UNIVERSITY OF PITESTI *SCIENTIFIC BULLETIN*
FACULTY OF MECHANICS AND TECHNOLOGY AUTOMOTIVE series, year XV, no.19, vol. B

COUPLING HIL-SIMULATION, ENGINE TESTING AND AUTOSAR-COMPLIANT CONTROL UNITS FOR HYBRID TESTING

Franck Le Rhun
AVL List GmbH, Graz, Austria

Abstract: *In a fast and cost-efficient powertrain development process several optimization and validation tasks are required at early development stages, where prototype vehicles are not available. Especially for hybrid powertrain concepts the development targets for fuel consumption, vehicle performance, functional safety and durability, which have to be validated on the engine test bed before integration and testing with real vehicle prototypes takes place. The integration of relevant control unit functions like transmission shift or vehicle stability as AUTOSAR software component into a simulation system at the engine test bed allows a fast and integrated workflow for series development. Complementary a high-quality combustion torque estimation and the consideration of driver behaviour and lateral vehicle dynamics improve the correlation of simulated to real world driving maneuvers.*

Keywords: Hardware in the Loop engine and hybrid testing, AUTOSAR-Compliant Control Units

1. INTRODUCTION

Energy-efficient vehicles are highly demanded in a context of declining fossil resources and increasing green house effect caused by $C0_2$ emissions. In particular the necessary fast and cost-efficient series development of hybrid and plug-in electric vehicles is challenging the current design and testing methods and their supporting tools. To illustrate this challenge a comparison of the engine speed in a mid-range passenger car with two conventional and one hybrid transmission variants is shown in figure 1. In conventional powertrain concepts the speed and load of the combustion engine is mainly determined by the selected gear ratio either by the driver for manual transmissions or the control unit for automatic transmissions. In a hybrid powersplit configuration the engine operation is mainly determined by the implemented control functions within the linked powertrain control units like Hybrid Control Unit, Battery Control Unit, Engine Control Unit, Transmission Control Unit and Vehicle Stability Control Unit.

2. MODEL-BASED DEVELOPMENT PROCESS

The integration, optimization and validation of hybrid and plug-in concepts is a difficult task because of the increased complexity from physical Powertrain components like battery and e-motor with interacting control functions. To reach the targets for fuel efficiency at the same time as the targets for safety, comfort and agility the whole vehicle dynamics has to be considered in all operating points of longitudinal, lateral and vertical dynamics. A feasible approach is to shift efforts from system integration tasks in the later phase of the development process to systems engineering tasks in the earlier phase as shown in figure 2. This frontloading concept will replace certain testing amounts of real prototypes by the earlier validation of virtual prototypes. The complex environment requires now an integral approach to analyze the system properties and functionalities under realistic vehicle operation conditions.

