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# IMPLEMENTATION OF A VEHICLE-IN-THE-LOOP DEVELOPMENT AND VALIDATION PLATFORM

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ABSTRACT - Due to the increasing complexity of modern vehicle concepts new methods to integrate simulation and test on each level of the validation chain are required. Especially for the development of advanced driver assistant systems with focus on safety and energy efficiency the interaction between the unit under test, the driver and the environment like traffic, road topology, etc. are very important and must be considered in detail.
In different domains there are existing established methods. Influences of human-machine-interfaces are analysed e.g. using very detailed driving simulators. The behaviour of control units can be tested in interaction with the vehicle without real vehicle components on a hardware-in-the-loop (HiL) simulator. Calibration of powertrain components like transmissions can be done automatically on a roller test bench.
Bringing together the advantages of domain-specific development and validation environments, the IPEK – Institute of Product Engineering has implemented a Vehicle-in-the-loop platform based on its X-in-the-loop approach. The open architecture to integrate different simulation models and real components, the usage of established tools and methods and the integration in a development process to realize new possibilities for frontloading are the main aspects of the system of objectives for such a platform.
In comparison with other concepts, this platform is based on a common hardware-in-the-loop-system with extended I/O-communication to the vehicle and optional to the test bench. The application is done in C and Matlab/Simulink. So an exchange of simulation models, test cases, etc. is possible; e.g. the same test cases using on a HiL-simulator for control unit testing can be used on the vehicle-in-the-loop platform. Furthermore different integration levels of the driver and the environment are possible. E.g. a real driver in the real vehicle, a real driver in a driving simulator (connected to the real vehicle on the test bench) or a virtual driver model can be applied. Application area of the Vehicle-in-the-loop-platform can be the roller test bench or a proving ground.
This allows doing highly reproducible and automated tests with the whole vehicle in the loop considering the influences of different driver types and different environmental situations. The advantages of the Vehicle-in-the-loop-platform are demonstrated in this paper with a concrete application example.

## TECHNICAL PAPER - INTRODUCTION AND MOTIVATION

The development and validation of modern vehicle concepts require a new operation system which means new, innovative and cross-linked development methods (1, F2010-B-084). Developing future powertrain systems and vehicle concepts against the background of decreasing raw material reserves, new legislations and high claims for NVH are a big challenge for the automotive industry in the future. Thus the optimization of such a complex system is characterized by different target functions in different areas of conflict. The first area of conflict is

the system of objectives for the product. Aspects like NVH and driveability, abrasion and durability, energy efficiency, $CO_2$-reduction, costs and safety must be considered at the same time. The second one is the area of conflict for the operation system. There are many established tools and methods for application, simulation, optimization, testing and rating available which are only particulate cross-linked. Further new advanced systems engineering approaches are required to consider the three complex interacting systems driver, vehicle and environment (1). The driver and the environment are very important influences for future operating and driving strategies.
To meet this challenge the X-in-the-loop-framework for powertrain systems was developed at IPEK – Institute of Product Engineering. This approach is an extension of the approach for the electronics development (2). One layer of this framework is the Vehicle-in-the-loop-layer which is presented in this paper in detail.

## SYSTEM OF OBJECTIVES FOR A NEW VALIDATION FRAMEWORK

To realize an efficient and sustainable application of such a new validation framework it is very important to define at first the system of objectives.
The application of a validation framework is only efficient if it is integrated in a development process. Multi-domain process models like the V-model for the development of mechatronic systems and domain-specific development processes must be considered. This is possible with the Integrated Product Development Model (iPeM) which is described in (1). Further the architecture of such a framework must be very flexible and extensible. Ideally there exists one platform for online (real) and offline (virtual) tests. This allows a holistic interchange of models, test runs or test cases and routines for automation and analysis from elemental analysis e.g. of friction materials to analysis of the complete vehicle. For this test runs and test cases must be defined standardized (4)
A complex unit under test e.g. a complex vehicle causes a more complex validation framework. That’s why there is the need for methods that support the engineer in using and configuring such a framework. IPEK – Institute of Product Engineering provides for this a configuration process based on SysML, SPALTEN and the Contact and Channel Model (C&CM). Details for this will be discussed in (3).

## THE IPEK X-IN-LOOP-FRAMEWORK FOR POWERTRAIN SYSTEMS

The IPEK X-in-the-loop-Framework represents a holistic and integrated development and validation framework for powertrain systems. The “X” is the substitution for the Unit Under Test (UUT). In addition to the established Hardware-in-the-loop (5) approach the UUT can be a real prototype (starting from elemental analysis e.g. of friction materials up to the complete vehicle) or a virtual prototype (6). This causes different layers in the XiL-Framework: the element-in-the-loop-layer, the subsystem-, the system and the vehicle-in-the-loop-layer (seen in Figure 1).
On each layer the rest vehicle is simulated and always connected to the driver and the environment with the goal to have loads on the UUT which are comparable to the reality. For the driver, the environment and the rest vehicle simulation there exist different levels which have to be chosen in context of the application and development task. In the XiL-Framework it is possible to drive closed-loop tests on each layer. So it is always possible to analyse influences of the driver behaviour and the environment. These aspects are very important for the development of future vehicle concepts, e.g. for the development of driving- and operating strategies, safety systems and powertrain calibration.

