Methodology for model-based development, validation and calibration of connected electrified powertrain systems

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***Abstract*—Connectivity of hybrid electric vehicles with the driving environment offers potential to reduce energy consumption and pollutant emissions while maintaining/improving vehicle drivability. Connected powertrain systems utilize information resulting from vehicle connectivity (V2X) for efficient powertrain operation. However, connectivity has widened the system boundary conditions for hybrid powertrain operation with driving trajectory planning as additional degrees of freedom (DoF) which cannot be effectively handled by classical development approaches. This motivates the need for novel methodology for development and testing of connected hybrid electric powertrains. This paper proposes a model-based methodology employing a development environment for function-driven design which exploits model-based development to achieve front-loading. Application of the presented methodology is demonstrated with an exemplary use case. Owing to the high number of parameters and limited time for simulation or test bench work, Design of Experiment (DoE) methods are used to calibrate the connected energy management functions in this use case.**

I. Introduction

With stricter legal limits for CO_2 emission and higher cost for fossil fuel, hybrid technology or fully electrified powertrains become an increasingly important powertrain variant. Hybrid powertrains benefit from operating modes which cannot be realized in a conventional powertrain such as recuperation during vehicle deceleration and pure electric traction. Connectivity with other vehicles and infrastructure along with in-vehicle sensors provide non-causal information with potential to reduce fuel consumption, pollutant emissions and travel time. This potential has been investigated in simulations [1] and confirmed using field measurements. Further, hybrid powertrains with additional degree of freedom to meet the motive power demand largely aid, in improving powertrain efficiency along with predictive information [2], [3].

Irrespective of powertrain variant, different approaches such as component level optimization, fuel technology, vehicle and traffic system level optimization have been investigated for reduction of fuel consumption and emissions. Component level optimization addresses energy efficiency at component level using advanced automotive propulsion technologies [4]. Fuel technology concerns the use of alternative fuels like natural gas, bio-fuels or synthetic fuels to reduce fuel consumption and \ or complexity of after-treatment systems. Optimization on vehicle and traffic system level targets improvement of traffic flow and transport network efficiency. Focus of this paper shall be at vehicle level and powertrain level optimization due to the reason that component level approaches have been exploited or do not offer cost-effectiveness [5]. Field studies of tailpipe emissions have helped identify the correlation between driving mode and fuel consumption/emission. Acceleration events have the highest share in the increased fuel consumption and emissions despite their lower occurrence frequency [4]. Ecological driver assistance systems aid the driver in improving the vehicle energy efficiency and reducing the pollutant emissions. Such systems could operate without preview information in post-processing mode, providing feedback about driving style. But effectiveness of ecological driver assistance systems can be increased using the information available through connectivity. ECOMOVE, an European initiative, targets reduction in fuel consumption and emissions using co-operative vehicle-infrastructure systems. Evaluation of developed measures in field trials and driving simulator studies was performed using comparison against a baseline. Fuel savings of 4.5 - 25% were achievable using anticipative driving behaviour without adverse effects on safety [6]. KOLINE, a research project funded by German Federal Ministry for Economic Affairs and Energy, demonstrated fuel reduction and travel time reduction potential in field tests. The approach was based on mutual optimization of the assistance system (vehicle level) and traffic light control (traffic level) using bidirectional information exchange [7]. In its present form, the proposed real driving emissions (RDE) legislation planned fro introduction in 2017 defines CO_2 limits for post processing (by CLEAR / EMROAD) using Worldwide harmonized Light vehicles Test Cycle (WLTC) [8]. Achievable consumption and emission reduction through connected powertrain systems is not quantifiable in pre-defined cycle based homologation. Crediting of such benefits whose effects are not measurable in cycle-based procedures is facilitated by Eco-innovations and Off-cycle credits in Europe and USA respectively. With the regulation (EG) No. 443/2009, OEM and component suppliers can avail benefits of such CO_2 reduction measures to meet fleet level emission targets. Such a system jointly developed by BOSCH and PSA Peugeot Citroen which uses navigation based data for pre-conditioning of battery systems has been approved [9], [10]. This development highlights the advantages of connected powertrain systems in real driving conditions which offers added value to customers.

Powertrains that use information arising from connectivity for efficient powertrain operation are termed as connected powertrains. Connected powertrains relying on ecological driver assistance systems cover a broad spectrum of assistance tasks ranging from monitoring, suggestive or intervening character [11]. Such powertrains in combination with predictive powertrain control show great potential to achieve best results in fuel consumption, pollutant emission and driver comfort. To take full advantage of this potential, a well-structured methodology for development, testing and calibration of connected powertrain is necessary. This paper presents a possible solution for such a methodology.

