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Test Driving Automotive Virtual Drivability Calibration and BMU

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Abstract: Automotive vehicle drivability calibration comprises development activities that are most influential to the final human driving experience of the car. At the same time these activities are performed in the latest phases of the process where any constructive changes to the powertrain are impossible or at least highly expensive. This paper deals with a methodology to make these and other calibration tasks virtual, i.e., to front-load them as much as possible to the early phases of the development process. A methodological approach will be introduced and applied to the practical case that is based on modeling longitudinal vehicle dynamics in real-time. This case will be used to reveal much yet unused potential in terms of interdisciplinary collaboration and systems engineering in current organizations. The paper will show how this potential can be unveiled using the case of virtual drivability calibration and validation as an example.

Key-Words: Virtual Powertrain Calibration, Drivability Calibration, Virtual Test Drive, Virtual Development Process, Behavioral Mock-Up (BMU), Real-Time Powertrain Modeling, Model Validation, Automotive Systems Engineering.

1 Introduction

1.1 Automotive Powertrain Development

The powertrain development process is part of the whole vehicle product creation process, which is concisely discussed e.g. in [1]. Fig. 1 shows the typical major phases, "stations", and activities of a representative holistic powertrain development process.

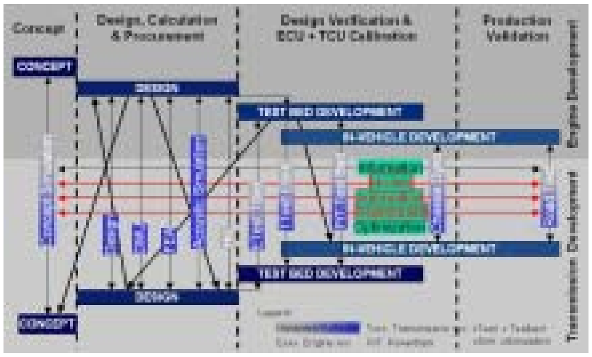

Fig. 1: Holistic Powertrain Development

The engine and transmission development processes run in parallel in very similar phases and they are closely linked by consecutive "vertical" tasks if the powertrain is developed in a holistic way. The permanent interactions and synchronizations between the two processes are sketched with the inclined arrows in Fig. 1. The largest part of powertrain calibration, which denotes the optimal adjustment of parameters of the electronic control units (ECUs) of the powertrain, is still done very late in the process, and predominantly in the car. This severely compromises the flexibility to implement changes, and the freedom to experiment with a sufficiently large number of parameter settings.

1.2 Front-Loading by Virtual Development

Front-loading of development activities to earlier phases demands the intensive use of simulation. From concept simulation via tests and calibrations on various kinds of testbeds to the phase with the vehicle prototype on the chassis dynamometer, simulation models with different levels of detail have to be used to substitute real components that are not yet available. There is already a clear trend towards the exchange of simulation models instead of hardware prototypes among manufacturers and suppliers. A huge yet unused potential is hidden in the consistency of such models in terms of exchangeability of models, re-use of measurement data, calculation results and model parameters, as well as in the transparency of the functionalities of simulation tools regarding arbitrary combinations from virtual (i.e., modeled) and real components.

2 Problem Formulation

2.1 The Virtual Test Drive

Nowadays test procedures executed on different kinds of testbeds are usually already highly systematic and automated, and the variety of measurement equipment that can be used there is much larger than it can currently be in road tests. The problem at hand lies in moving road tests to testbeds in the first step, and to the office environment in the second ("From Road to Rig to Office"). This problem formulation shall be denoted "The Virtual Test Drive" henceforth [2].

The main prerequisite for being able to move road tests to the test rigs is that the real driving conditions can be simulated with sufficient quality, and that the results and target quantities can be measured. If these requirements are fulfilled, tests on the rig will also enable dynamic multi-target optimizations like drivability and fuel consumption optimization for the calibration of transmission and engine control units [3,4]. Variations of constructive parameters or of the calibration or function design of control units can be judged in simulation only if the simulation models' modeling depths are such that the influences of the intended changes can become explicitly visible.