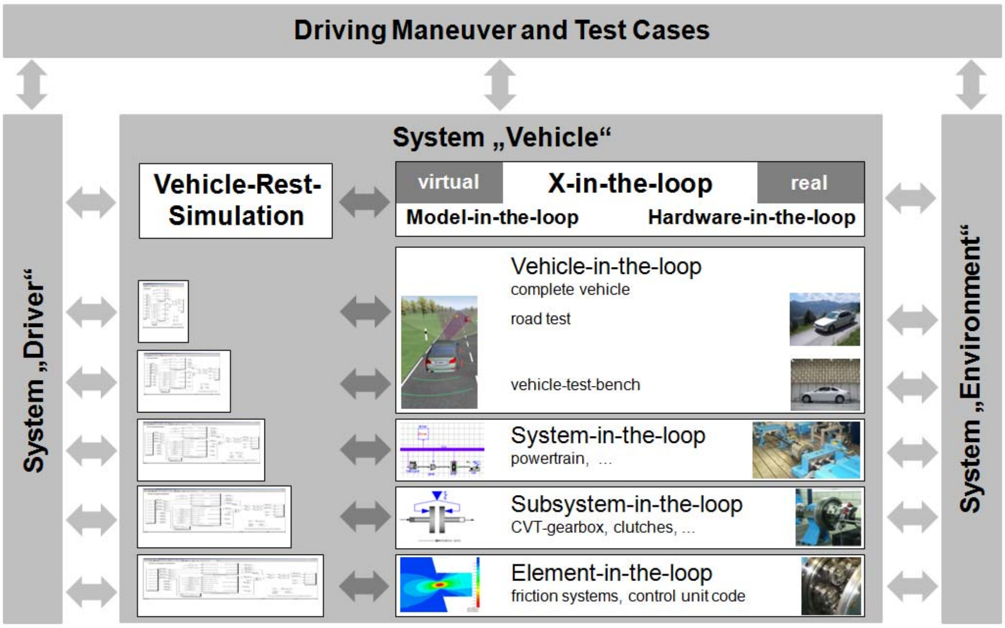


Figure 1: IPEK X-in-the-loop Framework for powertrain systems

<u>The Soft- and Hardware Architecture</u>

Based on the described theoretical approach the system of objectives must be detailed more and more. For this in the next step the soft- and hardware architecture is defined. The main components are the interface to the user (GUI), the interfaces to other soft- and hardware and a model library for the driver, the environment and the rest vehicle simulation. To achieve a high degree of customer and user acceptance, the XiL-Simulation platform shall be based on established tools. Here AVL InMotion powered by IPG CarMaker was chosen for the implementation based on an extensive benchmark. IPG CarMaker represents a development platform for control unit and control unit code and model testing. These tests can be operated online on accordant HiL-simulators or offline on a conventional office PC. AVL InMotion represents the interaction of IPG CarMaker with a test bench.

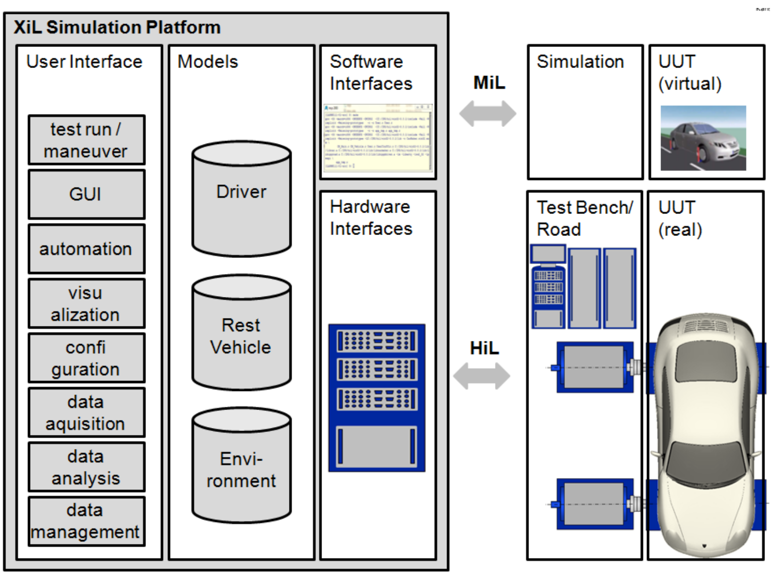


Figure 2: Soft- and Hardware-Architecture for the XiL-Framework

Development Process Integration

Hence the XiL-Framework is a manifold and complex environment. As described above a process to configure and specify such a framework is necessary (3). This process and the support for the application must be considered in the development process for a product. The iPeM as described in (1) represents the base for this. Using the established V-Model a pattern for the iPeM as a reference model was defined and is shown in Figure 3.
In addition to the V-Model the validation in very early stages of the product development is possible. Here, aspects like electromagnetic compatibility or efficiency can be analysed (concept validation, shown in Figure 3, symbols 61-64). Validation is the central activity in the product development (1). That's why it is very important to consider this activity in project planning to reduce time and costs. This is not explicit provided by the V-Model.

