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Co-Simulation of Multi-Domain Engine and its Integrated Control for Transient Driving Cycles

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Abstract: Virtualization of powertrain components allows the front-loading of conventional vehicle calibration and validation tasks to Model-in-the-Loop (MiL) and Hardware-in-the-Loop (HiL) simulations. This approach is based on the utilization of highly accurate physics-based powertrain models that enable a seamless system validation using virtual testing methods in order to ensure cost-effective powertrain development by reducing hardware tests. Proper modelling methods target the optimum between parametrization effort, model accuracy and required computing power to grant the real-time (RT) capability of the simulation, which is mandatory for HiL simulation. In this paper two validated modelling approaches and their implementation into a MiL environment are introduced and discussed. The approaches are the MATLAB/Simulink based Mean Value Engine Model (MVEM) and the Fast-Running Modelling (FRM) of GT-Power. After the models integration in a Simulink frame, the responses of a model-based control unit with the two simulation models were evaluated using real experimental data. In transient cycles, the controller showed a different reaction to the feedback signals of the two engine models. The purposes of the conducted investigation are mainly to evaluate strong and weak points of both approaches and to propose the best-practice modelling approaches for virtual calibration and validation. A comparative rating shows the main advantage of the MVEM in the flexibility for HiL-based systems and the model training effort for the FRM.

Keywords: Engine modelling, Closed-loop control, Model-based control, Real-time, Virtual development.

1. INTRODUCTION AND MOTIVATION

The increasingly restrictive emissions limitations are one of the greatest challenges that powertrain development has been facing in the recent years. The new emission requirements under real-driving conditions increased the challenges of engine calibration processes. To invest efficiently in innovative highly complex strategies with a wide range of working conditions, Original Equipment Manufacturers (OEMs) and Tier 1 suppliers need to minimize their costs. The virtualization of powertrain components is surely an efficient solution to fulfil this rush to technological innovation by keeping an eye to costs, test safety and accuracy targets. This has led to make modelling an important research and development field. Front-loading the hardware testing to Model-in-the-Loop (MiL) and Hardware-in-the-Loop (HiL) simulations is nowadays a commonly implemented process that seeks for a seamless system integration and testing by using virtual components. This Road-to-Rig-to-Desktop (R2R2D) approach prioritizes the search for the optimum between results accuracy, calibration effort and computing power (Lee et al. 2019). Additional advantages highlighted in the R2R2D approach are the system optimization in transient driving conditions and function development during the concept phase. The setup of a full simulation environment is highly dependent on model availability in the specific development phase and the reuse of those models in a co-simulation scenario is the base idea of R2R2D (Andert et al. 2018). In this framework, it is therefore necessary to choose carefully the powertrain modelling strategy and the simulation tools to be used to fulfil the desired scopes. Regarding the powertrain modelling and in particular engine modelling, different levels of detail can be targeted according to various project boundaries, control goals or accuracy to be achieved. Several simulation approaches can be implemented depending upon the development phase and the use cases (Millo et al. 2011) (Cosadia et al. 2013).

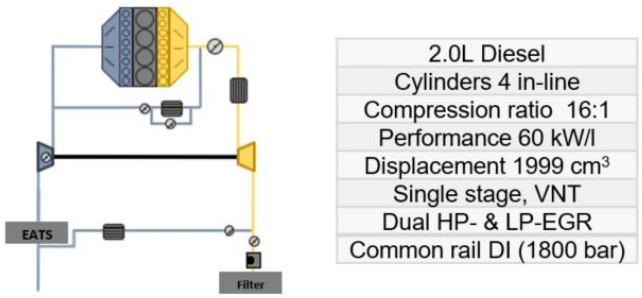
This research focuses on two engine modelling methodologies. A Fast-Running Model (FRM) could be created through model reduction from a 1D detailed GT-Suite model (Gamma Technologies 2018b) (Millo et al. 2013), (Ruggiero et al. 2014), (Xia et al. 2018). The potential of a crank angle resolved combustion combined with a 0D air path has already been demonstrated (Piano et al. 2016), (Xia et al. 2018), (Xia et al. 2019). The physics-based Mean Value Engine Model (MVEM) has been used to predict the engine behaviour over the complete operational driving cycle, also enhancing its adaptability with multi-scale engine modelling combining mean value air path with an empirical DOE combustion model (Lee et al. 2019). The real-time (RT) capability of both models was proved for HiL applications with real Engine Control Unit (ECU) hardware, like HiL-based calibration processes (Lee et al. 2019), (Kötter et al. 2018), (Lee et al. 2018b), (Xia et al. 2018).

