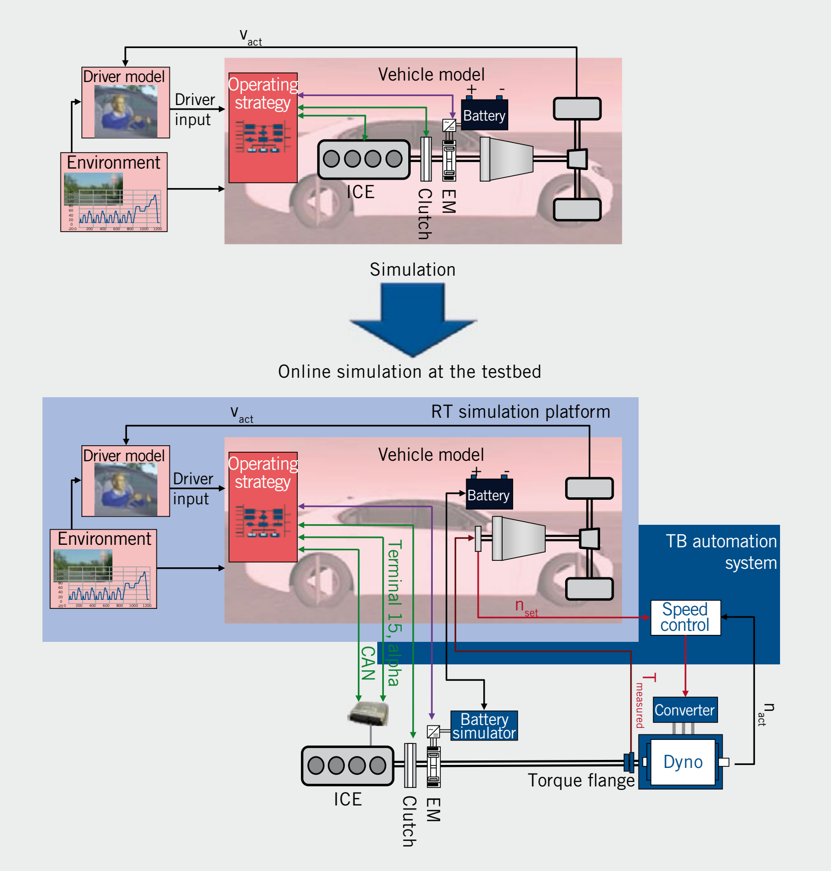
➊ presents the integration of a vehicle simulation at the XiL engine testbed at the Institute for Internal Combustion Engines and Powertrain Systems. The unit under test is a ICE to which an electric motor can be mounted, connected to the ICE by a clutch with low stiffness. The EM is powered by a battery simulator, a DC voltage source with parametrizable internal resistance, and a controller, developed at the institute, which allows varying the torque and power regime. Hence the testbed set-up enables virtual vehicle tests with a real ICE (engine in-the-loop – EiL) or a real EM as well as the integration of a P2-hybrid powerpack into a vehicle simulation.

The simulation runs on a realtime system, which is connected to the testbed automation system via CAN. The operating strategy (located on a Hybrid Control Unit – HCU), which is implemented as a part of the corresponding vehicle model, provides the input for the drive unit installed on the testbed. Partly these signals are passed on via additional signal lines, partly they are led through the automation system, thereby facilitating the implementation of security functions.