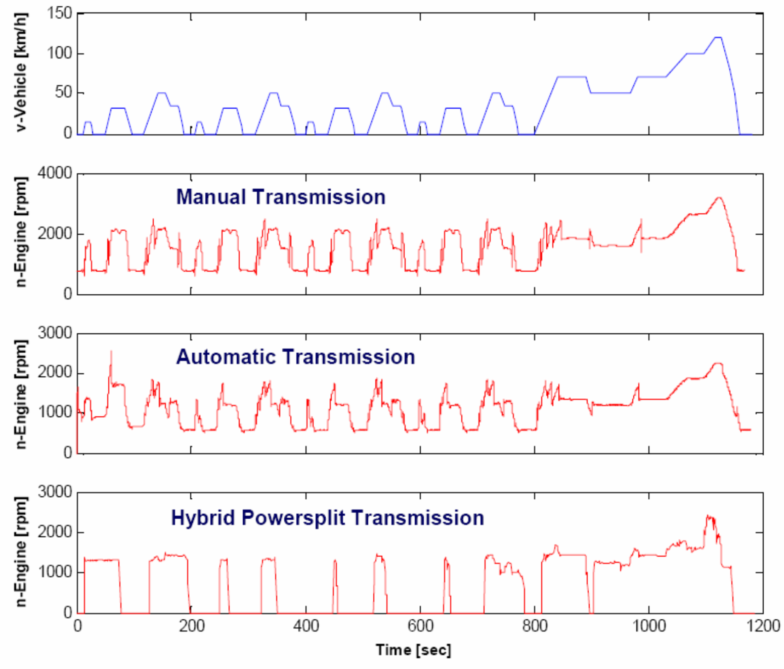

Figure 1: Comparison of transmission variants in the NEDC emission drive cycle

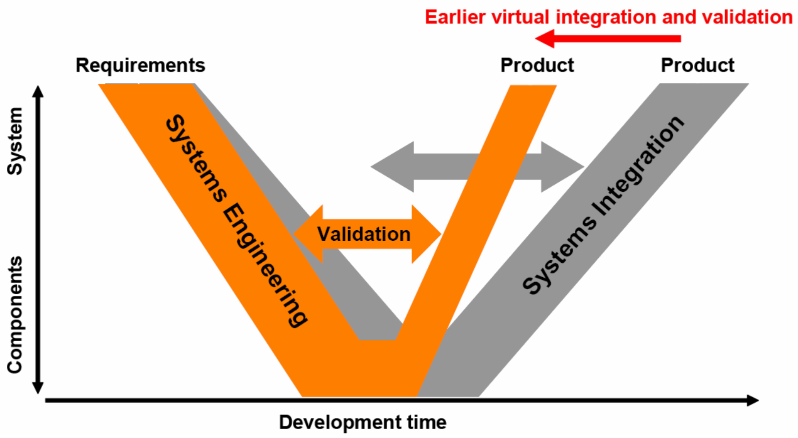

Figure 2: Frontloading supported by a model-based development process

A prerequisite of frontloading in the development process is the availability of a simulation and test environment to enable an efficient re-use of virtual prototypes in different test bed configurations. The proposed integrated validation chain as shown in figure 3 uses the same model environment for vehicle, driver, road and traffic within the different test bed configurations for components like control units, subsystems like engine, electric motor and gearbox, the complete hybrid powertrain and the complete vehicle [1]. In all configurations the targets for vehicle performance (longitudinal, lateral, vertical), fuel consumption and emissions in real world driving scenarios and legal drive cycles can now be evaluated and necessary optimizations performed.

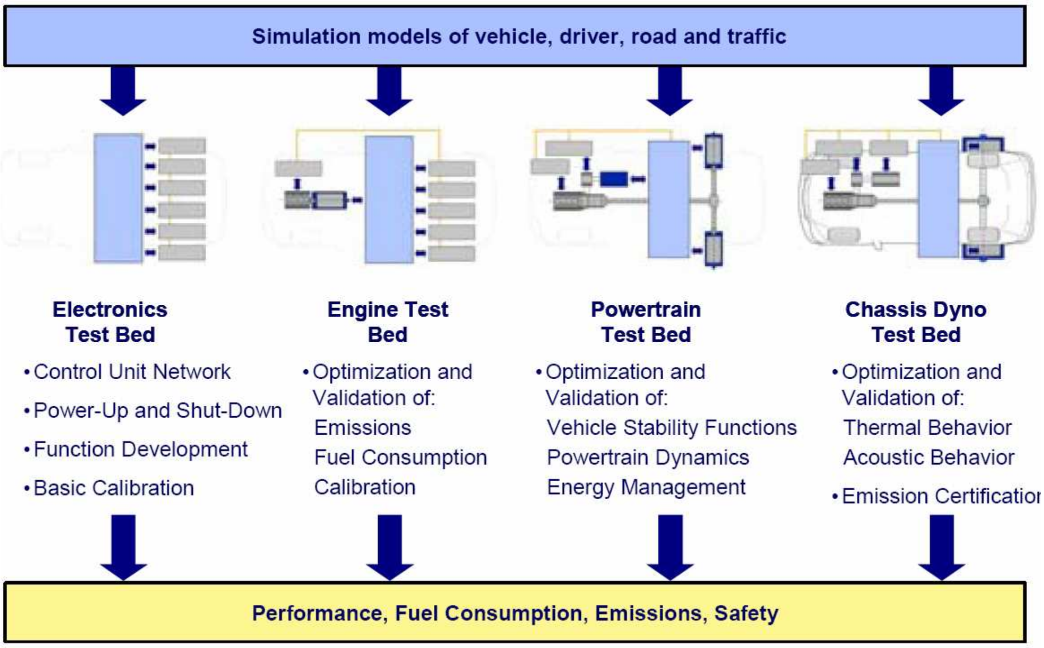

Figure 3: Integrated validation chain for Powertrain development

An object-oriented and real-time capable Powertrain simulation environment is used to supply detailed virtual prototypes for the powertrain (combustion engine, clutch, gearbox, electric motor, battery) and the auxiliary appliances (climatic, steering, body and stability control) as shown in figure 4.