The paper focuses on the different interactions with a ECU model, underlining the transient response of the air path controller. Finally, this co-simulation method has been used to estimate advantages and disadvantages of the both modelling approaches, outlining the most relevant characteristics with a view to real driving conditions and future multi-scale model improvements for HiL applications. The goal of the research is to investigate two different engine modelling approaches, their consistency across transient driving cycles, and their suitability for HiL-based ECU calibration purposes. A previous work with the FRM (Xia et al. 2018) can be seen as a proof of concept for the HiL-based virtual calibration. Precisely, a load step was tested, but no calibrated emission model was included in the engine model. Therefore, in the first part this research focused on the integration in the FRM of a semi-physical emission model, to consistently reproduce NOx prediction. In the second part, a methodology to develop a heterogeneous multi-domain environment containing FRM, MVEM and controller to perform MiL co-simulations, is proposed. Finally, an overall summary of models characteristics has been created, with an eye at future HiL-based ECU calibration purposes.

2. PHYSICAL REAL-TIME ENGINE MODELLING

2.1 Engine Specification

For this study, a state-of-the-art Diesel powertrain is used. It contains a turbocharged 4-cylinder, direct injection Diesel engine with high-pressure (HP) and low-pressure (LP) Exhaust Gas Recirculation (EGR) system. For the purpose of parametrizing the engine model and calibration of emission and control models, the following hardware specifications are considered (listed in Fig 1.).



2.0L Diesel
Cylinders 4 in-line
Compression ratio 16:1
Performance 60 kW/l
Displacement 1999 cm^3
Single stage, VNT
Dual HP- & LP-EGR
Common rail DI (1800 bar)

Fig. 1. Schematics and specifications of exemplary Diesel engine

2.2 Fast-Running Modelling

Information regarding the creation of this 0D FRM, the RT capability and its integration in a HiL environment on a third party tool for HiL-based virtual calibration is described in a previous work (Xia et al. 2018). The 0D air path has been modelled by a gradual conversion of the air path from a detailed model, which contains 1D flow elements, to 0D elements with same surface area and volume. However, the overall characteristic pressure traces in the exhaust manifold are well captured despite a slight loss of quality in capturing high-frequency wave dynamics. The engine components between the flow elements, e.g. cylinders, injector, valves or turbocharger, are not touched by this simplification process. The combustion model consists of a predictive model which reacts directly to injection rate and rail pressure. The same fixed time step of 0.334 ms from the 1D detailed model has been used, in order to reduce accuracy drawbacks of simulations results.

2.3 Mean Value Engine Modelling

The model-based structure of the MVEM is described in (Blanco-Rodriguez et al. 2016), (Lee et al. 2018a) and (Lee et al. 2019) but its major characteristics will be summarized in this paragraph. The MVEM consists of a near-complete range of components that would be expected to be found on any given engine. It is easily possible to change this general layout and to simulate a different engine with minimal effort thanks to the modularity of the model. The model is based on physics-based functionalities also to control the engine. The calibration effort is reduced to the calibration of the set points, artificial sensors, and efficiencies in standard conditions. The engine filling model is one of the critical components due to the high impact that it has on the emission model and oxygen set points calculation. It can consider changing in intake temperature and pressure, variations of exhaust manifold pressure and engine temperatures. The corrections calculated from physical equations do not require calibration. Temperature-based corrections do not vary that much and that is the reason why they can be carried over from previous projects.