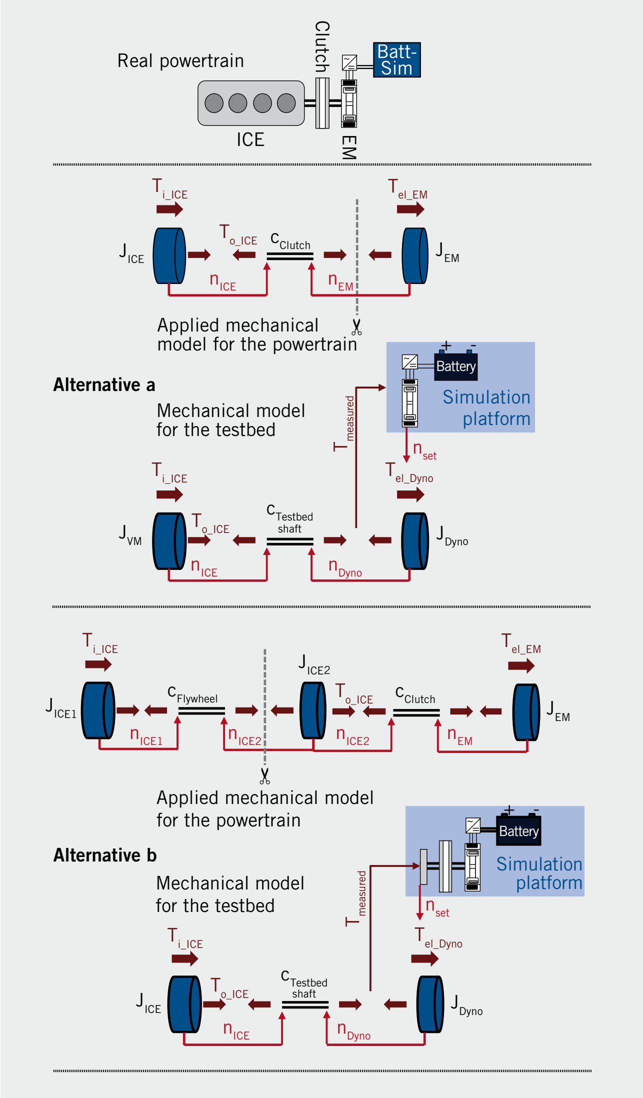
The installed powertrain components are mechanically coupled to the virtual part of the powertrain via the testbed shaft and the dynamometer (Dyno). The mechanical output of the unit under test has to be submitted at any time to the torque and speed that are present in a real vehicle with the current output torque. Due to technical principles deviations occur at an engine testbed: From the measurement of one quantity (torque or speed) the other quantity has to be calculated in the vehicle model and has to be regulated at the testbed with the dyno control. Setting this second quantity is delayed due to dead times in signal transmission and limitations in the dynamics of the testbed control. Ways to reduce these delays interfere with the attempt to keep the testbed set-up flexible and simple and facilitate the integration of the XiL method to existing testbeds. At the XiL testbed of the Institute for Internal Combustion Engines and Powertrain Systems the set values for the testbed are transmitted via the CAN connection, whereas the measurements for speed and torque can be sent directly to the realtime system.

The limitations of the dynamics of the testbed control are results of the mechanical configuration of the testbed. The unit under test and the dyno form a system susceptible to oscillations, which are mainly excited by the pulsating torque output of an ICE. To avoid constant operation in resonance the eigenfrequency is placed below the engine's idle speed, for a four-cylinder engine in a range from 10 to 15 Hz. Hence, the input to the dyno control is delayed when showing up on the unit under test, and torque or speed signals of the unit under test cannot directly be used as input signals to the dyno control. Compensatory approaches like a dyno control on an estimated unit under test torque require low signal dead times and are therefore difficult to reconcile with the target of a simple and flexible coupling of the realtime system to the testbed. For these reasons the concept presented here opts for a speed controlled dyno and for measuring the torque with a torque flange at the testbed shaft and providing it to the vehicle simulation. Accordingly, the interface to the testbed in the simulated powertrain has to be an inertia at the output side of the corresponding drive unit. The speed of this inertia has to be transmitted to the testbed. The drive unit installed on the testbed and the testbed shaft replace the corresponding drive unit and the nearby shaft element in the simulation model. The deviations to a real powertrain and which quantities can be investigated accurately in XiL tests will be evaluated in the following.