II. Model based development approach and system architecture

A. Model based development approach

Development of modern powertrain systems have become increasingly challenging due to system intricacy, due to technologies such as turbo downsizing and complexity of after treatment systems [12]. The realized powertrain solutions systematically exploit the different available operational degrees of freedom. In the setting of conventional powertrain, this would translate to optimize collectively available functionalities such as fuel injection, exhaust gas recirculation or Ad-Blue dosing to achieve fuel consumption and emission goals. In case of hybrid electric powertrains, this would require interoperation of the electric traction machine and combustion engine to meet the power demand. Increasing number of vehicle models and powertrain variants futher increases complexity. Classical development approach works with abstraction of normal conditions and corrections required in case of deviations. The nominal operating conditions are usually defined by synthetic profiles or typical usage patterns. The calibration associated with the nominal conditions and correction factors are parameterized using look-up tables. Such approach is less attractive due to complexities arising from enlarged system boundaries due to connnectivity. In contrast to set-value based approaches, model based approaches are based on models (from first principles or identified using experimental data) with physically motivated parameter set for development, diagnosis and calibration. Hence they provide consistent cross-domain interactions among the interacting agents and are suitable for the development of connected powertrain systems. Further, the ability to front-load development and validation tasks, helps avoid costly time-delayed system-level changes and is an other advantage of in view to shorter time-to-market requirements of automotive powertrains.

B. System architecture

The introduced methodology is based on a generic system architecture with two optimization layers: an offline, powertrain specific layer as well as an online optimization which is powertrain independent. The system architecture has been developed in [13] and is based on the analysis of basic physical principles in energy flows. Given the definition of energy efficiency:

$$\text{Energy Efficiency} \propto \begin{cases} 1/\text{Energy Consumption} \\ 1/\text{Energy Losses} \end{cases} \tag{1}$$

Energy efficiency can be improved by reduction of losses. But the effort involved to reduce losses using optimization of individual components has been already exhaustively investigated. On the other hand, reduction of (undesired) energy consumption offers potential from the efficiency viewpoint. The energy demand is a result of the driving resistance forces on the vehicle:

$$F_{res} = F_{aero} + F_{roll} + F_{acc} + F_{inc} \tag{2}$$

where F_{res} is the resulting driving resistance, F_{aero} the aerodynamic force, F_{roll} the rolling resistance, F_{inc} the inclination resistance and F_{acc} the acceleration resistance force. Thus, energy demand can be affected by design-engineering approaches like a flow-optimized vehicle body (F_{aero}) or lightweight design (F_{roll},F_{acc}), but also by choosing a different driving route with a different height profile (F_{inc}) or by optimization of the vehicle trajectory (F_{acc}). Energy losses on the other hand can be reduced either by improvement of engine technologies or, in case of a hybrid electric powertrain, by operating the energy converters in load points with a higher overall system efficiency.

The system architecture is divided in three major parts: Information collection, information processing and information output. Information collection module consists of a vehicle-independent environment model as well as a vehicle and powertrain dependent energy conversion model. The task of the environment model is to provide a consistent representation of the vehicle environment. Basic information required for building the environment model are obtained from digital maps with GNSS-based localization. These data are fundamental sources for static information about altitude and slope, speed limitation and curvature, which are essential for calculating future driving resistances. These static information can be complemented by additional dynamic data like position and velocity of other traffic participants or position and state of traffic lights by V2X Communication or on-board sensors (radar, video). The target of the vehicle and powertrain dependent energy conversion model is to quantify the energy flows in the powertrain including energy losses. The conversion model consists of a power demand model, which is dependent on environment information and the predicted vehicle velocity profile as well as a power supply model, which contains models of the energy converters and energy storages.

In the energetic optimization module, the minimal cost driving and/or operating mode gets calculated. Central element