2.2 Powertrain Modeling and Simulation

2.2.1 Model Classification

The required simulation models can be classified into non-real-time and real-time models. Non-real-time models represent complex mechanical, hydraulic and electrical effects of the vehicle without external restrictions to the length of a simulation time step. Real-time models can be simulated with a certain cycle time and are thus suitable to interface to the real world e.g. on testbeds. Currently this cycle time is typically equal to or smaller than one ms. Even though computing power is rapidly increasing, such real-time models of complex systems still have to be very efficient, and their structures have to fulfill special requirements. One of the most significant ones is the fact that they must abandon differential-algebraic equations which are usually used for automotive multi-body simulation, as under real-time conditions, ordinary differential equations show better behavior. This has lead and is still leading to the fact that state-of-the-art real-time models have been and are completely re-engineered, such that they normally do not have common data sources with other types of models.

2.2.2 Modeling Depth and Accuracy

For a specific simulation task, the system components have to be modelled with adequate depths (i.e., abstraction of the real counterpart) and accuracies (i.e., deviations of the simulation results from real figures). The meaning of "adequate" is strongly context-dependent and thus has to be defined (at least) in terms of

- the available system understanding,
- the available computing power,
- the desired parameterization effort,
- the required effects of the real system that the simulation shall be able to deliver.

Typical design tasks require the simultaneous use of models from different levels for the design of physical parameters, as well as for the verification of the modified component in the overall system.

2.2.3 Consistency of Models and Simulations

Obviously a large number and variety of models arises throughout the individual phases of the development process. Since every single model requires a lot of time and effort to be built and verified using measurements, the aim should be to make these models easily reusable and exchangeable. However, this is currently not possible mainly because of the following reasons:

- Models created with different modeling tools do not consist of the same model elements with identical underlying mathematical equations and parameters, and the internal formats used for the description of the elements are not compatible.
- The numerical capabilities of the simulation tools are different. Many problems require very special solver capabilities. Some applications require simulation speed and numerical stability rather than accuracy or vice versa.

Simulation tools and models have been designed for specific viewpoints. The decisive problem is to provide sufficient information about the individual tools and models such that they can be interconnected to simulate the whole mechatronic system using a federation of specialized simulation tools, and to make this information available in form that is easy to understand and to use.

3 Problem Solution

3.1 The Control Loop Methodology

A methodology for the systematic derivation of the real-time models for different kinds of testbeds from arbitrarily complex CAE calculations is required to be able to derive and re-use information from early CAD and CAE models to testing environments and vice versa. Fig. 2 shows the so-called “Simulation Control Loop”, which basically derives real-time models for the components of the powertrain from complex models that are created very early in the process. The feedback loop from the testing environments, where hardware prototypes can be used to validate real-time models, is closed when experiences gained in these environments are fed back into the complex simulation models for validation, verification and improvement. Nowadays this feedback is very often painfully neglected for a number of both technical and non-technical reasons. A thorough treatment of this methodology and associated process issues can be found in [5].

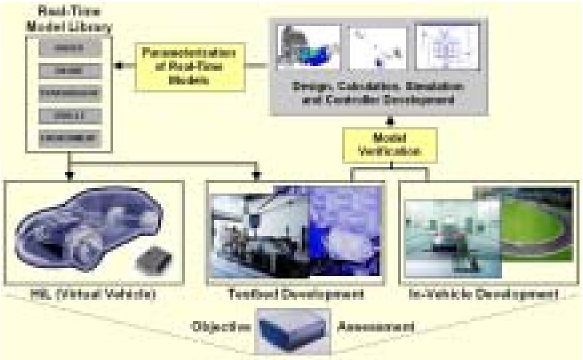

Fig. 2: The “Simulation Control Loop”

This methodology will guarantee that the effects and interactions that are necessary and sufficient for the simulation target can be implemented in the real-time simulation models of the vehicle components seamlessly and transparently with minimal dependency of real hardware prototypes [6]. Since the implementation of all the relevant details usually leads to models that are highly cumbersome to handle, measures have to be taken to adjust the modeling depth according to the specific variation tasks without compromising the quality of the simulation results [5].