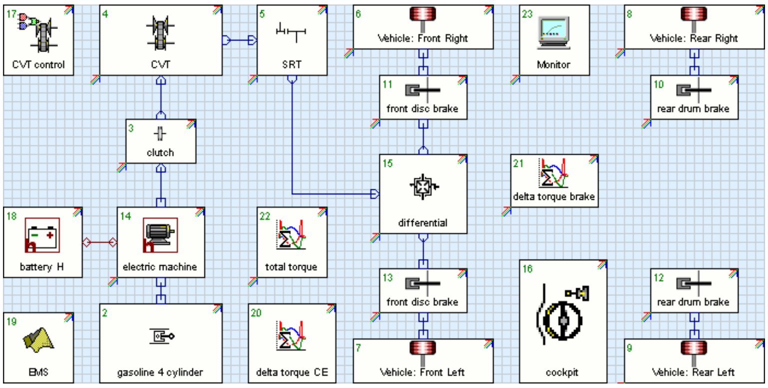

Figure 4: Object-oriented powertrain simulation environment

Those powertrain models are embedded within the simulation platform AVL InMotion powered by CarMaker which supplies detailed models of the chassis, suspension, steering, brake and tires including the detailed loss power sources like rolling power, longitudinal slip power, side slip power, vertical tyre deflection power, chamber change power, back alignment torque power and 3D aerodynamics.

Combined longitudinal, lateral and vertical dynamic driving events and scenarios are defined in a fully automated test process to enable manoeuvres like city, cross country and highway traffic, mountain road, race track and handling course, legal drive cycles and real world consumption tests driven by motor journalists.

The 3D road models used in driving scenarios are derived from digital map data, GPS/DGPS measurement or even from high-resolution track measurements [2]. The manoeuvre based analysis as shown in figure 5 allows detailed answers to questions concerning the coherence of hybrid powertrain and vehicle dynamics.

Braking
- Low / high µ
- µ-split / µ-jump
- Brake in corner
- Brake stability

Starting/Traction
- Low / high µ
- µ-split / µ-jump
- Starting stability
- Flat / uphill

Cornering
- Self-steering behavior
- Power-off /on steering
- Tracking stability
- Self-steering at unevenness
- Limit behavior and threshold correctability

Comfort
- Body characteristics
- Springing and damping
- Lateral shaking
- Steering reactions

Figure 5: Maneuver based analysis

3. ENGINE-IN-THE-LOOP WITH CONVENTIONAL CONTROL UNITS

The determination of engine speed and load cycles as input to an engine test bed using a Hardware-in-the-Loop system (HiL) with connected control units is described for example for heavy-duty applications in [3]. The difficulty with such a concept is the need for a highly detailed and well validated engine model including the thermodynamic behaviour of the engine and exhaust system. Otherwise the simulated operation of the engine and hybrid control unit might not correlate with the real vehicle.

The basic idea of the “Engine-in-the-Loop” concept is to combine the capabilities of a Hardware-in-the-Loop system with a dynamic engine test bed as described for example in [4], [5], [6] and [7]. Those concepts combine a SIMULINK-based simulation system with an automation and test bed control system as shown in figure 6. Since most development projects have an engine prototype available this concept enables a good correlation of the physical engine operation on the test bed with the real vehicle especially for emission drive cycles. It allows to feed back measured signals from the engine and exhaust system into the hybrid and transmission control units, which is a very important requirement for emission calibration.

The concept has been proven very well for research and predevelopment tasks using SIMULINK models for the required control functions. For series development tasks the difficulty is to ensure the same behaviour of the networked control units (xCUs) on the test bed as in the real production vehicle. This requires typically the connection of at least the real transmission, hybrid, battery and vehicle stability control units to the HiL-System in the engine test cell. From this follows a huge effort to physically interface and validate all necessary electrical signals from the xCUs to their associated real-time models on the HiL system.