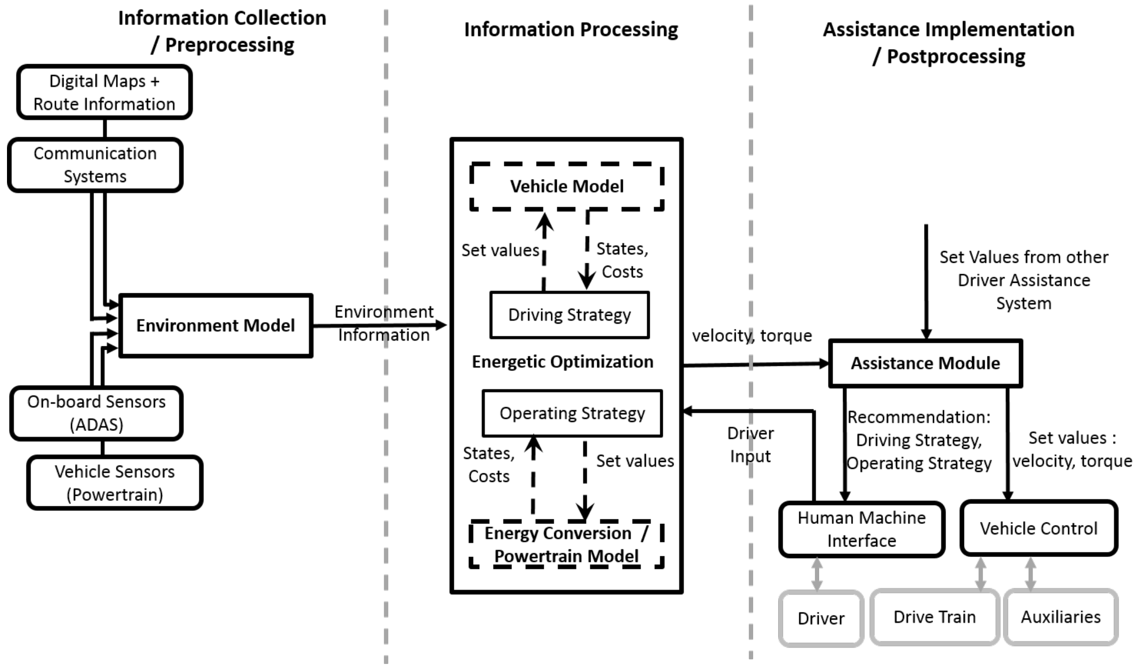

Fig. 1. System architecture based on [13]

is the optimization of a cost function, which can be a function of energy, time, comfort and/or other target values. Input of the energetic optimization are boundary conditions derived from information in the environment model module. Based on these boundaries, a vehicle velocity corridor with a minimum and maximum velocity gets calculated. Within these bounds, the driving mode module performs an online optimization of the cost function with the optimum velocity profile as a result. Target of the introduced system architecture is to modularize between optimization on the vehicle level and powertrain level. The operation strategy on the powertrain level is superimposed by the vehicle level driving strategy module. Fig. 1 gives an overview of the generic system architecture defined in [13]. The Assistance module receives set point values for velocity and torque. In case of conventional powertrain, velocity would serve as demand value. Hybrid powertrains with operating strategy would request torque set-points for the energy converters and braking system. As discussed in [13] this module also functions as an arbitration unit prioritizing requests from conventional ADAS guidance functionality like ACC. The generic system architecture modularizes and defines the interfaces between the modules but does not favor certain functional realization. Depending on data availability, either causal, anticipatory or even full-prescient energy management strategies can be realized. Further suitable numerical approaches such as dynamic programming, indirect and direct optimal control can be selected [14]. The developed modular system architecture scales to different horizon lengths. It can either be used to pre-compute driving and operating profiles for the entire trip (long horizon length) or compute online the respective profiles on a maneuver level (resulting in a short horizon length). System architecture was developed in a way to ensure applicability and if necessary adaptability as well as extendability for current and foreseeable future powertrain variants.

III. Methodology

A. Methodology for functionality development

The development methodology for connected powertrains is an extension of the development methodology of the Institute for Internal Combustion Engines and Powertrain Systems (VKM) [8], which in turn is an adaption of the normed V-Model (VDI 2206) for powertrain development. Extensions ensure flexiblity of the approach for development of components, complete aggregates and control strategies as well as calibration. Fig. 2 depicts the proposed development methodology. The process is started with investigation of functional requirements, followed by the design and implementation phases. The design process begins with acausal simulation model, which is mainly used for assessment of potential (derived from requirement analysis) and component dimensioning. Functional development is carried in the subsequent step using causal models. Subsequently the developed artifacts are validated in the actual / emulated operating environment ranging from simulation through engine-,powertrain- and chassis-dynamometer In-the-Loop to real world driving. The abstraction level in the development environment is enabled by In-the-Loop systems which couple real components with simulation models. Further information about In-the-Loop test environment for connected powertrain development can be found in [15] and references therein. An important aspect of this methodology is the seamless transition between the different development phases. This is achieved using the same development environment from simulation studies through implementation and verification in In-the-Loop configuration. The functionality under development and its performance in nominal and off-nominal conditions define requirements of the used environment.