3.2 Targeted Applications

3.2.1 Model Classification

The Virtual Test Drive implements the proposed methodology, which ultimately aims at moving calibration-relevant activities to the earliest phases of the development process, i.e., CAD and CAE [2]. A smaller aim that is more likely to be achieved in the near future is to implement the best possible preparation of real road tests by

- pre-testing ECU software,
- plausibility checks of ECU parameters,
- pre-calibration of the adjustment parameters with respect to all relevant target functions,
- investigation of the quality and stability of trade-off calibrations,
- stability checks of best parameter settings,
- pre-check of the effects of hardware-modifications,
- virtual variant investigations,
- preparation of test procedures in the office.

In the ideal case of the Virtual Test Drive, the real road tests should only be required for the verification of the calibration that has been determined in the simulation environment. As was shown above, on the way to this ultimate aim there are numerous small steps forward, that already have enormous economic potentials in terms of shortening the development process, improving quality, and saving costs by avoiding failures and late modifications.

3.2.2 Drivability Calibration Issues

Low-frequency (up to 100 Hz) longitudinal vehicle dynamics influence the driving comfort and the drivability of a vehicle most decisively [7]. They thus require highly sophisticated calibration that can only be done subjectively. There are tools available on the market that objectify such subjective driving experience and thereby enable the objective drivability assessment. AVL DRIVE [8] can be used for the objective assessment of the drivability in the real vehicle as well as on testbeds and in simulation environments.

3.3 The Testing Equipment

A consortium research project that is described e.g. in [9] provided the basis for the results presented in the rest of this paper. The reference test vehicle was a BMW 523i (MY 1998) sedan. It was equipped with a set-value based engine control unit from Siemens, and a five-gear manual transmission. A chassis dynamometer and a dynamic engine testbed were used for engine measurements and simulation result verification.

Extensive measuring rides with numerous characteristic load-reversal maneuvers delivered a sufficiently broad basis for model verification. A lumped engine model (see section 3.4.2) was created using the results from measurements that had been obtained from the unmodified vehicle on a chassis dynamometer. Tip-In/Let-Off (i.e., sudden full/zero throttle) and shifting maneuvers were primarily used for the virtual calibration of the load-reversal damping and the anti-jerk function.

3.4 The Real-Time Vehicle Model

A real-time capable model of the transmission and the drivetrain was developed to provide the basis for the investigations of how seamlessly longitudinal vehicle dynamics can be simulated on various different kinds of testbeds.

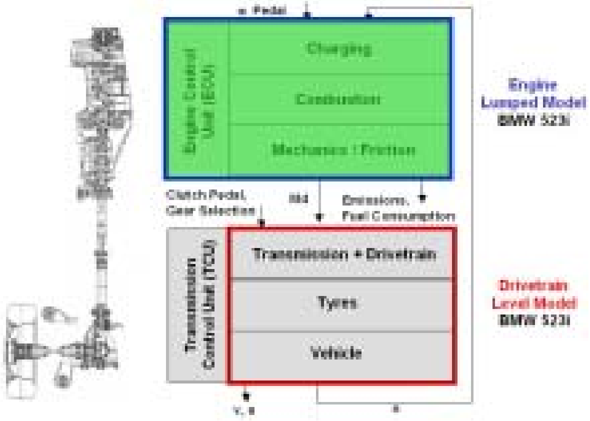

Fig. 3: The Real-Time Vehicle Model

The two major requirements to this model were the simulation of

- all the quantities that are relevant at the crankshaft, as well as
- the low-frequency (up to 100 Hz) longitudinal dynamics effects like load-reversal and jerk [10]

with a quality that is sufficient for the pre-calibration of the affected control unit functions and for variant investigations. In this context it was important to take into account the following demands according to the requirements mentioned in section 2.1:

- The parameterization of all model components has to be easy and sufficiently accurate (ideally by the only use of data from calculation and design).
- The model shall be especially suitable for parameter studies and variant investigations in real-time.

3.4.1 The Drivetrain Model

All these requirements were fulfilled by the implementation of a component structure which corresponds to the real drivetrain, and where every individual component is self-contained in terms of consistency and parameterization. This structure certainly implies that the model has more inner (i.e., rotational) degrees of freedom than required for the solution of the special problem that is presented here. This structure was used because for this application, the system's variability and the transparency were more important than the — for complexity reasons usually required — reduction of the number of its degrees of freedom.