The reference is a testbed set-up with a real ICE and a real EM, only coupled with each other by a clutch. With this set-up one can represent the charging of the battery in serial hybrids. The battery is represented by the battery simulator and the corresponding battery model. In the following this testbed set-up is the reference for the EiL testbed. ② presents the mechanical model of the reference – the real powertrain – and how it is implemented in the EiL concept. In the alternative a the input side of the electric motor is the interface between the simulated and the real components. Consequently, the testbed shaft replaces the real clutch and its



① Implementation of the vehicle simulation at the XiL engine testbed at the Institute for Internal Combustion Engines and Powertrain Systems

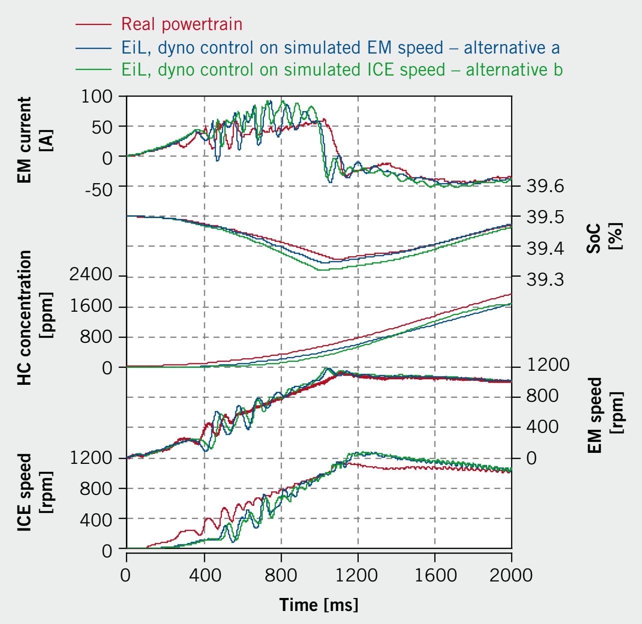


❷ Possible interfaces between the simulation and the testbed for the implementation of EiL in the contemplated example

mechanical behavior resembling the dynamics with different damping. If, however, the inertia of the ICE is used as the interface between simulation and real component (alternative b), an additional inertia for the speed calculation has to be added to the system, which changes the vibration characteristics of the mechanical system.

For the comparison of these two alternatives the EM drags the ICE to 1000 rpm and is afterwards used as a generator to load the battery. Representing this kind of engine start with an EiL set-up is challenging because of the unsteady ICE torque exciting resonance vibrations in the critical speed range. The specific application of the ICE for this testrun enables the injection for an engine speed higher than 900 rpm. The torque demand for the ICE is 50 Nm. Prior to this, it was stopped in a defined manner, so that there is residual gas in its exhaust gas system.

❸ shows deviations in the speed and current curves, which can be related to the differences in the mechanical set-ups and to the different damping values and to a higher total inertia respectively.