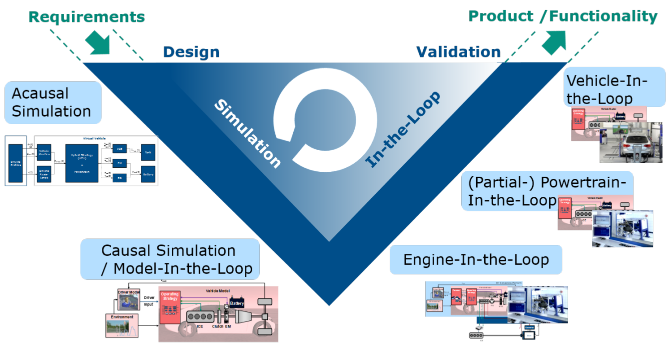

Fig. 2. Proposed development methodology based on [8], [15]

1) Nominal functional requirements: The functionality of connected powertrain systems can be broadly modularized as:

- Representation of environment model with tracking of relevant objects using sensor fusion
- Detection and assessment of relevant driving situations
- Deduction and implementation of appropriate intervention in accordance with current situation

Data for environmental perception may originate from on-board sensors, digital maps or through communication with other stationary and non-stationary traffic participants. Electronic horizon constitutes a key element in the development and validation of connected assistance systems. It uses map data along with vehicle connectivity and on-board sensors providing dynamic data to a spectrum of systems such as predictive curve light, curve speed warning, and traffic sign detection or range determination [19]. Though the focus from development perspective shall be on functional requirements, non-functional requirements such as scalability, re-usability have been considered in the development of the system architecture.

2) Robustness requirements: Connected powertrain systems operate using non-causal data from information sources which exhibit uncertainty. Reasons for uncertainty could be systematic distortions, exogenous disturbances, noise or due to electromagnetic compatibility issues. Further failure of data sources could also result in unreliable data. This data with uncertainty serves as basis for generation of the environment model, which in turn is used to evaluate the situation and to perform appropriate action. Hence, data uncertainty influences the anticipatory operation of the powertrain system and may lead to either sub-optimal / non-optimal operation or failure of functionality. Sensing methods with different functional principles such as optical, acoustic or inertial along with machine learning algorithms find applications for sensing the vehicle environment [17]. Resolution of the data obtained depend on the operating principle of the used sensing techonology. [17], [18] and [15] as well as references there, compare the features of sensing technologies used for assistance systems in automotive domain. In order to ensure proper functionality, connected powertrain systems shall be robust under certainty within sensor tolerance limits. Further increasing length of the prediction horizon, reduces the accuracy of the non-causal data. Approaches have been presented to deal with uncertainty in data acquisition for environmental model using multi-layered data processing techniques [20]. Nevertheless, connected powertrain systems have to exhibit robustness beyond its nominal functional specifications during initial stages of introduction owing to the defects in the data quality and to gain increased acceptance. Hence, the development and validation environment shall not only reproduce the nominal interactions but also offer possibilities to study robustness of the functionality by emulating non-nominal operating conditions. Depending on the focus of development, phase of development and availability of virtual as well as real components allows decision on the abstraction levels. Based on the required level of abstraction, the scaling between real and simulated components shall be interchangeable.

3) Functionality development using online optimization: To illustrate the applicability of the proposed development methodology, this section discusses an automated longitudinal guidance system that was developed using the methodology. The approach uses dynamic programming (DP) (the discrete time, state and control space variant of the Hamilton-Jacobi-Bellman equation) [21]. The vehicle velocity is used as state as analysis of data collected from real driving shows that the subjective perception depends mainly on free choice of speed without traffic and in presence of traffic on the choice of speed difference and time-gap to the preceding vehicle [3]. Goal of the applied dynamic optimization is to compute the torque set value for the powertrain. Though DP suffers from the curse of dimensionality, the exponential increase in the computational demand increase with the state and input resolution, usage of the method is enabled by an iterative reduction of the search space. Such a search space is shown in Fig. 3.

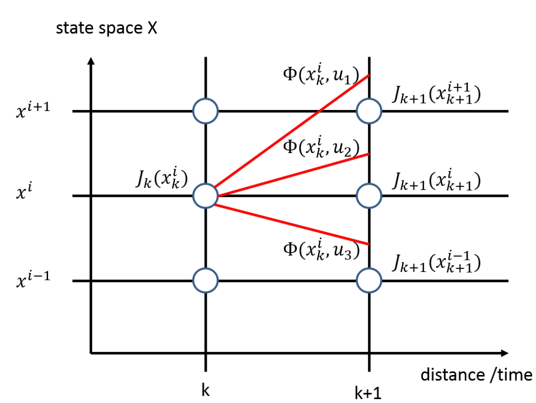

Fig. 3. Discrete state and input space of DP

$$x_{k+1} = \Phi(x_k, u_k, w_k), \quad x(0) = x_0 \quad (3)$$
$$k = 0, 1, ..., N-1 \quad (4)$$
$$J_k(x_k) = \min\{g_k(x_k, u_k, w_k) + J_{k+1}(\Phi(x_k, u_k, w_k))\} \quad (5)$$