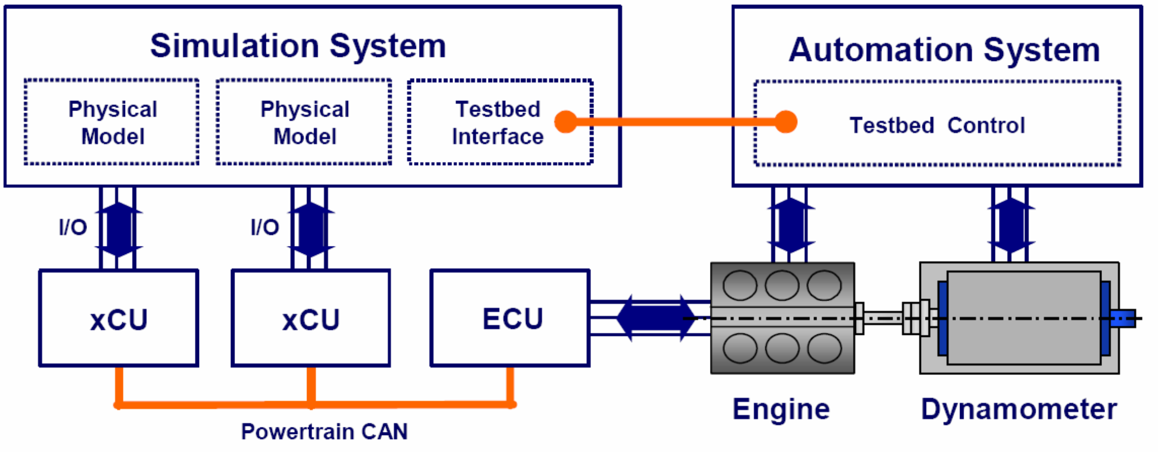

Figure 6: "Engine-in-the-Loop" test bed with conventional control units

4. ENGINE-IN-THE-LOOP WITH AUTOSAR SOFTWARE COMPONENTS

AUTOSAR defines a new standard for the architecture of automotive embedded software [8]. It contains interfaces, exchange formats and processes supported by development tools in an integrated design workflow. The main advantage of an AUTOSAR-compliant architecture is the separation of the application from the basic software. This enables a modularity, scalability, transferability and reusability of application software developed as software components (SWC). Figure 7 shows for example the architecture of the new generation of AVL transmission control units for heavy duty applications.

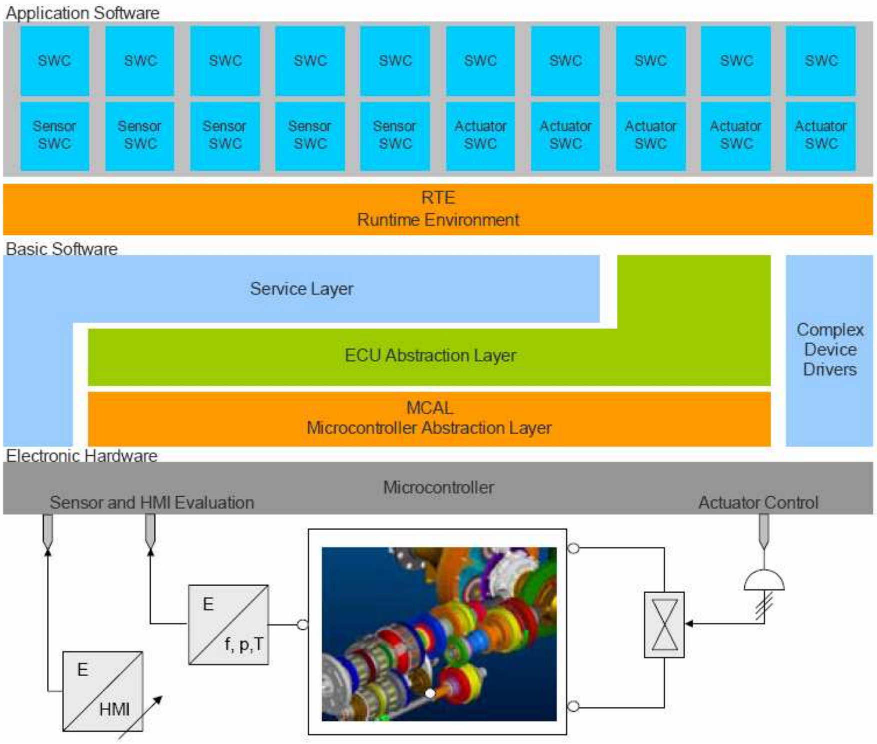

Figure 7: System architecture of an AUTOSARcompliant transmission control unit

The relevant AUTOSAR software components can now be embedded directly into the simulation real-time node using a minimal runtime environment (RTE) as shown in figure 8. The signal communication between control functions and physical systems is based on the same definitions for the AUTOSAR Virtual Functional Bus as in the series vehicle. It allows also the integration of the simulation real-time node as virtual xCU within the AUTOSAR workflow. This is now a very fast way to integrate software modifications in control units within the engine test bed environment compared to the flash procedure of each single conventional control unit. The software components and the physical models can be integrated either as open source code or as protected object file to ensure the intellectual property of the model creator.