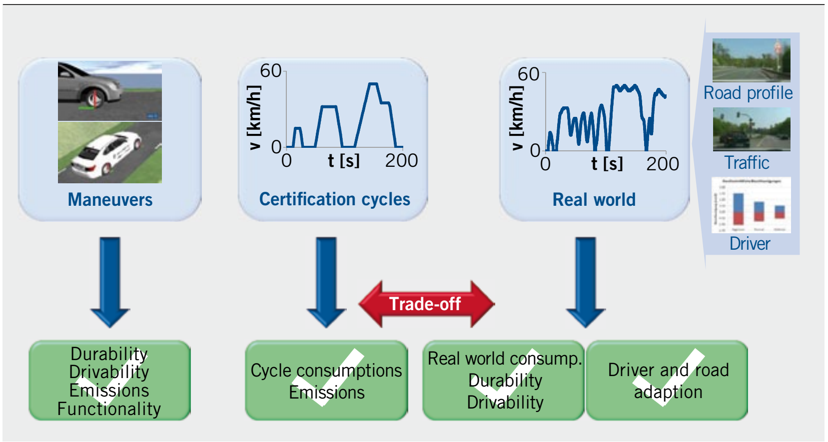


❸ Comparison of the engine start for real powertrain and EiL simulation

Besides, the deviations can be explained by the delayed setting of the speed values on the dyno. Above all the speed overshoot is evident. Consequently, for a short time the real ICE converts more power than calculated in the corresponding real time simulation, as this calculation is based on the set speed rather than the actual speed. However, in relation to the energy conversion in an average engine runtime these deviations as well as the differences in the power demand for the engine start are small (< 1 kJ) and negligible. In the emission measurements one cannot identify an effect provoked by the different engine start-ups. So one can conclude that, if the development targets energy conversion and emissions are considered, an analysis on an XiL testbed with both presented interfaces to the simulation is feasible. Nevertheless, the differences in the speed curves between the completely real components and the EiL set-up postulate that for a drivability examination or detailed power contemplation it is necessary to install the adjacent components on the testbed or to use a highly dynamic testbed concept, as described in [2, 6].

3 SIMULATION ENVIRONMENT AND TEST SCENARIOS

It is necessary for the simulation environment for XiL tests to run in realtime and be configurable flexibly with powertrain models and hardware I/Os. Further requirements result from the test scenarios. Typically, powertrain systems are tested with speed profiles for longitudinal dynamics, like certification cycles. Furthermore, the functionality of the complex interaction between the operating strategy and the real drive units should be tested and applications for the corresponding control units and the strategy should be found. Therefore it is necessary to be able to flexibly set realistic as well as extreme input values to the vehicle. Moreover, the operating strategy should be fed with the same input signals as in a real vehicle. Hence the simulation environment must be able to calculate in three dimensions so that maneuvers as electric break-