DP minimises a dynamic cost for the horizon with an objective / cost function, which is sum of the terminal cost and stage cost. The state transition is described by $\Phi(x_k, u_k, w_k)$ depending on initial state, input and disturbance (external inputs and unmodelled dynamics). Bellman principle that states, along any optimal trajectory the stage cost $g_k(x_k, u_k, w_k)$ plus the cost of a single transition adds up to the remaining optimal cost. In discrete time, recursive computation can be used to reduce the multi-stage optimization to a sequence of single-stage optimization problems [21]. Using DP based on selected optimization criteria, an optimal velocity trajectory is computed. The development environment provides the maximum and minimum limits of the velocity corridor and torque set point. Further the computed velocity is realized by the vehicle level controllers which are part of the development environment. Based on the desired driving behavior, the driver can choose between dynamic, comfort and economic modes as in [3], [2]. Energy mode aims to reduce the energy demand for traction at wheel. Consideration of energy consumption at wheel reduces dependency of powertrain configuration. Improved driving dynamics is achieved in dynamic mode using higher acceleration limits and increase of the average speed. Driver's subjective perception of comfort is a complex criterion for the longitudinal vehicle guidance [3]. In comfort mode, the driving strategy uses jerk as a minimization criterion which corresponds to a homogenous velocity profile [3]. Fig. 4 shows three different velocity profiles, optimized for dynamic, comfort and energy demand in given velocity boundaries with pre-defined initial and final velocities.

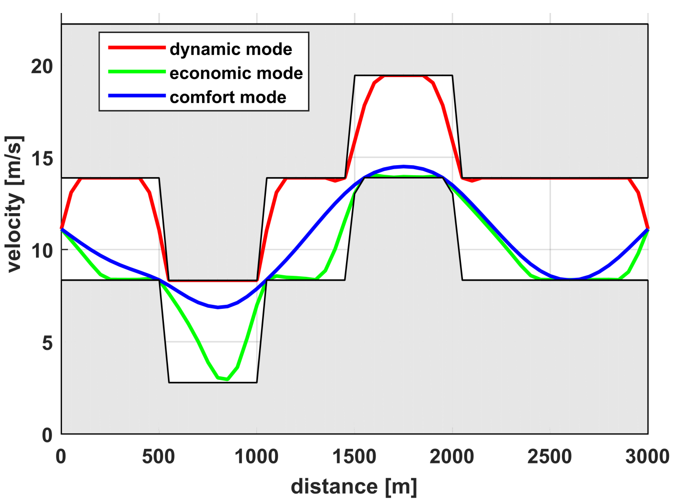

Fig. 4. Exemplary velocity corridor with trajectories for different modes

B. Validation methodology

Validation methodology is constituted by validation strategy based on test methods suitable for connected powertrains. Challenges in system validation arise due to extended system boundary and dynamic change of associated boundary conditions. This requires an appropriate validation environment which represents the interactions between vehicle, driver / assistance functions and vehicle environment along with interfaces to ensure the connectivity required by the function to be validated. Though the data availability through connectivity offers advantages, it also presents challenges due to the complex cross-domain interactions. In addition, the developed functionality shall be robust against dynamic and signal uncertainty originating from data sources. [16] recommends a test strategy for the system test of highly networked systems. The test strategy is based on the test methods which can be characterised as below depending on features and definition of test cases:

- Systematic tests : systematic approach to achieve complete coverage of requirements through methodologically structured test specificiations
- Manuever based tests : realistic tests which complements or reduces real driving
- Evolutionary tests : tests generated by evolutionary algorithms with proper initialization targeting critical events
- Statistical tests : test generated using statistical methods