In both engine modelling techniques, the NOx emission modelling is based on a semi-physical approach. The turbocharger model is based on physics-based turbine efficiency and mass flow models, to reproduce the non-linear behaviour inside the turbine. The valves are represented inside GT-Power with the throttle template, which describes a throttle placed between two flow components. The effective area of the throttle depends on the throttle angle, imposed by the controller. In contrast, in the MVEM the valves are represented with an empirical map-based approach.

2.4 Semi-Physical NOx Emission Modelling

Generally, semi-physical emission modelling has important advantages to the pure empirical approaches (Quérel et al. 2015). The semi-physical approach used for the in-cylinder NOx evaluation combines the parametrization of maps using experimental data, and the physical correlations formulated in mathematical equations. The estimation of the engine out NOx molar fraction is based on the O_2 and NOx correlation, by

$$\psi_{NOx} = \psi_{NOx,0} \left(\frac{\psi_{O2}}{\psi_{O2,0}} \right)^{k}, \qquad (1)$$

where $\psi_{NOx,0}$ and $\psi_{O2,0}$ describe the previous state of the reference NOx and O_2. The calibration of the parameter k is usually done for different correlations, which are associated with test bench data and based on previous experience with different engines. The newly produced NOx after combustion is estimated by

$$\frac{dn_{NOx,i}}{dt} = e^{\sum_i^j k_i \cdot \Delta S_i(t)}, \tag{2}$$

where $n_{NOx,i}$ represents the NOx molar quantity, which is estimated to equal the NO molar quantity. Each applied correlation ΔS_i that is impacting the reaction is defined by the indices $i..j$ (Lee et al. 2019).

In order to focus the study on the different engine modelling approaches and their influence on the emissions evaluation, the base NOx modelling approach was kept the same for both MVEM and FRM. Consequently, the semi-physical model in a Simulink-based environment containing the NOx model has been calibrated for the reference light-duty Diesel engine and compiled. The same NOx emission model is already embedded into the modular structure of the MVEM. In order to do that, in the FRM a Simulink Harness has been used and configured to be run from GT-Power.

2.5 Air Path Control Modelling

The air path control used for this research study is part of a model-based control structure, which evaluates the optimal engine air content to fulfil the demanded torque and the emissions within calibrated limits (Schaub et al. 2015). The controller mainly consists of map-based functions for the definition of the set points, and an inner engine model, responsible for the evaluation of the physical quantities. Specifically, the set points for the EGR control are the engine-out NOx emissions, selected according to the desired efficiency of the aftertreatment system. The in-cylinder oxygen concentration target is firstly obtained through the inversion of NOx model and then split into targets for HP-/LP-EGR paths and internal EGR by the EGR coordinator. The EGR split decision considers both the boosting and cooling system, in order to compensate the LP-EGR path during transient operating conditions. EGR targets are translated into valves positions, and the consequent EGR mass flows. The turbocharger behaviour is controlled by the Variable Nozzle Turbine (VNT) flow section. The desired boost pressure also controls the intake valve throttle position to assure the correct delta pressure between exhaust and intake manifold to achieve the desired EGR rate. An interface has been defined to allow engine plant model to be easily connected to the engine control model. Consequently, an investigation has been carried out to detect the required I/O signals for a robust and reliable co-simulation.

3. CO-SIMULATION IMPLEMENTATION

In order to frontload the conventional vehicle testing to offline MiL simulations, the global framework containing the two engine models and the controller is setup in the Simulink environment. Fig. 2 is showing the framework of the MiL environment where it is highlighted the “onion” structure chosen for the simulation:

1. The NOx emission model has been calibrated and compiled into a .dll file to be run from GT-Power
2. The FRM, containing the compiled emission model, is compiled into a .dat file to be run from the Simulink environment of the air path control model
3. The upper Simulink environment, where the air path controller and the MVEM are modelled, contains the GT-Suite library that is targeting the compiled FRM (Gamma Technologies 2018a).

