Model Based Steering ECU Calibration on a Steering-in-the-Loop Test Bench

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Introduction

Modern electric power steering (EPS) systems allow a flexible adaptation of the same steering hardware to different vehicle types by calibration of the corresponding control unit (ECU). As the steering behavior is one of the major factors influencing the end customers` buying decision and driving experience, the steering ECU calibration has to fit very well to the customer requirements. A growing number of functions in the steering ECU offer increasing possibilities to influence comfort, safety and steering feel and must be validated in different driving maneuvers (figure 1). However, several trade-offs of these characteristics have to be solved such as the driver's steering effort vs. the steering feedback while cornering.

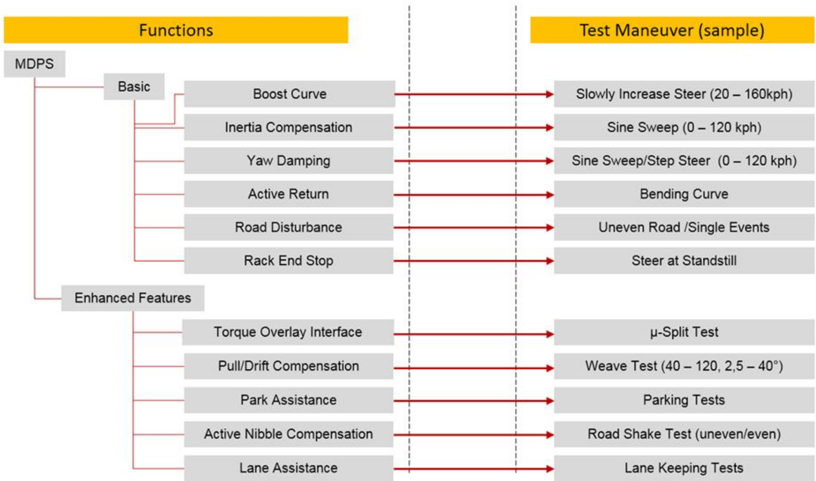

Figure 1: Functional hierarchy EPS (sample) and test maneuvers for tuning and validation

The resulting steering feel as important part of the driver's perception of a vehicle's handling characteristics is increasingly gaining importance as a customer-relevant criterion and as an element of the brand's DNA. A high-quality steering system will make the driver feel safe and comfortable; the aspect of driving pleasure is addressed by matching the driver input and the steering feedback with the vehicle's reaction. State-of-the-art simulation with CarMaker and hardware-in-the-loop (HiL) test rigs offer the possibilities needed for a reproducible and efficient tuning process in laboratory conditions. For example, the steering boost curve can be adjusted depending on the steering wheel torque and the vehicle velocity (figure 2). Hyundai Motor Europe Technical Center (HMETC) has proven the feasibility of virtually tuning the steering logic of an electrically assisted power steering (EPS) system. Automation will be a major advantage of this fully objective tuning process [1], [2].

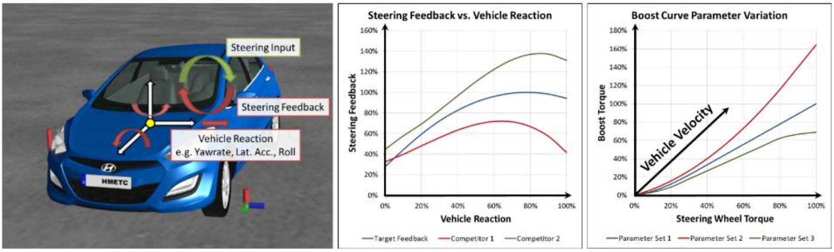

Figure 2: Steering input and feedback with vehicle reaction and the resulting task of boost curve calibration

Model Based Tuning

Figure 3 shows a generalized development environment, which appears in an analog way for any Unit Under Test (UUT), like an engine, a gearbox or a power steering.

As shown in part a) of figure 3, in case of manual tuning, the engineer operates the UUT with a certain setting of control parameters in certain maneuvers. The engineer observes the behavior of the UUT and performs a judgment according to his experience. He or she defines the next setting with the intention to better approach the desired behavior.