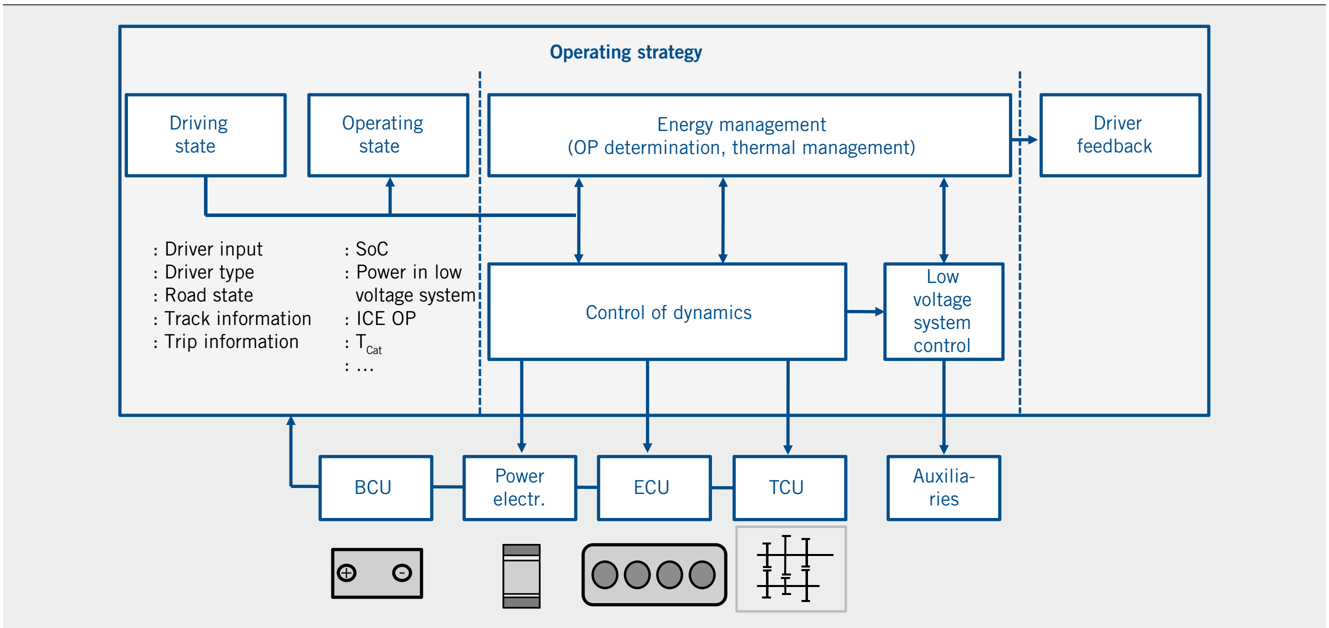


❹ Overview over tests scenarios and development targets

ing during cornering are represented correctly. For the testbed presented here the test environment AVL InMotion powered by IPG CarMaker was chosen. It meets the requirements mentioned before and can be used consistently for pure simulation as well as for simulation at powertrain or chassis dynamometer testbeds. With this environment a set of testruns, which represent real vehicle tests on reference tracks in and around Darmstadt, were created, taking into account the traffic obstacles and giving the opportunity to choose between different types of drivers [2].

With a simulation environment of that kind it is possible to address not only cycle results, but also realistic testrun results as development targets. One can also test operating strategy functions like a driver or road adaption and quantify their effect with measurements at the drive unit, ❹. Cycle tests can be used primarily for the first functionality tests and the determination of global strategy parameters, which refer to the runtime of the drive units and the power demand for them. For these tests it is sensible to use an EiL testbed set-up, mainly in order to record the emissions correctly. The application of the dynamic interaction between the different drive units can be realized most efficiently with specific maneuvers which represent a desired driving situation. A testbed set-up with several real drive units increases the quality of the test results. In order to be able to facilitate parallel development for the different development tasks it is proposed to structure the operating strategy modularly and divide it mainly into a global (Energy management) and a dynamic part (Control of dynamics) [7], ❺.

❻ presents a successful functionality test for the P2 powertrain with the powerpack testbed set-up on the TU Darmstadt reference city cycle. The ICE is started by closing the clutch when the strategy identifies a high power demand. In the next steps of the development the interaction of the different drive units can be improved using specific maneuvers in order to reduce the drop of the powerpack output torque at the engine start.