The I/O interfaces of the engine models were standardized in order to grant an easy selection in the co-simulation platform. Consequently, the controller interface has also been adapted to allow a proper communication with both FRM and MVEM. The desired cycles to be tested can be easily selected by changing the file given as input to the control model. Furthermore, since one of the future purposes of this MiL environment is to serve HiL, the RT capability is required and preserved.

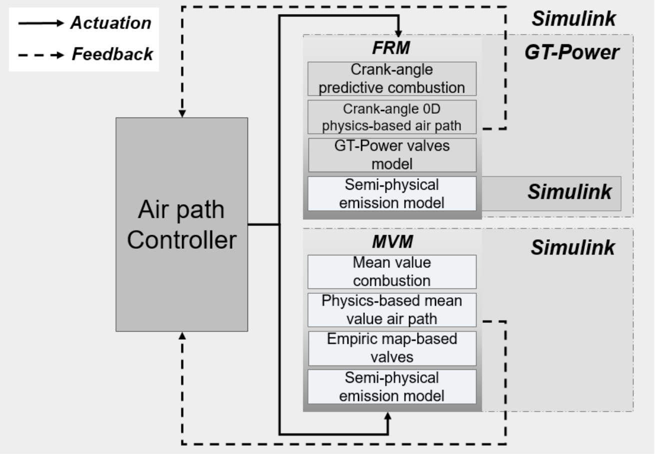


Fig. 2. Overview of the communication logic in the multi-domain environment for co-simulation

3.1 ECU controller simulation: Model-based engine control without virtual engine feedback

A simulation without the feedback of an external virtual engine can be run from the control model in Simulink using the desired engine speed, engine torque, and environment conditions as inputs. Consequently, the controller will evaluate the actuators position and the fuelling characteristics required to the engine models to fulfil the desired torque and speed. Regarding the fuel path, the injected quantities are evaluated starting from the smoke limited desired fuel energy. To target the combustion efficiency according to the specific operating point, the set points for the centroid of heat release rate are calculated and used to evaluate the unlimited desired fuel energy, by paying attention to safety limitations. With this co-simulation logic, the controller is not able to see if any disturbance or interaction is affecting the behaviour of the engine model.

3.2 ECU controller simulation: Model-based engine control with virtual engine feedback

In the following step, a Closed-Loop (CL) simulation environment is setup. To enable a CL testing environment, feedback signals must be sent from the engine models to the controller. The interface of the controller allows the selection of the feedback signal. Specifically, it is possible to choose between a model-based sensor connected to the inner engine model and an external source. Since the connection between this controller and an engine model from another domain was not tried before this study, a procedure to accomplish it has been defined. Furthermore, each of these signals has been integrated in the interface one by one, and the consequent simulation results have been validated against measurement data.

4. VALIDATION OF SIMULATION RESULTS

To assess the characteristics of the two modelling methodologies, the multi-domain frame was used to simulate different driving cycles and to compare the results with measurement data. The results of both engine modelling approaches will be compared, highlighting differences and commonalities, considering the use case and the project boundary conditions. Comparisons have also been made with the purpose of identifying the limitations of the controller. In particular, two driving cycles have been simulated, a World harmonized Light-duty vehicles Test Cycle (WLTC) and a Real Driving Emission (RDE) cycle.

4.2 WLTP

The WLTP cycle is characterized by a relatively aggressive driving style. The first step consists of Open-Loop (OL) simulations, where no feedback is sent back from the engine models to the controller. The response of both models in terms of actual torque is accurate. Since with OL simulations no feedback effects are influencing the controller outputs, they are exactly the same in both approaches.

Fig. 3 shows that when performing CL simulations the outputs of the controller are slightly different (up to 7% HP-EGR actuation.).