This process might become complex in case of many relevant tuning parameters. The quality of the optimization depends on whether the engineer considers all the parameters that are relevant for the desired behavior and on the experience of the engineer. Further subjective decisions are not traceable in general and a reuse is not possible for future projects, e.g. if the parameters have to be tuned for different driving modes. Thus, in case of the manual tuning process, each variant has to be calibrated separately.

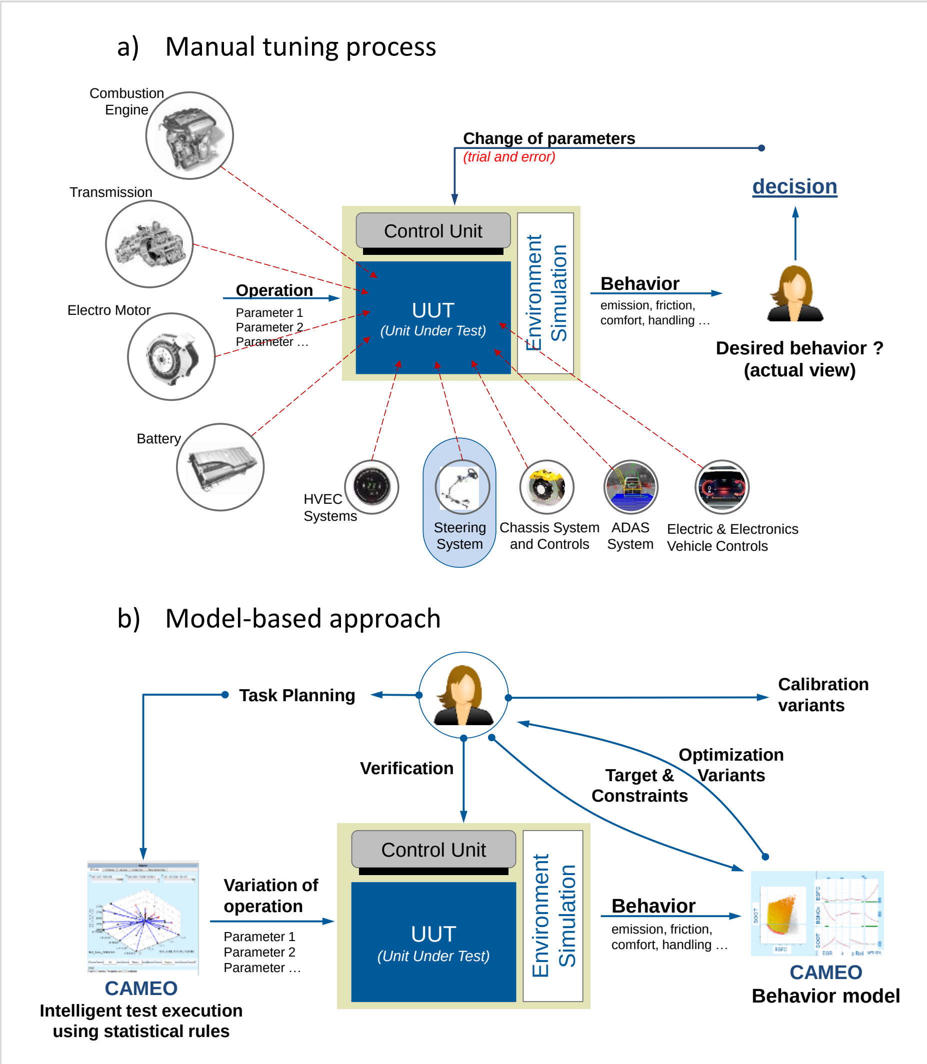

Figure 3: Calibration and optimization methodology in a generalized development environment

In part b) of figure 3, the model-based approach is shown: Here, the user starts with a task planning for a measurement series. The user aims to guide the experiments in a way allowing him/her to obtain behavior models for the evaluation criteria, which describe the UUT behavior for a wide range of possible calibration settings. These tests can be run fully automatically over several hours, like proven in the area of engine calibration e.g. [3, 4, 5].