❺ Structure for an hybrid operating strategy

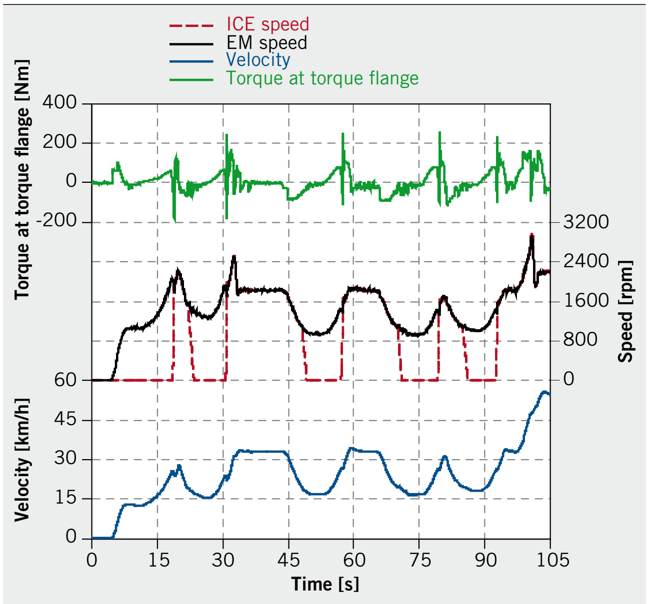
4 APPLICATION SCENARIOS

Problems like the not optimized start of the ICE in hybrid vehicle operation reveal the potential of the XiL concept, as adaptions to the drive unit can be tested together with the operating strategy in an early phase of the development process. In addition to the optimization of the operation in quasi-static load points like the application of an Atkinson cycle [8], one adjusts the start-stop application of the engine, as shown for a power split powertrain in the following. In ❼ the two different start applications are presented, one focusing on high comfort (hybrid start initiated by the vehicle system), the other one focusing on fast torque build-up (driver-initiated hybrid start) [9]. In the upper part of ⑦ the operating strategy initiates a comfort orientated engine start because of a low battery SoC. By evacuating the intake manifold, enabling the injection at high engine speed and retarding the ignition angle, the torque build-up is smoothed and therefore has little influence on the vehicle speed. In the lower part of ⑦ the operating strategy starts up the engine as fast as possible because of a driver input demanding high power. Injection is enabled at 600 rpm, the throttle is opened the ignition angle is advanced. Consequently, the first combustion cycles present high peak pressures and the engine can contribute immediately to the vehicle acceleration. However, these settings provoke higher vibrations in the engine mounts (a_z). Such tasks directed at the tuning between operating strategy and engine application can be realized at the XiL testbed even before the engine control unit (ECU) is equipped with an adapted interface, due to the use of the standardized CAN calibration protocol (CCP) for the communication between the realtime system and the control unit [10]. Alternatively, a rapid control prototyping to bypass the ECU can be used or the communication can be realized with the protocol ilinkRT in combination with an ETK control unit [11].

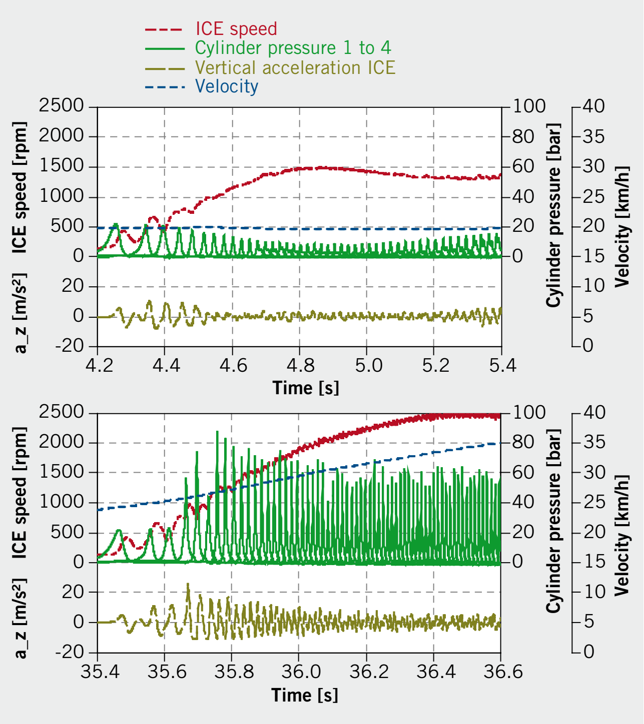
As mentioned at the beginning, an analytical approach towards parametrizing the global energy management of an operating strategy is difficult because of the complex correlations. The algorithms applied on control units apt for vehicle use are heuristic, which implies that different thresholds have to be parametrized in an application process [12]. As EiL or XiL testbeds are tools which present the influence of parameters on the development targets (consumption, emissions and durability) in a reproducible way, their availability facilitates the use of optimization methods for parameter determination. Direct optimization, i.e. the control of the testbed by an optimization algorithm, is very costly and time-consuming due to the simulation in realtime. Therefore it is proposed to apply a model based optimization with previous design of experiment (DoE), ❽, [13]. [7] presents a basic example, in which strategy parameters are optimized. The target is the weighted sum of measured fuel consumption, measured emissions and the battery stress based on a damage model. To avoid information losses due to the combination of different targets, a multi-criteria optimization algorithm can be used. The result of such an optimization is the pareto set, a set of optimal configurations [14]. ❾ shows such a pareto set, which is obtained from parameter variations for a driving simulation. Knowing this pareto set makes it possible to implement an adaptation into the operating strategy that activates optimal parameter configurations depending on the driving situation.