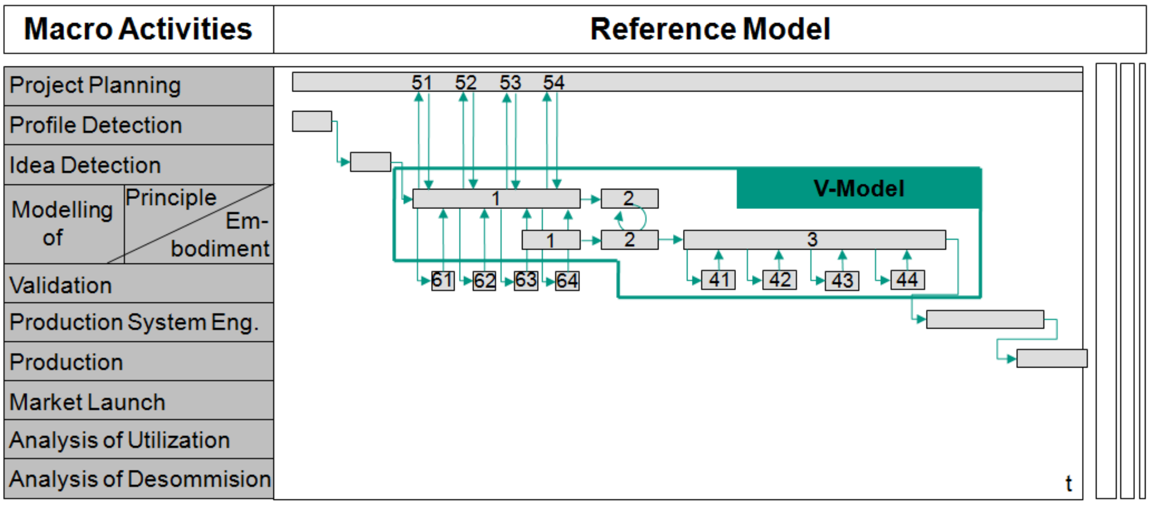


Figure 3: process pattern for the application and specification of the XiL-Framework as iPeM reference model

REALIZATION OF THE VEHICLE-IN-THE-LOOP-LAYER

In the following the XiL approach is made clear using the example of Vehicle-in-the-loop. On this level the entire vehicle is the UUT. Especially the integration of the vehicle on the roller test bench and the combination with a real driver in a driving simulator shall be explained. Everything is modular. So the real vehicle can be replaced by a vehicle model and reverse. Switching between model- and hardware-in-the-loop is very easy and is implemented in the graphical user interface (GUI) of the XiL-Simulation platform. The same applies to the driver model and the real driver in the vehicle or in the driving simulator.

The real vehicle as unit under test

In addition to the open-loop-manoeuvre on a conventional roller test bench with the vehicle-in-the-loop concept it is possible to drive closed-loop-manoeuvres. This requires an integration of the real vehicle with the hardware-in-the-loop system (XiL-Simulation platform). To move the vehicle in the virtual environment the wheel speed or vehicle speed is essential. These are provided by the Vehicle CAN or the roller test bench data acquisition. The operation mode of the roller test bench is road load simulation parameterized with the coast down curve of the real vehicle. Using an analogue output channel it is possible to

control the force of the bench in terms of the road gradient based on the topology of the virtual road. With this the interface between the powertrain of the real vehicle and the virtual environment is specified. For the interaction of a driver model respectively a driving simulator with the real vehicle an interface to the acceleration, clutch, brake pedal and the shifting lever is required. For the presented application example in the last chapter an interface to the acceleration pedal was realized by transferring the acceleration pedal signal of the driver to the electric acceleration pedal of the vehicle using the voltage-pedal travel-map
This model which substitutes the virtual powertrain in the CarMaker model library is realized with Matlab/Simulink in combination with C.
As described before an operable user interface is necessary for the application. The user doesn't want to work on the model level but with the common GUI. The choice between real powertrain (real vehicle as UUT on the roller test bench) and virtual powertrain can be made in the Vehicle Data Set GUI of CarMaker (shown in Figure 4)