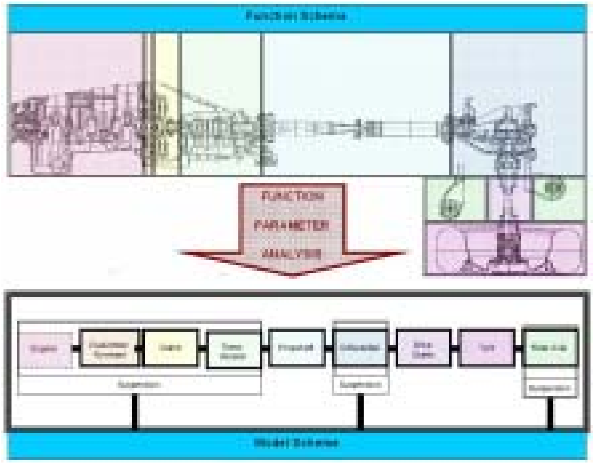

Fig. 4: Block Structure of the Drivetrain Model

The decisive influence factors on longitudinal vehicle dynamics were determined by the stepwise enrichment of a minimal functional model. This approach ensured that the complexity of the model and its parameterization effort did not exceed the minimally required measure without compromising the accuracy of the final result. The resulting model can be parameterized almost completely with data from design and specifications, and all its parameters correspond to physically meaningful quantities. In [11] both the model and the methods of data procurement are discussed in greater detail.

3.4.2 The Engine Model

In the special application of longitudinal dynamics investigations, the engine can be seen as the torque actuator within the total vehicle system. A suitable simulation model must therefore simulate the dynamic engine torque with the accuracy that is determined by the application. This requirement is a special case of a multitude of ways to mimic an internal combustion engine by means of simulation.

If, like in the scenario that is presented here, selected functions of the engine control unit that are relevant for longitudinal vehicle dynamics are to be investigated, and the engine is already designed and available in hardware, a so-called *lumped model* can be used [12].

Such a model works primarily torque-based by simulating the sum of all the influences of the levels. Therefore the individual levels need not be modeled explicitly, and the cumbersome task of gathering the required parameters is thus also eliminated. Fig. 5 shows the fundamental structure of the BMW lumped engine model.

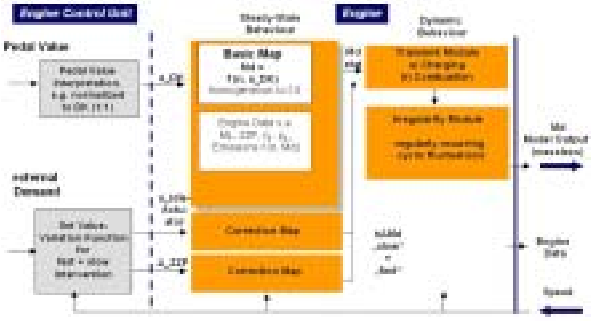

Fig. 5: Lumped Real-Time Model of the Engine

A lumped model of the BMW engine was created by taking characteristic measurements in the relevant operating areas both on the chassis dynamometer and on the dynamic engine testbed. Instead of creating a complicated Hardware-in-the-Loop (HIL) environment, those engine control unit functions that are relevant for vehicle longitudinal dynamics were re-implemented in software:

- Throttle pedal characteristics and throttle pedal value interpretation,
- idle control,
- load-reversal damping and gradient delimiter,
- deceleration damping (“dashpot”),
- anti-jerk function,
- trailing throttle fuel cut-off and fuel-feed restart,
- internal driving controller,
- interface to external torque demands (e.g., transmission control unit).

However, this was only possible because the ECU manufacturer Siemens provided all the information needed to correctly re-implement these functions as Simulink models. If this information had not been available, the ECU would have had to be operated in a HIL environment with a so-called *level model* of the engine, which resembles the major process levels of an internal combustion engine on a physical basis. This alternative approach is described in [12]. Apart from the fact that these properties were not required for the particular application, this approach was not taken because it would have complicated the data procurement process unnecessarily.

3.4.3 Data Procurement

The amount of efforts for gathering model data and parameters strongly depends on the results from previous or parallel work. In many cases complex CAE models are already available, and data can be taken over directly. Data from testruns on testbeds and from road tests are also valuable resources. The more data a modeling concept can make reasonable use of, the greater is its practical relevance.