The optimization and calibration process uses these models. Thus, the engineer gains several calibrations with different target(s). Multi-objective optimization and trade-off analyses offer additional mathematical support to the calibration engineer. In this paper, the model-based steering ECU calibration on a Steering-in-the-Loop test bench will be discussed by the example of the boost curve calibration.

Figure 4 shows the Steering-in-the-Loop test bench architecture. The system setup consists of two rack force actuators and a steering wheel actuator. In order to make sure that the mechanical behavior is comparable, the test subject is built on a stiff holder with the same fixing points and geometries as in a car. The electrical behavior is also the same as inside the car. The rest bus simulation is needed for the communication between the electrical control unit (ECU) of the steering system and the steering system test bench (STB). The communication between the ECU and the STB runs via a CAN or FlexRay interface on the real-time environment. The dSPACE real-time system serves to control the actuators and to run the virtual car model [6, 7].

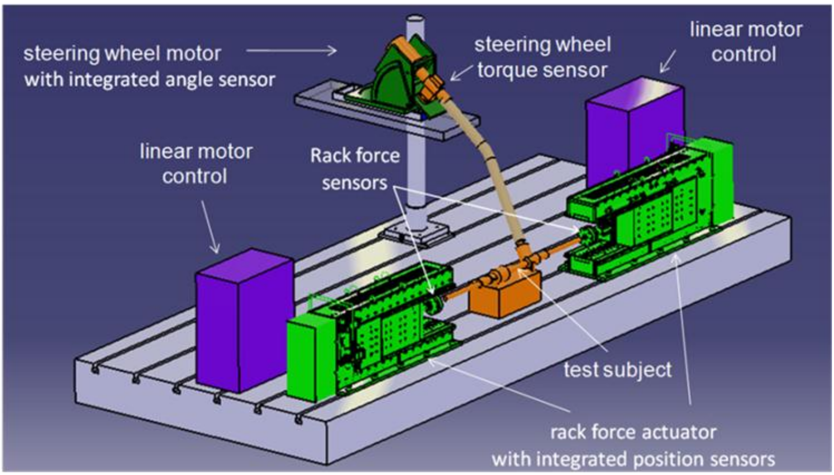

Figure 4: System setup of the steering system test bench at Munich University of Applied Sciences (MUAS)

The integration of a virtual car model into the real-time simulation environment enables the hardware-in-the-loop simulation. IPG CarMaker calculates the rack force for specific steering wheel angle inputs. The output quantities of the test subject are the resulting steering wheel torque and the rack position (Figure 5). The closed-loop simulation principle for the steer-by-torque control mode works complementary to the described steer-by-angle simulation.

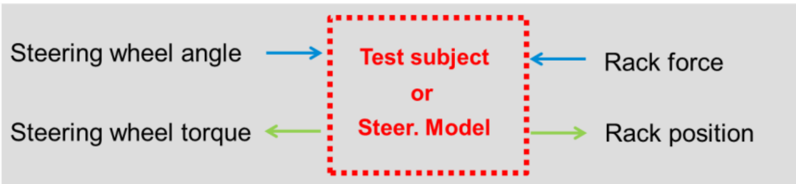

Figure 5: Steering system interface for steer-by-angle testing

The software to operate this Steering-in-the-Loop test bench runs on a workstation PC equipped with a real-time operating system.

In order to perform automated test runs according to figure 3b AVL-CAMEO is connected to both: The IPG CarMaker real-time vehicle and environment simulation as well as to the ECU application tool according to the ASAP 3 standard. The tuning parameters in the steering ECU can be overwritten for a certain maneuver by this application tool (figure 6).