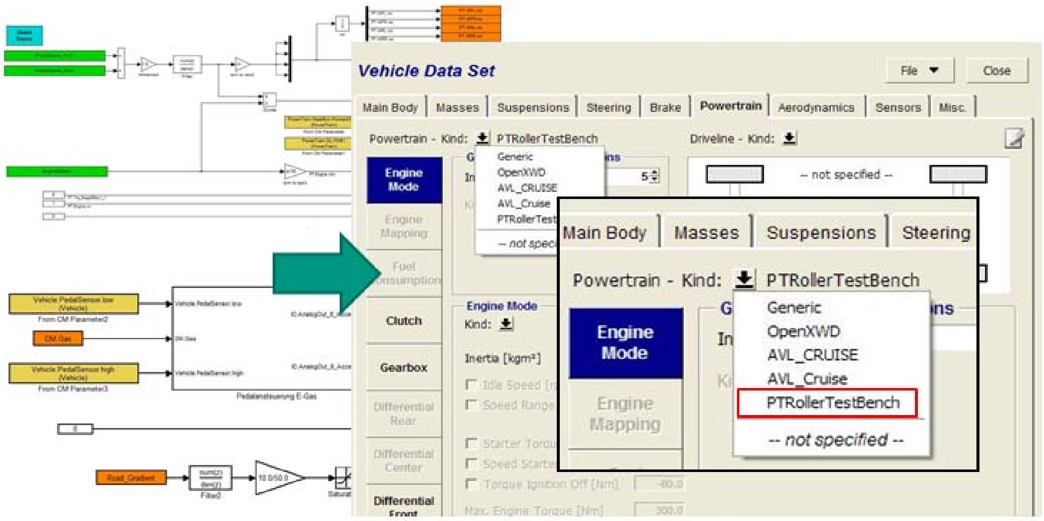


Figure 4: model level and GUI for the powertrain substitution

## Integration of a real Driver using a Driving Simulator

In the chapter above it was pointed out that it is now possible to drive closed-loop manoeuvres on a roller test bench using the real driver or a virtual driver in combination with a virtual environment. In some special cases it is necessary to have a real driver in a driving simulator in combination with a test bench. E.g. on the system-in-the-loop layer with a powertrain test bench it is possible to drive the powertrain with a real driver in a simulator without having a prototype of a vehicle. Also on a roller test bench this configuration can be necessary. Analysing the driver behaviour in terms of driver guidance a driving simulator can be a very powerful tool. New concepts for driver guidance can be integrated easily by measuring the real consumption or the real behaviour of the traction battery in case of a (hybrid) electric vehicle of the real vehicle on the roller test bench.
For the integration of a driving simulator the communication model was realized in Matlab/Simulink and C, too. Here, enable logics, component maps, etc. are modelled. Also this model was implemented in the CarMaker-GUI (Figure 5) using a combination of virtual driver and real driver (driving simulator). The advantage of this combination is that the sub function clutching or shifting can be executed by the virtual driver, braking, accelerating and steering is executed by the real driver in the simulator.

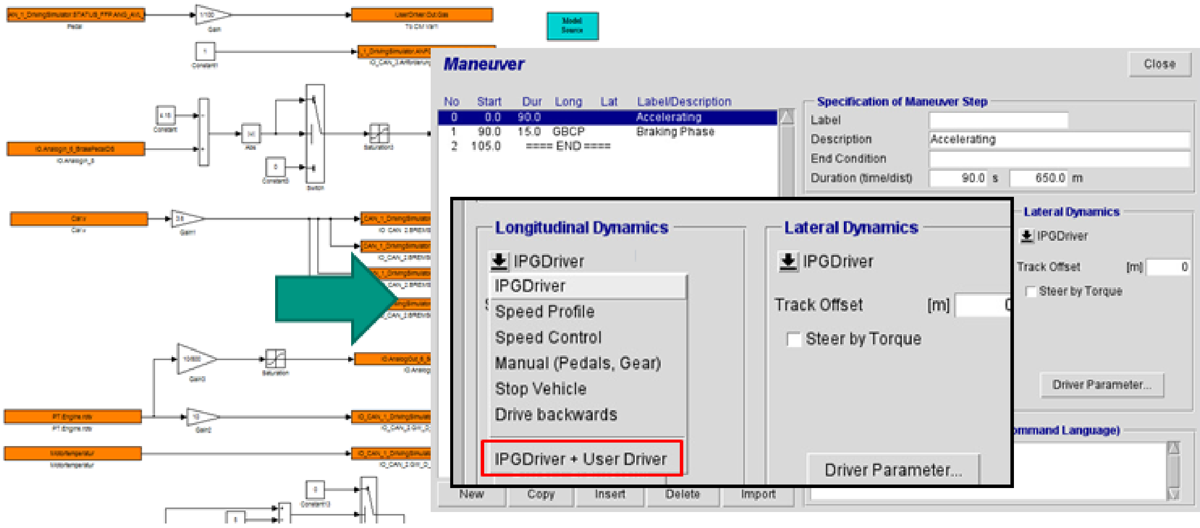


Figure 5: model level and GUI for the driving simulator

## Application fields

With this highly integrated framework many new applications are possible especially on test benches. Road test can be reduced to save time and costs. Some possibilities are listed here and one concrete example is discussed in the next chapter:

- environment simulation (closed-loop manoeuver on the roller test bench, reproducible test in virtual traffic situation, consideration of influences like wind, rolling resistance or weight reduction based on fuel consumption, potential analysis of new sensor concepts to detect the environment, etc.)
- driver simulation (detailed driver models like the IPG driver in combination with real UUTs, special controllers like force controller in speed regulation of the test bench, cycle driver, real driver in a driving simulator, etc.)
- automated model updating and system calibration e.g. for customer cycles

## APPLICATION EXAMPLE: ENERGY EFFICIENT DRIVING STRATEGY FOR HYBRID ELECTRIC VEHICLES (HEV)

Hybrid electric vehicles (HEV) are complex mechatronic systems with complex operation strategies. Many functions in terms of efficiency and comfort are realized by the hybrid control unit. An important aspect is the influence of the driver to this operation strategies the so called driving strategy. Especially in scenarios like Stop-and-Go, etc. it is possible to reduce the consumption by an intelligent driving strategy.