5 SUMMARY

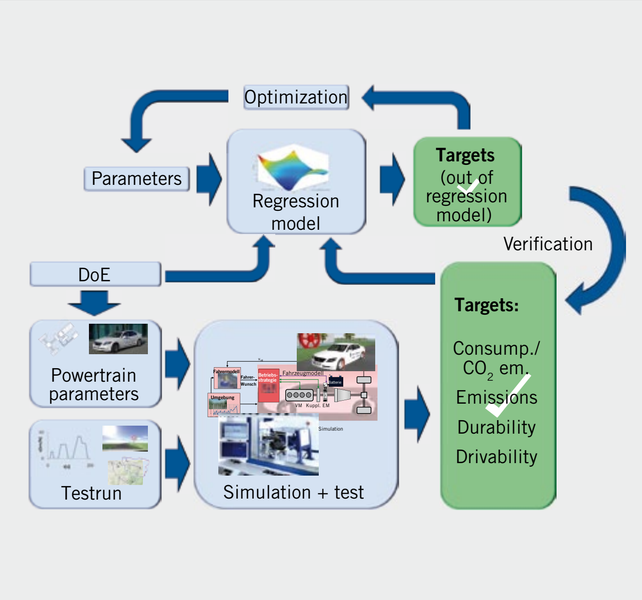
The concepts presented in this paper are aimed at the holistic optimization of the powertrain in a wide range of the development process. The flexible EiL and XiL methods with scalable hardware integration support the development in the early concept-orien-



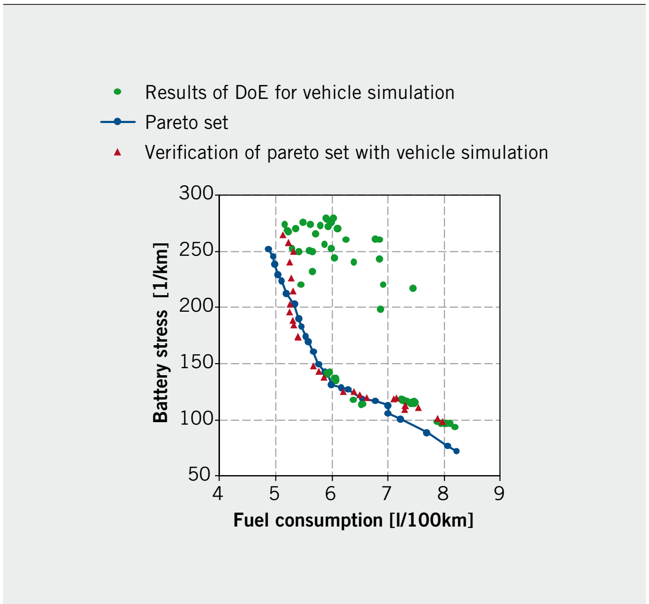
❻ XiL simulation with real combustion engine (ICE) and electric motor (EM) on the first part of the TU Darmstadt city cycle



❼ Application of different engine start types in a power split powertrain; hybrid start initiated by the vehicle system (top), driver-initiated hybrid start (bottom)



⑧ Scheme of the process of a model-based simulation at the XiL engine testbed



⑨ Pareto set as result of a multi-criteria optimization of parameters in a simulation model of a power-split hybrid

tated phases with reliable consumption and emission measurements using a real ICE and a real exhaust gas system, in later phases with tests of prototypes of drive units and in the integration phases with testruns for the control unit application and durability tests of powerpacks with realistic load profiles. The fact that the testing environment at the testbed is conditionable offers advantages, especially regarding the development and application of functions: reproducibility and the possibility of automation. The automation reduces development time and costs and, in combination with the presented approach of a systematic optimization of control unit parameters, secures high powertrain quality while mastering the high number of variants. The high comparability of the in-the-loop method facilitates the validation of the optimization results in various real-world scenarios with alternating constraints, given the complex interaction of operating strategy, combustion engine, electric motor and battery.

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