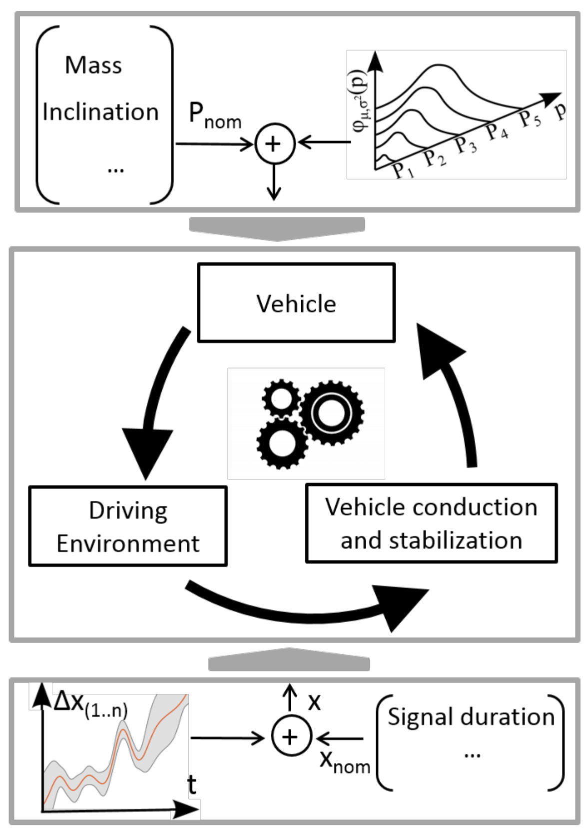

Fig. 5. Proposed validation methodology

The proposed validation methodology aims to incorporate a priori knowledge for the selection of parameters and definitions of their limits considering possible physical limits of the time-variant uncertainty. These requirements lead to an event-based test method which is capable of analyzing the effects of uncertainty on the system performance. This method represents a combination of manuever based and statistical methods. An event can be triggered unilateraly or collectively by ego-vehicle, traffic elements and infrastructure. Example of such an event would be traffic light approach. The known disturbance sources which can vary dynamically can be modelled using gaussian processes.

Variable parameters are classified on lines of temporal variations during test scenario execution as static and dynamic scenario parameters. Dynamic scenario parameters can vary during execution of a test scenario, whereas static scenario parameters are fixed during execution but can be varied in the initialization phase. Examples of static and dynamic parameters are curvature of road and time for a particular traffic light to switch to green from red respectively. Fig. 5 depicts the validation methodology. The quantities P and x represent the static and dynamic scenario parameters respectively. In the initial phases of functionality development the validation methodology can be used for functional evaluation. In subsequent phases, robustness can be analysed by allowing variations within the predefined limits of the corresponding quantities. Validation methodology can be applied irrespective of the realizations of vehicle, driving environment as well as vehicle conduction and stabilization as real or virtual entities. This scalability between real and virtual components in the validation methodology helps gain benefits of reproducability in case of virtual and accuracy with more real components.

1) Scenario catalogue: The system stimuli used along with the validation environment is defined using driving scenarios. These scenarios characterize realistic connected powertrain relevant driving maneuver with/without events hence ensuring traceability to customer usage patterns. Such an event can be switching of a traffic light or shear-in of a vehicle to the ego-vehicle's driving lane from another lane. Further the scenarios are associated with evaluation criteria to objectify the validation results. A typical criteria in case of functional validation would be fuel / energy consumption. Minimum time and minimum energy consumption are evaluation criteria during approach of traffic light. Validation scenario for ecological driver assistance systems are not restricted to stimuli from communication with traffic or infrastructure. Drive on changing topography involving dynamic cornering can be performed by regenerative braking before the turn to charge the battery, use the recuperated electrical energy to accelerate at the end of the curve and hence optimize energy consumption. A detailed description of the validation scenarios for functional validation and robustness analysis of connected powertrain systems can be found in [11]. Transferability of scenarios is ensured by the usage of methodology (which ensures seamless transfer between validation environments) and consistent as well as realisitic development environment / simulation platform (which ensures representation of the interacting agents namely vehicle, vehicle environment and driver / driving strategy with corresponding accuracy)

C. Calibration methodology

Due to increased number of actuators, the associated complexity in calibration and increasing model accuracy as well as their prediction capability, model based methods are increasingly applied for calibration of automotive control units [24]. Using DoE based workflow, system behaviour is abstracted using mathematical models which are used to calibrate control functionality. Experiment design plays an important role in model-based calibration workflow. Using a priori knowledge of dependencies between objectives and parameters help reduce the effort in experimentation and measurement. With these mathematical models multicriteria optimization is possible using suitable methods like genetic algorithms. The result in case of multiple objectives is the pareto set, a set of optimal configurations. Such a procedure has been shown for calibration of energy management functionality at Engine-In-the-Loop testbed [23]. If the system response characteristics is known beforehand and mathematically describable, e.g. using polynomial functions, the D-optimal design provides the possibility to run the experiment with as few as possible parameter variations while producing sufficient data to derive mathematical models with high accuracy. In case the system response is unknown, the D-optimal design is not applicable. It can be handled by the s-optimal design which distributes a given number of testing points equidistant in the experimental space to cover a maximum of possible results while leading to a higher number of experiments and a higher effort in time compared to the D-optimal design.