## Application Task

The influence of an intelligent driving strategy in terms of the consumption of a power split HEV as demonstrator on a flat road shall be analysed. The reference scenario is a stop-and-go traffic situation on the autobahn. In the first step the real traffic situation must be measured an applied to the vehicle-in-the-loop test bench using the developed IPEK traffic synchronizer. In the second step a real driver drives on the roller test bench the real vehicle in the measured

traffic situation several times. After this the potential of the driver knowledge about the situation shall be analysed (both configurations seen in Figure 6). In the last step a controller shall be applied to drive the vehicle automatically like a well-trained driver.
The goal is to drive the vehicle electrical as much as possible. Nonessential starting of the internal combustion engine (causes by a wrong estimation of the acceleration and deceleration of the target vehicle in front by the real driver) shall be reduced. On the autobahn after this traffic situation an efficient loading of the battery is possible.

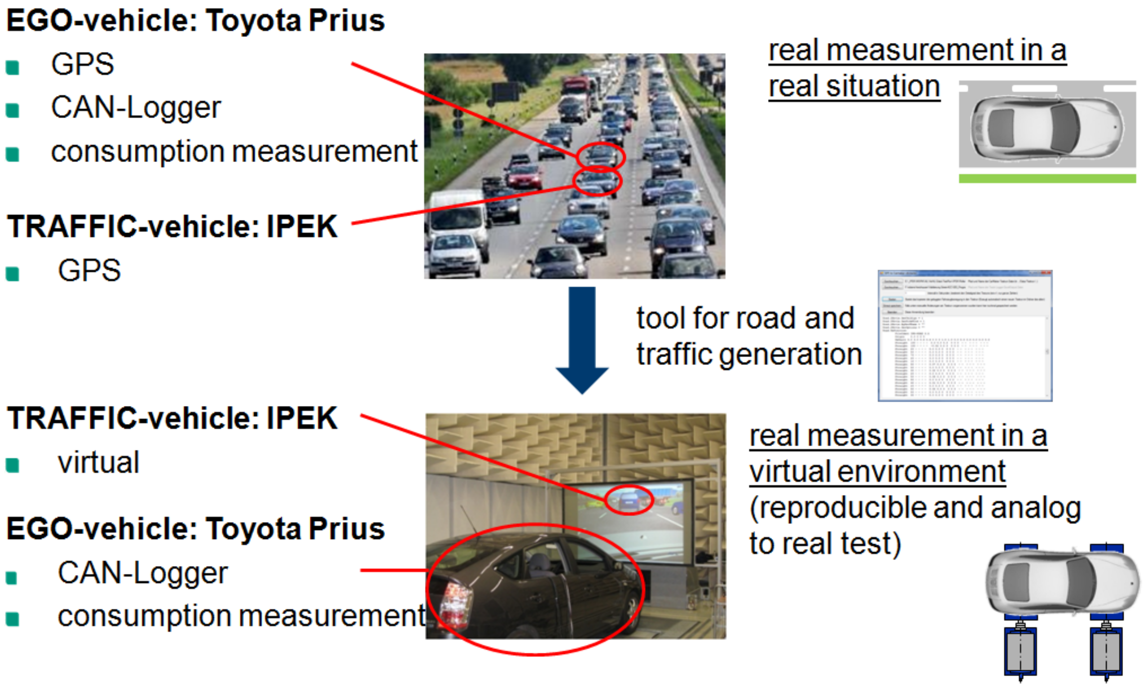

Figure 6: portability between road test and test on the roller test bench in terms of a traffic situation

## Application and Results

After analysing the task in detail and defining a system structure and system behaviour for this application the Vehicle-in-the-loop layer was implemented. This consists of modifying the Input-/Output-Interfaces and the expansion and parameterization of the models. For the definition of structure and behaviour, SysML in combination with the Contact and Channel Model and the problem solving process SPALTEN is used. This will be described in detail in (3).

In the following the results based on measurement data of the test environment shall be discussed. For the different test runs vehicle speed, engine speed, absolute consumption and the SOC of the battery were evaluated. For these data three test runs are compared to each other. The first run is the reference on the real road in the real traffic situation with the real driver. The second one is the reproduced traffic situation on the roller test bench with vehicle-in-the-loop technology with the real driver. The presented data were measured after different iterations, so the driver was well trained. In the third one the applied controller is shown.
The diagrams in Figure 7 to 10 show a very good reproducibility of the traffic situation on the test bench in terms of the vehicle speed profile. Further the impact of a non-trained driver compared to a trained driver is presented in terms of the engine speed. In many cases starting of the combustion engine isn't comfortable and efficient but happens due to the wrong estimation of the acceleration and deceleration of the traffic obstacle in front.