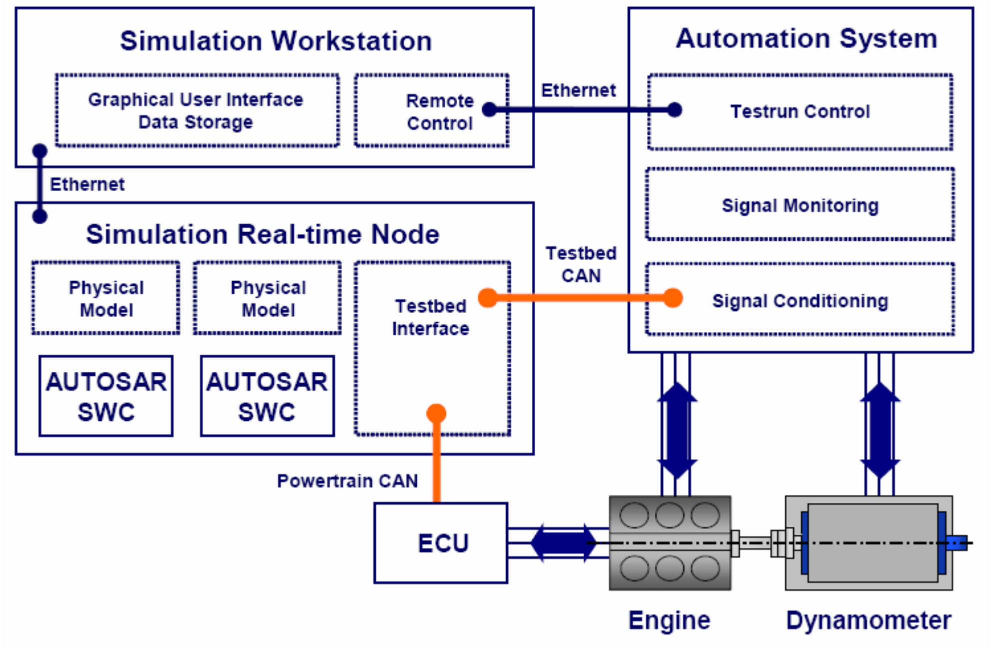

Figure 8: “Engine-in-the-Loop” test bed with AUTOSAR software components

The interface from the simulation system to the automation system uses the concept of External Simulation as introduced in [4]. A unique feature is the connection of the simulation system with integrated AUTOSAR components or connected real control units to the automation system using a prepared CAN and Ethernet interface. This allows the usage at different test beds in a development project without time-consuming system installations or changes. The signal conditioning and monitoring modules of the test bed automation system ensure the safe operation of the engine and dynamometer, while the testrun control manages the measurement devices like fuel meter, indicating system or emission benches. For legal emission test runs the automation system controls remotely the simulation system.

5. COMBUSTION TORQUE ESTIMATION

Besides the identical behaviour of control functions an appropriate signal input into the simulation models of the physical systems enables a good correlation between results from the test bed and vehicle measurements in all driving scenarios. At engine test beds the combustion torque is always input into the vehicle simulation model. The only torque measurement available is usually the shaft torque which is measured between engine and dynamometer. The actual torque is time-based measured using a shaft torque meter as shown in figure 9. A high-quality engine torque signal as input into the driveline model has to be decoupled from test bed vibrations, has to deliver a delay-free and phase-lag free estimation of the combustion torque and to ensure a noise-free insertion into the driveline model.

A newly developed algorithm from AVL based on a Parametric Constrained Kalman Filter fulfils those requirements and has been implemented in the simulation real-time node. The PKF algorithm uses in addition to the measured shaft torque signal also the measured signals for engine and dynamometer speed.