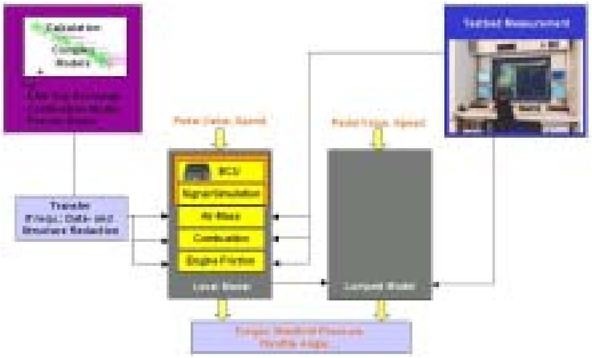

Fig. 6: Data Sources for Real-Time Models

The presented concept for structuring the powertrain model enables the implementation of different modeling depths in a very transparent fashion. Since the relationship among the individual models will remain if they have a common source, parameters and simulation results are mutually usable and comparable. Fig. 6 shows possible ways of obtaining parameter values both for level and lumped models using the combustion engine as an example. As mentioned in section 3.4.1, CAD drawings were the major data source of the drivetrain model.

3.4.4 Simulation Results

In earlier publications related to this project it was already shown that the simulation result quality that can be achieved without any model tuning is sufficiently high at least for hardware variant investigations and for the pre-calibration of ECU functions that influence longitudinal vehicle dynamics, e.g. [12]. Since the focus of this paper should be on a new model-based methodology for virtual vehicle calibration and the requirements to the supporting development platform, simulation results will not be analyzed in detail here.

Fig. 7 shows the example of a Tip-In maneuver in the second gear at an engine speed of approximately 2500 rpm once with active (orange color) anti-jerk function of the engine control unit, and once with this function deactivated (green color). There is a clearly visible difference between the shapes of the two red-colored longitudinal acceleration signals.

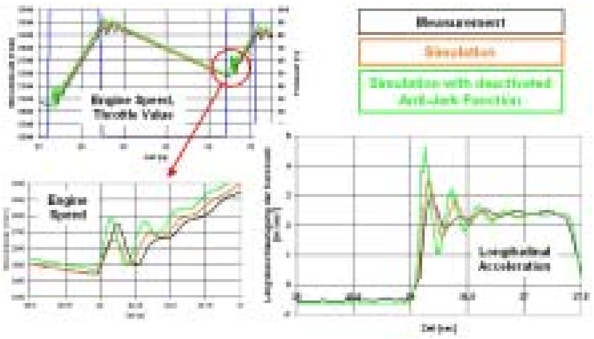

Fig. 7: Tip-In with/without Anti-Jerk Function

The corresponding AVL DRIVE assessments differ by more than one grade. This complies very well with the situation in the real vehicle. For all the investigations of interest, no matter whether they affect electrical or mechanical components, the *relative* assessment results are the decisive help or basis for design decisions. The absolute accuracy of the assessment results is a secondary issue. This is a very important fact to be considered when looking for the minimum required model accuracy.

3.4.5 Systems Engineering for Data & Models

As was pointed out above, the key factor for the validation of prototype vehicle components on test beds and the pre-calibration of powertrains without vehicle prototypes is the capability to simulate the non-existing vehicle components in a very realistic and consistent way. This requires an integrated modeling, simulation and validation environment that supports all the stakeholders in the process to

- access requirements and design information,
- access data from CAD, CAE, and CAT,
- exchange simulation models,
- parameterize the simulation models,
- set-up and perform test runs,
- validate the simulation models,
- maintain relationships and dependencies among different models,
- etc.

Although neither the modeling nor the validation process can be fully automated, it is still possible to support engineers and managers in this process by systems engineering methods. In order to be helpful to the engineer in his everyday work the support is to precisely describe the components of the vehicle in digital models consistently. The methodical approach that was pursued especially for validation purposes consists of modular component prototypes which were extended with functional and mathematical properties to create so called “Behavioral Mock Up” (BMU) modules for the different parts of the vehicle, as defined in [11].