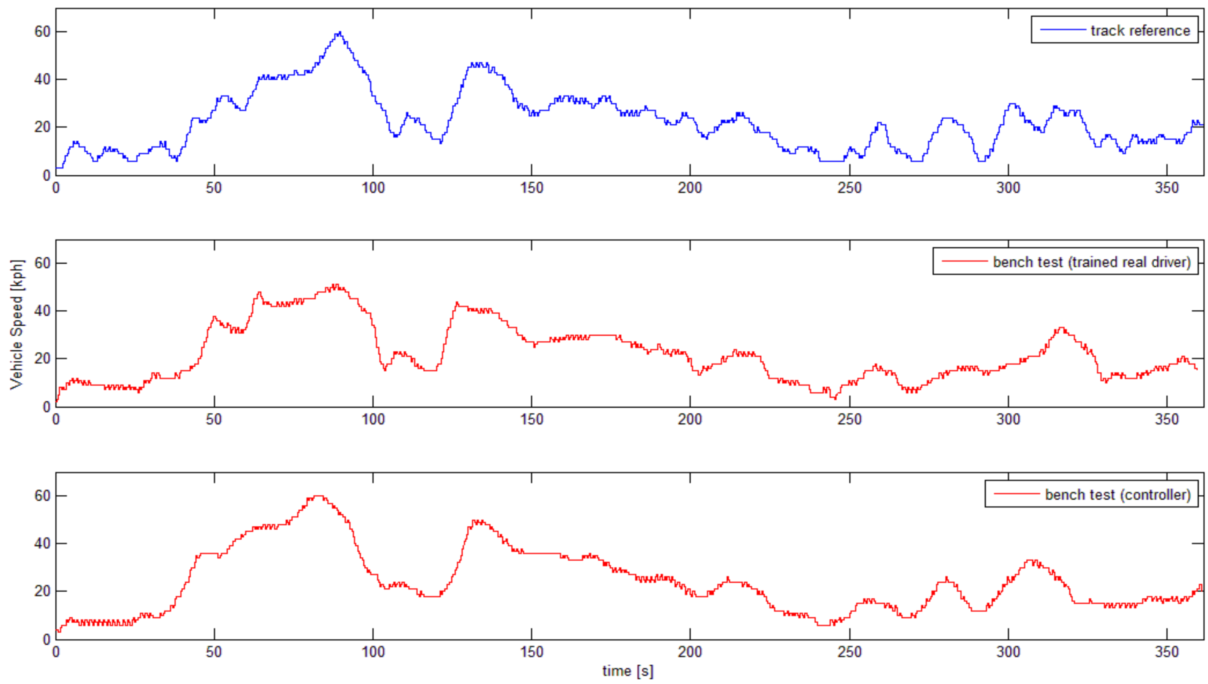


Figure 7: vehicle speed

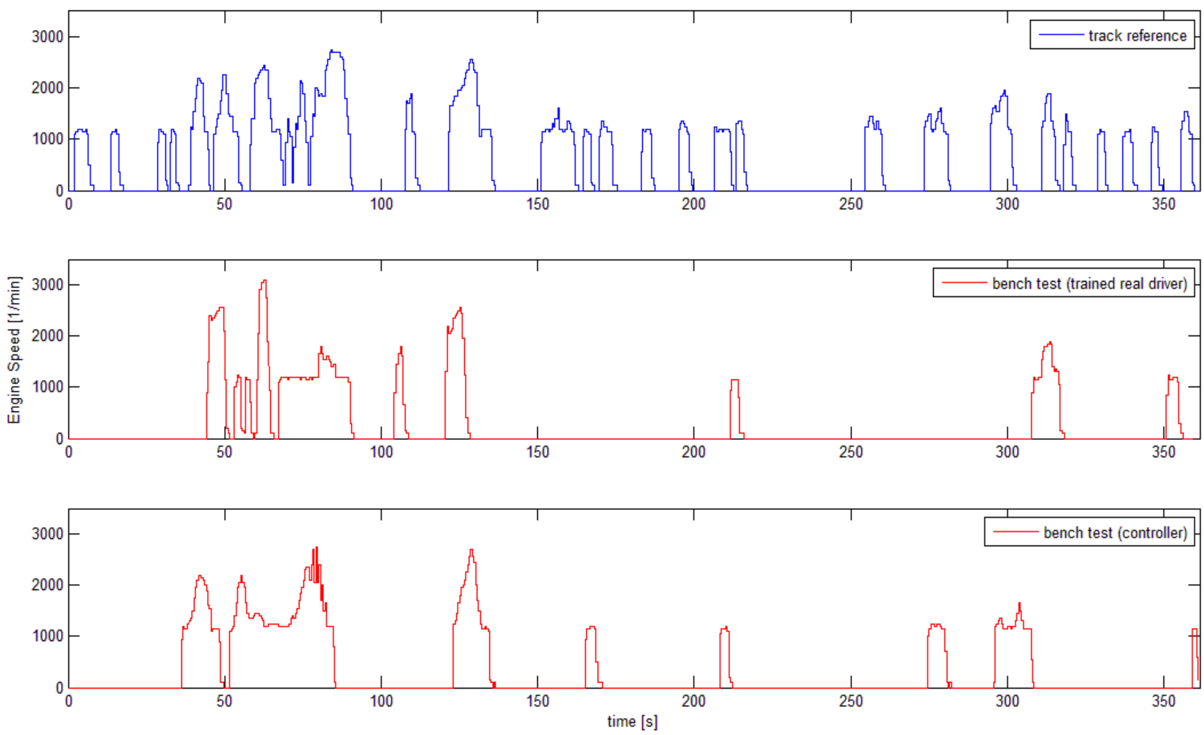


Figure 8: engine speed

These frequent starting of the engine cause an increasing absolute consumption but on the other side an increasing SOC during the test run (seen in Figure 9 and 10). The reduction of the unnecessary engine starts is especially for stop-and-go and traffic situations on the autobahn relevant. After the traffic situation in many HEV it is possible with a load level increase of the engine to load the battery very efficient. It isn’t possible in the real world to train such traffic situations. That’s why an intelligent Adaptive Cruise Controller especially for HEV is necessary.