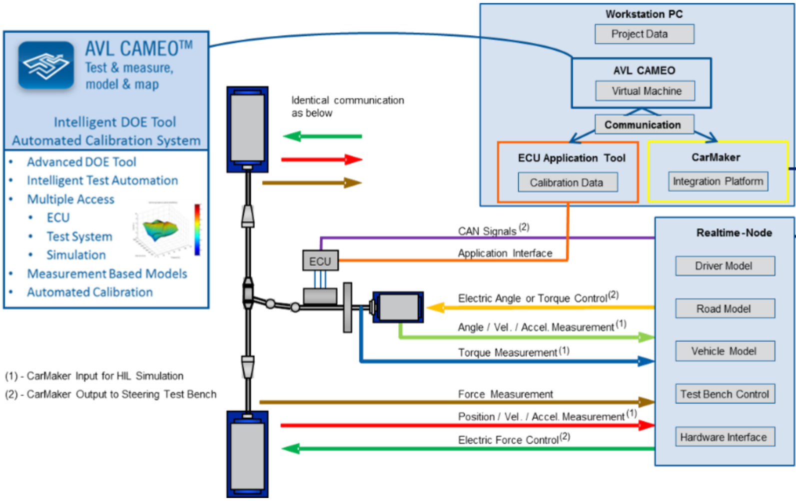

Figure 6: Hardware-in-the-Loop integration with AVL CAMEO

Task Planning, Test Preparation and Test Execution

According to figure 1 and 2, the shape of the boost curve, which can be described by 5 to 9 parameters for each vehicle velocity, should be calibrated in a way that the driver feels a suitable steering feedback while he is driving a "Slowly increased Steering test" (SiS test).

The calibration engineer starts the Parameterization with the upload of parameters into the CAMEO database: on the one hand, the variation parameters, which can be set on the two systems "CarMaker" and the "ASAP 3 –System", and on the other hand the resulting key values, which characterize the driver feedback. Such key values will be transferred back to CAMEO after the maneuver has been finished. Using the same naming for the parameters, the calibration engineer parameterizes a DoE based test run in CAMEO, which triggers several SiS tests with different calibration settings. For the example shown, the 5 most relevant ECU parameters (depending on Var0 to Var4) were selected and the velocity of the vehicle in the SiS test was varied in a range from 90 to 160 km/h. The result of using the Design of Experiment techniques (DoE), which supposed high nonlinearity of the measured responses, was a list of 326 SiS-tests. It took less than 6 hours to run these tests (figure 7).

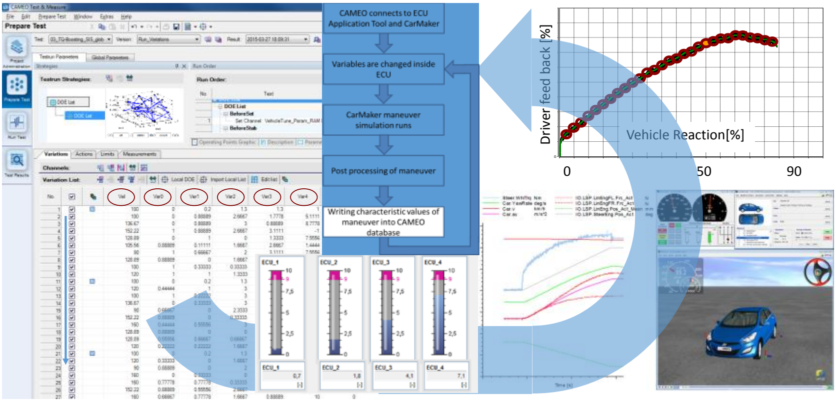

Figure 7: Test automation of the MUAS (compared to Figure 4) by AVL – CAMEO

Raw Data Analysis

28 to 30 single steering feedback values at defined vehicle reaction situations are calculated out of the resulting low pass filtered curves during the SiS test. Figure 8 shows one of these values (Driver_feed_back_at_50%_vehicle_reaction) for the 326 SiS tests as an example. It can be seen that the reproduction of the settings (repetition points colored in green) causes only very small noise in comparison to the effect that is caused by different tunings. The reproducibility provides important information about the quality of the experiments. With very high probability, the reproducibility on the Steering-in-the-loop test bench is better than the one in the real car on proving grounds. The reasons for this are additional disturbances such as temperature changes, wind or the unevenness of the road which occur on the proving ground but not on the bench.