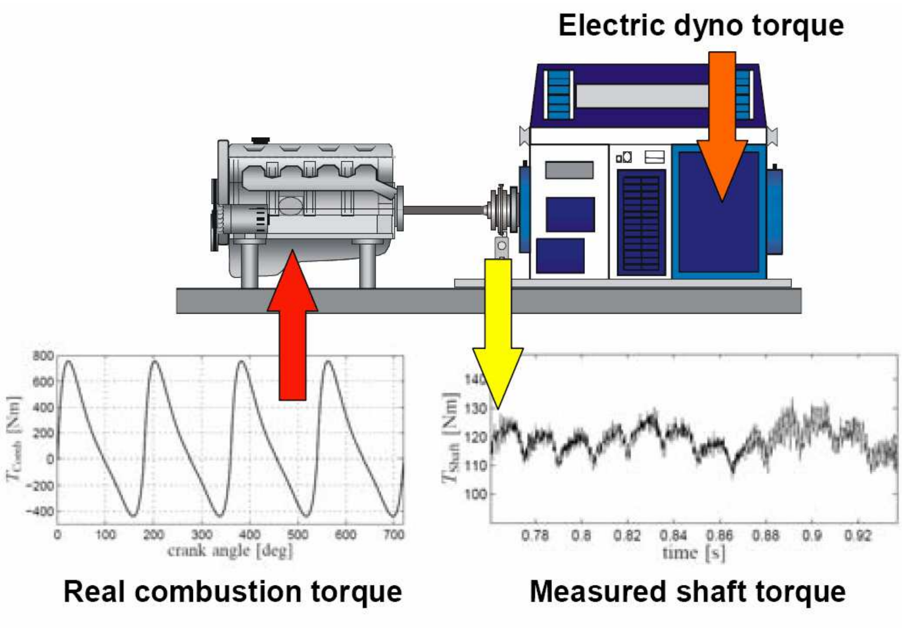

Figure 9: Torque at the engine test bed

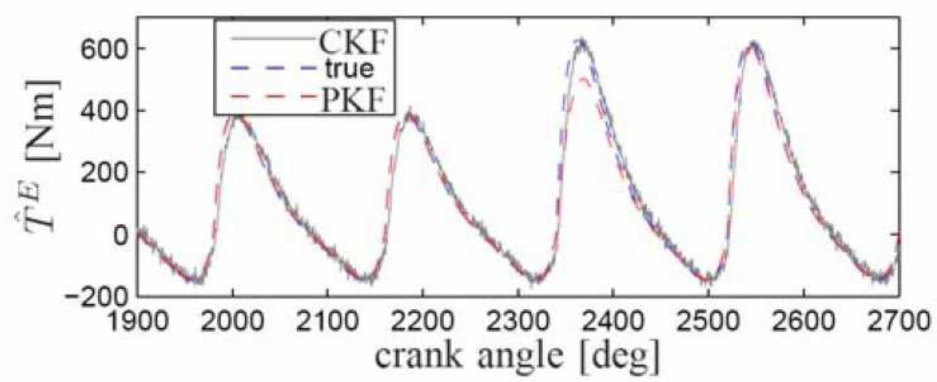

Figure 10: Indicated and estimated combustion torque

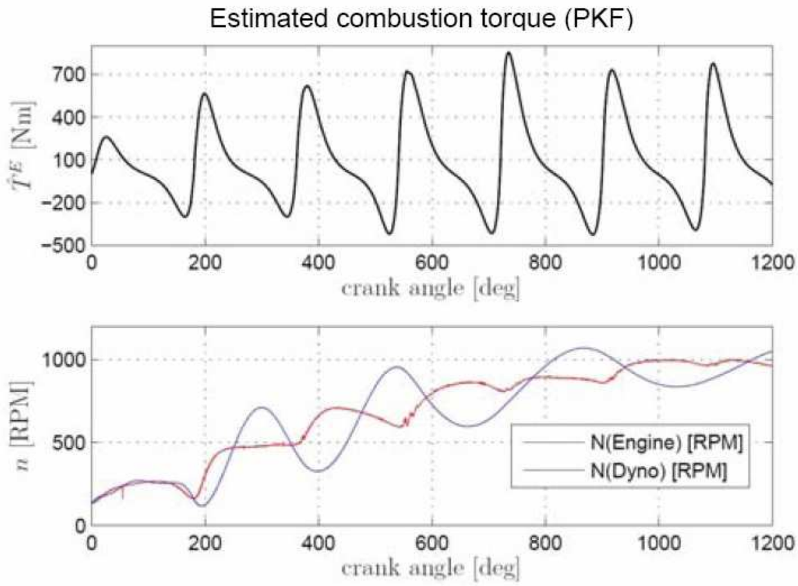

Figure 11: Estimated combustion torque at engine start

The correlation in steady-state condition between the indicated engine torque from combustion pressure measurement (true), a Constrained Kalman Filter (CKF) and the Parametric Constrained Kalman Filter (PKF) is shown in figure 10. For an engine start scenario, typical hybrid application, the estimated combustion torque based on the PKF is shown in figure 11. The estimated torque is ideally suited to drive the real-time simulation of detailed effects in the vehicle model like clutch judder or gear rattle.

6. INFLUENCE OF DRIVER AND LATERAL VEHICLE DYNAMICS

One important task on engine test beds is the validation of real world fuel consumption generated on routes like the Auto-Motor-Sport (AMS) test in the Stuttgart area as shown in figure 12. It consists of two A-route segments (A-B, D-A), one cross country segment (B-C) and one highway segment (C-D). The legal speed limit and the actual driven speed in one specific test are shown in figure 13.