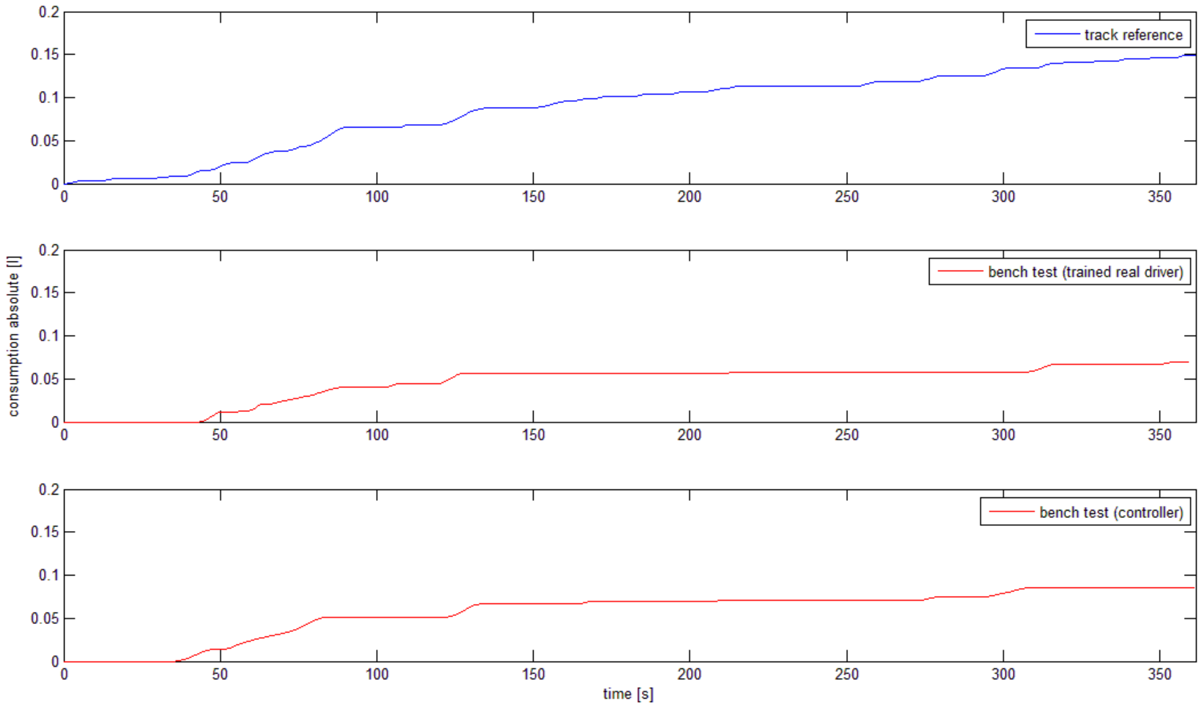


Figure 9: absolute consumption

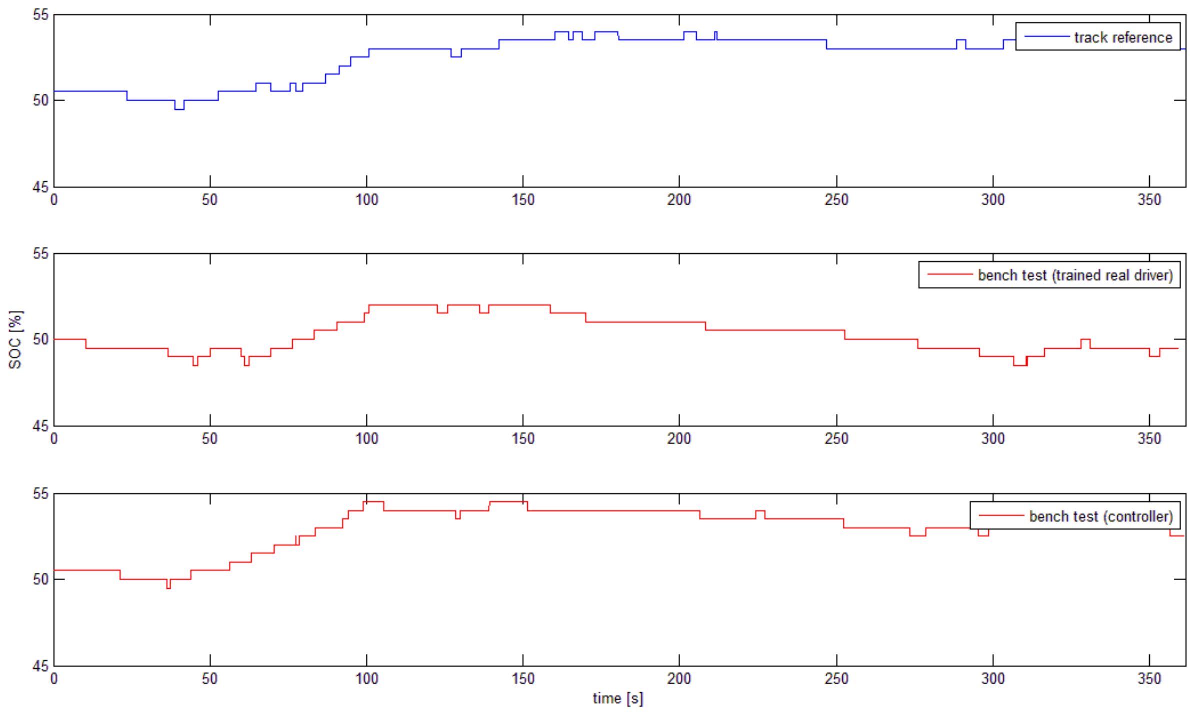


Figure 10: SOC

Such a controller was applied. It is based on about 20 sub-controller based on 5 sceneries which allows a driving of a HEV as shown in Figure 7 to 10 (respectively in diagram 3). An optimization of the controller parameters is possible with a closely interaction between the ACC controller and the operating strategies. The results shown above are based on a system analysis before without interaction to the hybrid control unit. However, they are showing the potential of such a controller very good.

SUMMARY

The growing complexity of modern vehicle structures usually implies a growing complexity of development and validation environments. This paper introduces an approach to meet this challenge. Aspects like an integrated, cross-linked development and validation framework, support methods for the application and process