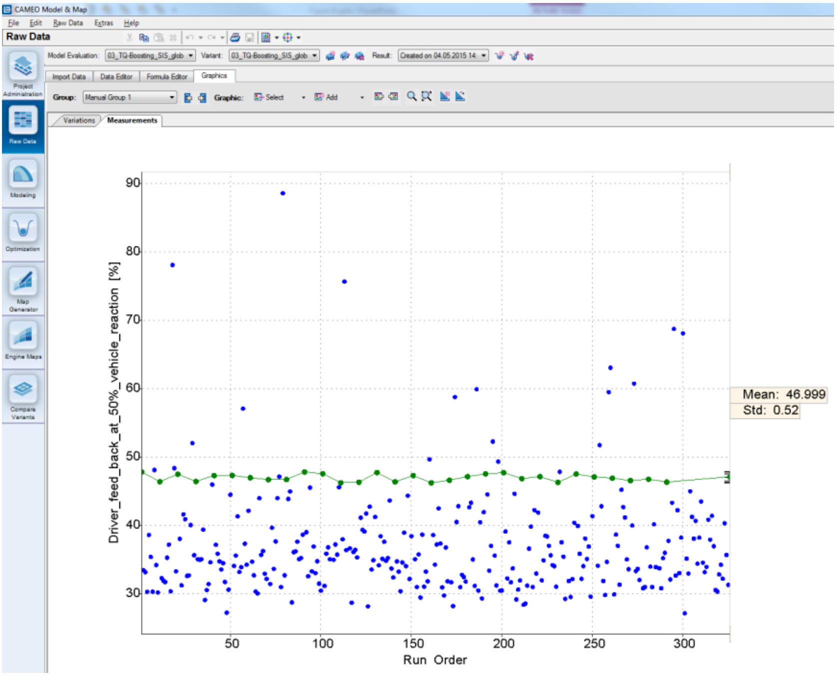

Figure 8: Raw data view of one driver feedback result with repetition point statistic

Modelling

The target of the measurement series is to get behavior models. Thus, the next evaluation step is to build behavior models that will be the base for the following steps to optimize the tuning for the desired behavior. Figure 9 shows the result of that modeling process. The engineer gets support by an automatic suggestion of the model type taking into account several model quality criteria like “Goodness of fit” or “Significance compared to Repetition point noise” [8]. Independent from the model building process, the model visualization is important. As it can be seen on the left side of figure 9, a conventional 3D visualization can only show the dependency of the result as a function of two input variables (Var0 and Var1) in this example.

The intersection graph on the right side of figure 9 shows all six model dependencies (from velocity, var0, var1, var2, var3 and var4) around a certain cursor position. This graph gives the user an immediate impression which variable affects the desired behavior and how strong the influence is.

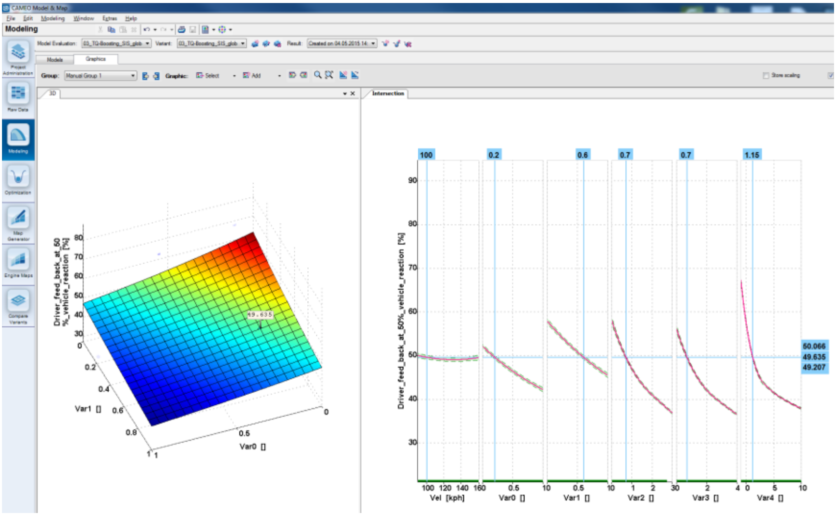

Figure 9: Behavior model of one driver feedback result in 3D mode and intersection graph with 95% confidence intervals for the model.