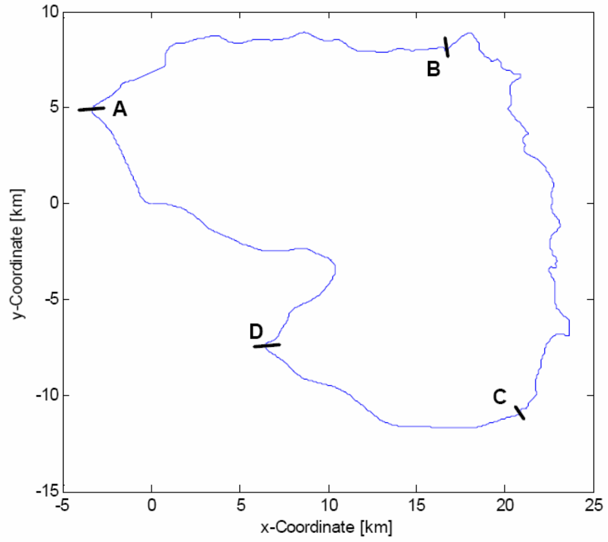

Figure 12: Test track for real world driving [9]

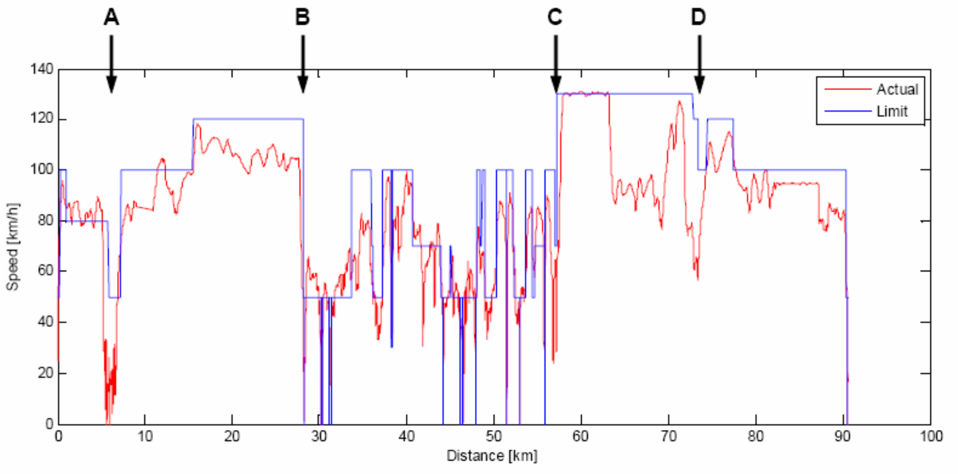

Figure 13: Speed profiles in real world driving

The impact of the driver behaviour on real world fuel consumption is especially relevant for full hybrid vehicles as presented in [10]. The reason is that an intelligent and foreseeing driver can improve fuel economy much more with full hybrid than with conventional vehicles. Therefore a comparative analysis of three different driver types has been done on an “Engine-in-the-Loop” test bed. The driver simulation incorporates the maximum longitudinal (ax) and maximum lateral (ay) acceleration as shown in figure 14.

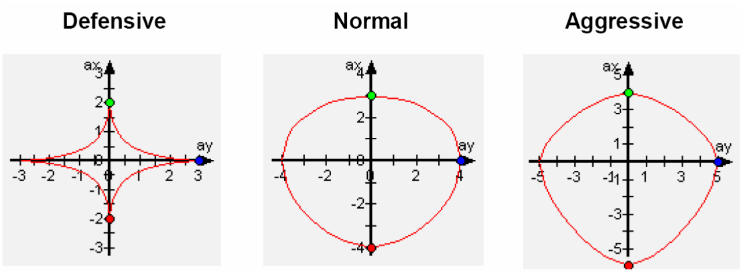
Defensive
Normal
Aggressive

Figure 14: Driver simulation for real world driving

In addition the influence of the lateral vehicle dynamics onto the real world fuel consumption has been analyzed. The road shown in figure 12 was measured with GPS in three dimensions and imported with the speed limit information into the simulation environment. A version with only longitudinal profile (s-z) and one with full 3D profile (x-y-z) has been generated as shown in figure 15.