integration are considered in the IPEK X-in-the-loop approach. Everything is based on established tools and methods which allows transferability to industrial applications. The Vehicle-in-the-loop layer (on the roller test bench) was presented in detail. A modular concept allows the combination of different drivers (real in the vehicle, real in the driving simulator, virtual), of different types for a virtual environment and for a rest vehicle simulation (seen in Figure 11). After this the application field was shown and demonstrated with one concrete example. The first result of this example was the development and application structure for an advanced ACC controller for HEV. The second result was the presentation of the possibilities of the Vehicle-in-the-loop layer in terms of the development of new driver assistance systems.

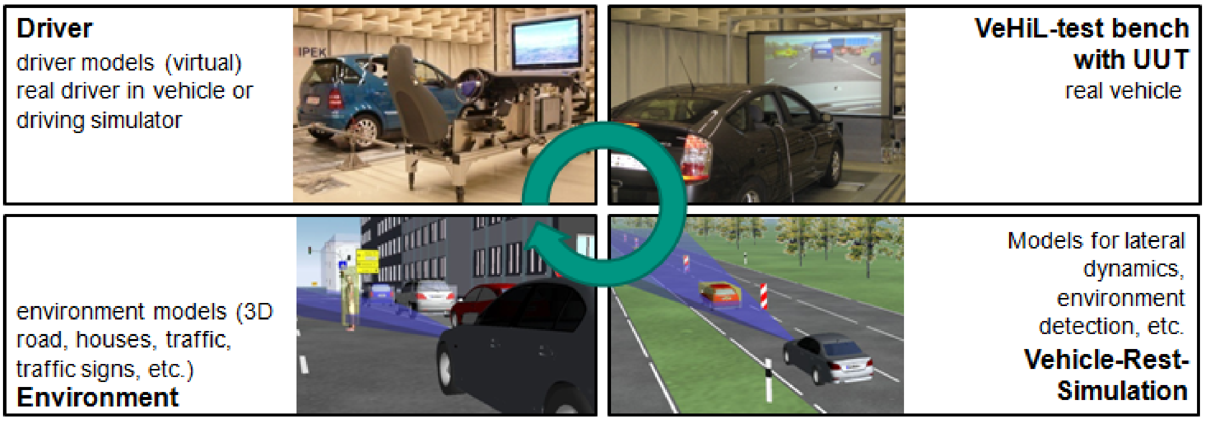


Figure 11: Vehicle-in-the-loop layer

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