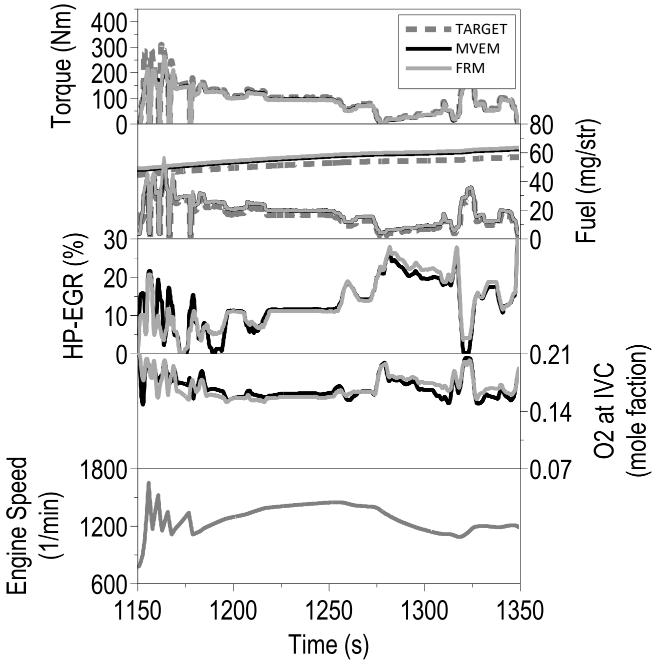


Fig. 3. CL results in a zoomed-in section of WLTC

This is due to the different nature of the feedback signals. The target torque from measurement data is still reached with both modelling methodologies. The variation of the oxygen concentration at Intake Valves Closing (IVC) is causing a 3% deviation in NOx emissions when comparing MVEM and FRM. The absence of a fuel path controller, and consequently of diversified injection strategies, is the cause of the deviation between desired injected fuel measured on the test bench data and the ones simulated in the ECU model.

In Fig. 4, the intake manifold temperature evaluated in the FRM is plotted against the temperature in the MVEM, in both offline (with the same control model.) and online simulation with the MVEM and a real ECU. The root cause of the higher temperature observed in the FRM (up to 40 K.), is the absence of calibrated thermocouple models. This is causing the controller to evaluate a higher HP-EGR mass flow to reach the NOx set points.

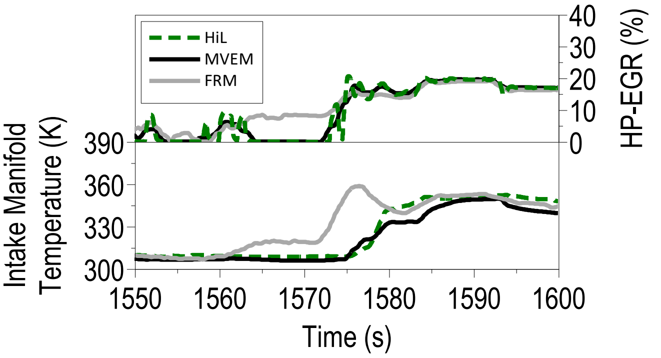


Fig. 4. A comparison of online HiL, offline FRM, offline MVEM simulation results

4.3 RDE

The performance of the two modelling approaches has been tested under Real-Driving conditions. The test cycle has been recorded in the Eifel region, a low mountain range in western Germany and eastern Belgium.