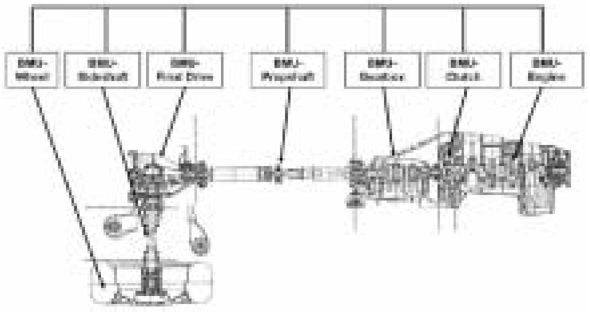

Fig. 8: The BMU Structure of the Powertrain

The BMU structure, which is shown in Fig. 8, corresponds to the one presented in Fig. 4. The elementary design model “Contact & Channel Model C&CM” was used to connect the shape-oriented level of describing technical systems with the corresponding function-oriented level [13]. The individual modules are easily interchangeable due to very clearly defined und physically understandable interfaces. The automated maintenance of parameter dependencies inside and between the modules within the BMU environment enables the prediction of the consequences from design changes without the necessity to build new and expensive prototypes.

3.4.6 From DMU to BMU

The BMU concept as it is introduced in [14] uses the well-established DMU methodology to provide access to behavior (i.e., functional) models of the powertrain components via their corresponding geometrical models. Its particular focus is on all stages of product *development*, and it aims at leveraging the front-loading of the “late” CAT and Calibration phases by enabling the seamless federation of data, models and tools from the early phases of CAD/CAE throughout the whole development process. This is shown in Fig. 9.

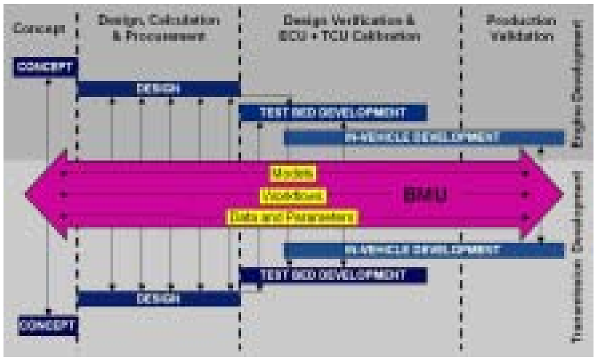

Fig. 9: Scope of the BMU

The BMU provides an environment that helps to keep all the assets and activities involved in this process consistent. The project members have to have seamless and consistent access to models, data and parameters. The project managers shall be able to derive a holistic and up-to-date image of the current development status within the BMU environment at any time.

As is pointed out in [15] the BMU modules of the different vehicle parts are used in different simulation environments during the calibration and validation process, which is between the design and the production process. In Offline Simulation all parts of the vehicle including the human driver have to be simulated using mathematical models. For Hardware-in-the-Loop testing only the electronic control units of the vehicle are used as a real prototype, all other components are simulated. At the engine test bed only the engine with ECU is set up using real parts, all other components are simulated and so on. Finally the complete real prototype vehicle is tested on a real track during the last phase of the calibration and validation processes.

4 Conclusion

The powertrain modeling approach that is presented here enables the investigation of causes and effects of longitudinal vehicle dynamics phenomena in real-time. The interactions of components and systems and their mutual dependencies can be modeled transparently. The real-time models are structured in a way that the system’s behavior can be transferred analytically from multi-dimensionally calculating CAE tools. The model architecture and the methods of parameterization were shown. The input information to the simulation are data from design to the greatest possible extend, and to the least necessary amount measurement data obtained from real components. The necessity to use measurement data depends on the result quality that can be achieved with pre-calculations for the affected component. The comparison between measurement and calculation is basically used both for quality check and for model refinement. Due to the consistency of the models the quality check can be done on any suitable kinds of testbeds. Moreover, the verified models can be used for diagnosis during testbed operation (e.g., using on-line comparisons). A seamless platform for data from modeling, measurements and calculations leverages the consistency of arbitrarily complex scenarios of simulation and reality.

Basic methods from the BMU concept were applied to maintain all the simulation models and their mutual dependencies consistent throughout the development process.

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