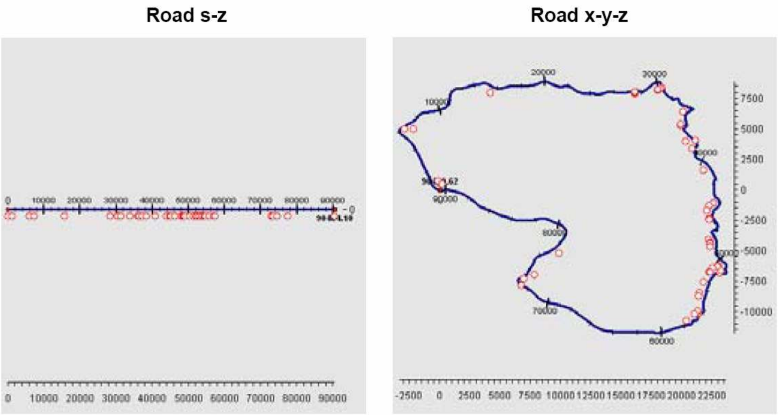
Road s-z
Road x-y-z

Figure 15: Road simulation for real world driving

A 2.2L gasoline engine combined with a simulated full hybrid vehicle was used to get the following results from the fuel measurement on the engine test bed:

	Driver Defensive	Driver Normal	Driver Aggressive
Road s-z	6.7 l/100km	6.9 l/100km	8.5 l/100km
Road x-y-z	6.9 l/100km	7.2 l/100km	8.9 l/100km
Difference	+3 %	+4 %	+5 %

It is noticeable that the simulation of the 3D road profile will result in increased fuel consumption between 3 % and 5 % compared to the longitudinal height profile, which is usually the fuel reduction target range for a new engine series development.

Thereby it must be considered, that the Engine-in-the-Loop test was conducted without chassis related auxiliaries appliances, such as Electric Power Steering (EPS), to simplify the test in this stage. Therefore the differences between s-z and x-y-z roads will be significant higher in the next stage of model detailing. For comparison the fuel consumption in the NEDC test was also measured on the engine test bed :

City	5.8 l/100km
Extra Urban	6.2 l/100km
Combined	6.0 l/100km

7. CONCLUSION

A model-based development process enables the analysis of fuel economy, emission, vehicle performance, safety and comfort in one integrated simulation and test environment with consistent parameters and results. The integration of AUTOSAR components in combination with an estimated engine torque signal into the simulation platform at engine test beds ensures the consistent operation of the networked control units in all development phases while reducing the necessary test bed preparation efforts.

Complex interactions between longitudinal, lateral dynamics and fuel economy can be explored at early design and validation phases. An aggressive driving style on a lateral road profile significantly increases fuel consumption.

The presented concept allows to higher the efficiency and to wider the range of use of engine test beds, in the series development of conventional or hybrid vehicles.

8. REFERENCES

[1] Schyr, C.; Gschweitl, K. – “Model-based Development and Calibration of Hybrid Powertrains”, SAE Technical Paper, 2007-01-0285 (2007)

[2] Schick, B.; Witschass, S.; Gimmler, H.; Rauh, J. – “3D-Track – Give the Simulation the Chance for a Better Work! Mobile, High-Resolution Topology and Roughness Measuring of Road Surfaces to Create 3D Track Models”, FISITA World Congress, Yokohama 2006

[3] Morita, K.; Shimamura, K.; Ichikawa, J. – “Fuel Consumption and Exhaust Emissions Test Method for Heavy-Duty HEVs by Using of HILS”. Automotive Engineering 27 (2006)

[4] Schyr, C.; Putz, G.; Zrim, A. – “Flexible Simulation Models at the Test Bed”. Proceedings of the VDI Conference “Test and Simulation in Vehicle Development”, VDI-Report 1335 (1997)

[5] Walker M.; Ford, R. – “Hardware-In-The-Loop,Dynamometer Based Driver and Vehicle Simulator”, SAE Technical Paper, 2000-01-0289 (2000)

[6] Dorey, R.; Thring, R.; Clarke, D.; Hopwood, P.;Marshall, A.; McLaggan, J.: Vehicle Calibration onthe Test Bed (VCOT), SAE Technical Paper 2000-01-1144 (2000)

[7] Filipi, Z.; Fathy, H.; Hagena, J.; Knafl, A.; Ahlawat, R.; Liu, J.; Jung, D.; Assanis, D.; Peng, H.; Stein, J. – “Engine-in-the-Loop Testing for Evaluating Hybrid Propulsion Concepts and Transient Emissions” –HMMWV Case Study. SAE Technical Paper 2006-01-0443 (2006)

[8] AUTOSAR – Automotive Open System Architecture, http://www.autosar.org

[9] Bangemann, C. – “Rollenspiele”, Auto-Motor-Sport 22 (2007), p. 180 – 182

[10] Hohenberg, G. – “Replacing the Hybrid by Intelligent Driving”, VDI-Verlag Düsseldorf, VDI Report Volume 12 Nr. 672, 29th International Vienna Motor Symposium 2008