D. Usecase

The application of the presented methodology is shown on an exemplary use case. The implementation is done in AVL InMotion powered by IPG CarMaker in a co-simulation with Matlab/Simulink and AVL Cameo. Driver, vehicle dynamics and driving environment are modelled using AVL InMotion / IPG CarMaker. It shall be noted that the driver model is only responsible for lateral stabilization tasks, whereas the longitudinal guidance and stabilization is performed by the driving strategy module. Suitable realistic representation of the driving environment is a prerequisite for representation of the vehicle driving environment and hence for proper function of the driving strategy. The use case considered is approach of a traffic light with known duration of green or red phases and known traffic light position. These information are input values for the predictive system as well as vehicle velocity and position. The first step is to check, if a traffic light is located within the preview horizon. Based on the outcome of this check, a velocity profile is calculated using the known phase duration of traffic light switching and actual position of the vehicle. Based on the available data, vehicle and powertrain state, the operating strategy could request to maintain a particular speed, accelerate, decelerate, brake to a stillstand. The demanded vehicle trajectory is used to compute the torque requests to powertrain and braking system by the

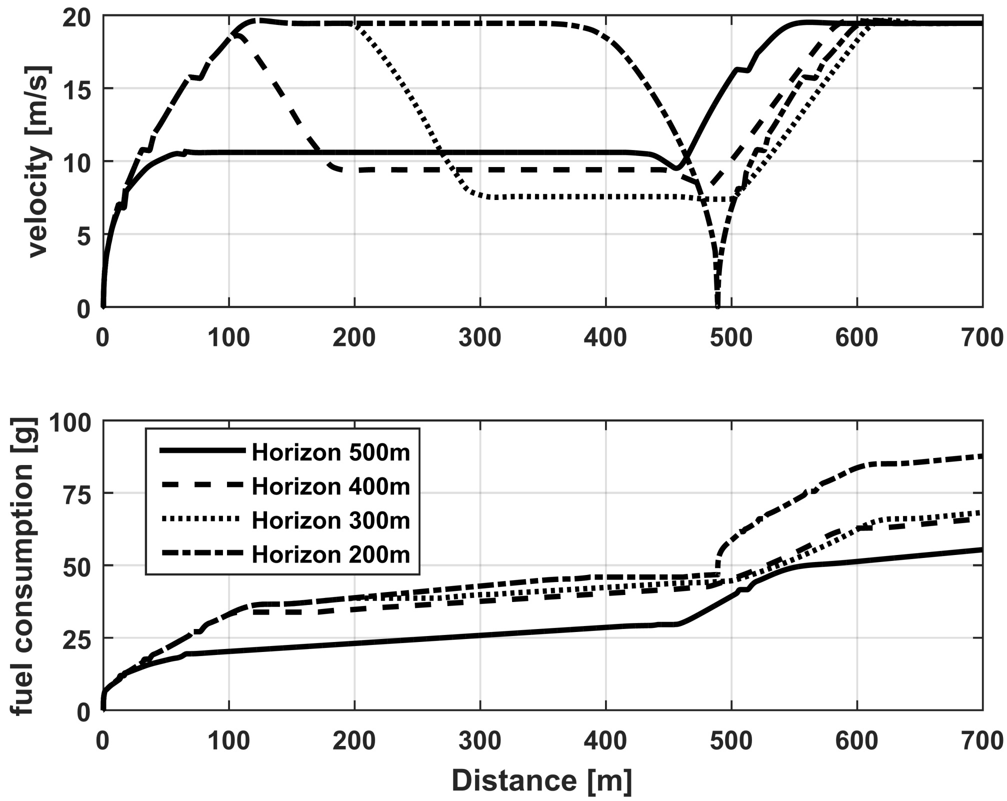

Fig. 6. Velocity and fuel consumption during traffic light approach

operating strategy, which is realized on the component level by the assistance and vehicle control modules. Fig. 6 presents results of such a traffic light approach scenario. A traffic light is positioned in a distance of 500 meters from the start point of the vehicle with initial state red. The preferred velocity of the vehicle is set to 70 km/h. For function-testing the prediction system, the length of the preview horizon is varied from 200 up to 500 meters. Resulting velocity profiles and energy demands are shown in Fig. 6. With a preview horizon of 500 m, the vehicle only accelerates up to a velocity of 40 km/h and passes the traffic light in a green phase with lowest energy demand. With a preview horizon of 200 m, the predictive system detects the traffic light too late to pass it in a green phase and the vehicle is stopped in front of the traffic light resulting in the highest energy demand due to the acceleration after the light turning green. The higher fuel consumption rate during the acceleration from braking to stop can be observed. In comparision during other acceleration events in the region between 450 and 500 m, the fuel consumption rate is comparably low.