Only by using such behavior models in a manual way, the tuning process, which remains manual, can be run much faster and traceable than performing and evaluating new SiS tests for each setting. In addition, the calibration engineer can get support by algorithms that optimize several behavior targets simultaneously.

Optimization

In our example we would like to get 4 driver feedback values (at 10%, 30% , 50% and 70% vehicle reaction in the SiS-test) under the constraint of certain target ranges fitting a desired company steering DNA. Moreover, the function of all 28 to 30 driver feedback values should show a smooth behavior as function of the vehicle reaction. This smoothness is ensured by minimizing the smoothness indicator as target function for the optimization. Figure 10 shows the corresponding suggestions delivered by CAMEO for the target speed 100 km/h.

The left upper part shows the model section of the driver feedback as function of the vehicle reaction. This is gained by using the 28 to 30 driver feedback values as one model with the vehicle reaction as additional input parameter. This view gives the calibration engineer the perfect feeling for the immediate result of his tuning.

The right side shows the model of the smoothness index as well as the four driver feedback models at defined vehicle reaction values together with its ranges as constraint values (D_f_b_xx%). The green bars on the x-axes show the design space, which is the area of interpolation.

Since it turned out, that it is not easy to meet all ranges with a smooth curve - especially the D_f_b_50% model tended to be too low - a multi-objective optimization was used to find the right decision. The picture on the bottom left shows the corresponding trade-off behavior: Out of 25000 randomly distributed settings within the design space, the gray ones do not fulfill all the constraints at the same time and the yellow ones do. The borderline of that definition is the so-called Pareto front, shown in blue. The calibration engineer can now select between highest “D_f_b_50%” and best “smoothness_index” on this basis. He can be sure that his choice will be the best obtainable compromise between both.

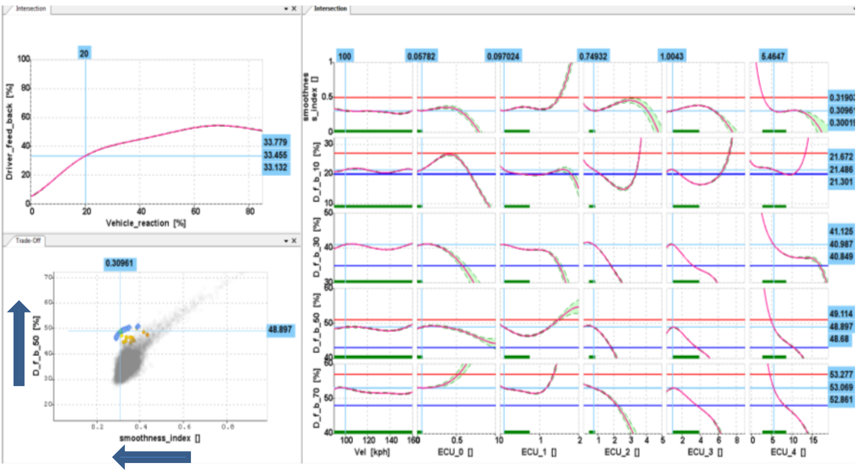

Figure 10: Optimization of the calibration setting at the vehicle velocity of 100 km/h

Similarly, the calibration engineer can derive traceable boost curve calibrations for different vehicle speeds out of this one measurement series.

Conclusion

Virtual tuning of steering feel on a HiL test rig together with an optimization tool can be a powerful combination to provide an efficient process for the development of a brand's steering DNA. The classic approach of subjective steering tuning by expert drivers on proving grounds and public roads can be supported and accelerated by delivering parameter sets matching the main targets. The application of DoE studies with CAMEO increases the number of tunings significantly compared to the manual generation on the test rig. In addition, the number of targets and tests to match these targets can be increased. This allows the engineer to cover a wider range of steering feel in more driving situations. Achieving the desired steering characteristic by the use of the presented approach will underline the unique brand DNA for both, Hyundai and Kia cars.

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