The parameterization of the operating strategy in the energetic optimization module is done in an offline optimization using DoE methods. This exemplary optimization is performed using AVL Cameo. The first step in experiment preparation is the definition of variation and target parameters. Both variation and target parameters are vehicle and/or powertrain dependent. With contrary change of the result values in dependency of the variation parameters, both result parameters can be plotted in a pareto-set like shown in Fig. 7. The figure shows exemplary the trade-off between fuel consumption and battery stress for a traffic light approach with a hybrid electric vehicle. Every point in the figure represents the results of one specific input parameter combination. Heuristic parameters varied to obtain the paretofront are the vehicle speed and minimum gas pedal position which would switch on the internal combustion engine. The pareto-set is limited towards the co-ordinate origin by the pareto-front (blue line), having the property that an improvement of one target value results in a worsening of the other value: A Reduction of fuel consumption is achieved by electrical support resulting in a higher battery stress and vice versa. Hence, a final selection of variation parameters has to be done manually or with additional decision criteria. An interesting prospect in case of heuristic operating strategies knowledge of pareto set can be used to tune online its behaviour in drive-aware scenarios to improve subjective driver acceptance maintaining optimality.

IV. Conclusion

Automotive powertrains with no/limited environmental awareness are being developed to achieve predefined emission and fuel consumption targets in a well-known test procedure based on a predefined, synthetic driving cycle. This methodology is not applicable to the development of interconnected hybrid powertrains due to the strong limitation in DoF and the

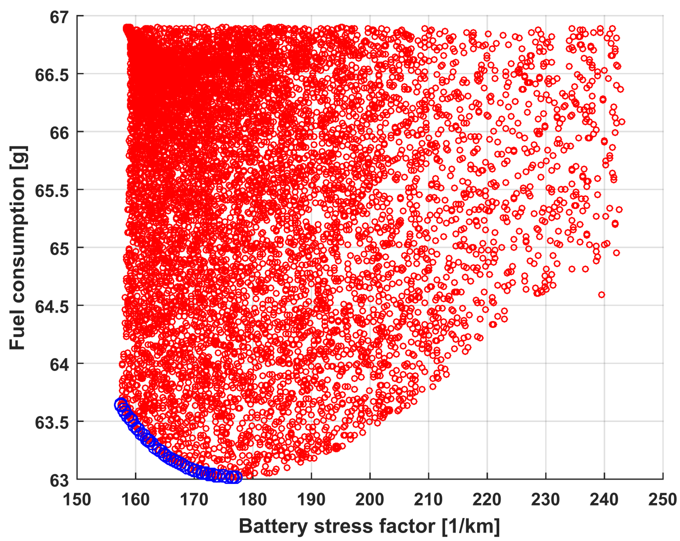

Fig. 7. Paretofront from optimization of heuristic parameters

inability to cover the variability of system boundary conditions in real world driving scenarios involving influences of traffic and environment. Increasing complexity due to additional degrees of freedom, wide variety of variants, faster development cycles with shorter phases necessitate efficient and comprehensive methods for development, validation and calibration of modern automotive powertrains. These methods have to be supported by standardized developed and test environments ranging from simulation tools through test environments to vehicle procedures. Further, they shall ideally be automatable based on viability and necessity. This paper presented a methodology based on a consistent model-based environment for development, validation and calibration of connected powertrain systems with variable levels of hybridization. The methodology enables flexible integration of relevant dynamics with different abstraction levels ranging from virtual behavioral models to real components integrated in an In-the-Loop test setup. Task of connected anticipatory powertrain development is modularized in a generic system architecture and a layered control architecture. The generic system architecture decouples the vehicle independent functionality from powertrain specific energy conversion model. The layered controller constitutes event triggered functional modules. This approach provides a basis for environment-aware functionality development regardless of their realizations such as classical rule-based or optimization based systems. Challenges from the validation perspective is to ensure functional reliability and robustness in presence of uncertainties. These have been overcome using an event-based validation strategy to realize the relevant system stimuli retaining causality and consistency. The methodology supports environments with different scalability of real and virtual components and facilitates transferability of validation scenarios between simulation and In-the-Loop test environments. As presented, calibration of the heuristic parameters of the controllers can be performed using model-based calibration methods.

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