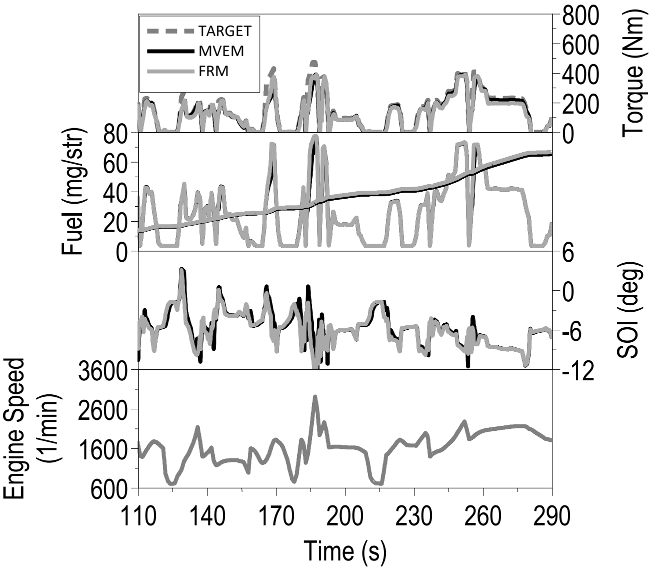


Fig. 5. Overview of torque and fuelling quantities in a RDE zoomed section

Fig. 5 shows the actual torque and the fuelling control signals in a portion of RDE cycle. The results depict a good match between target and actual values. The difference in the cumulative fuel consumption is below 2%. However, a comparison of the actuators position in some aggressive phases of the cycle highlights major differences, as presented in Fig. 6. For the overall behaviour of the model-based controller, the higher aggressiveness of RDE cycle is a critical factor, especially in terms of LP-EGR position. In fact, between 265 and 275 seconds, the LP-EGR valve is almost fully opened for the FRM, while in the MVEM the opening is around 40%. The controller tries to increase the boost pressure, but the lower oxygen concentration at IVC is causing lower NOx emissions. In fact, the oxygen at IVC is the major input required by the NOx emission model. This deviation could be minimized by the calibration of correction maps in the semi-physical emission model, such as maps for the influence of environment conditions, main temperatures and pressures, and SOI. Due to these limitations, the comparison of NOx emissions with experimental data cannot be considered for a reliable comparison.

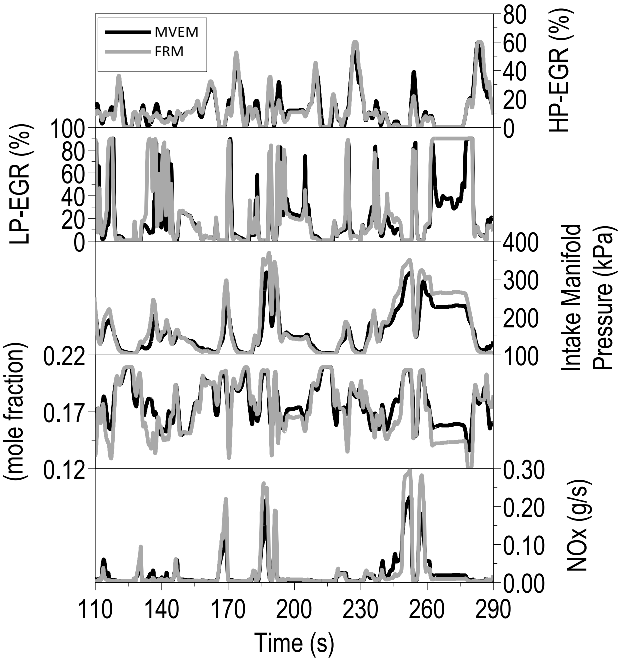


Fig. 6. Overview in a RDE zoomed section

5. CONCLUSIONS AND OUTLOOK

This paper describes the behaviour of two different modelling approaches, for the same real engine, when they are in co-simulation with a model-based air path controller. A standardized communication interface between the controller and the engine models has been developed. A semi-physical NOx emission model has been integrated in the FRM to provide a reliable comparison with the MVEM in terms of in-cylinder NOx emissions. In conclusion, the EGR control path showed higher sensitivity to the physics-based FRM air path, and the coarser discretization of the flow elements is one cause of the different quality of feedback signals. However, the air path controller showed its high adaptability with both the engine models, bringing forward the possibility to use it as a virtual testing platform for engine plant models.

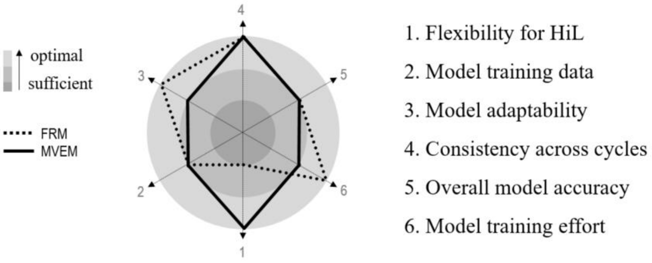


Fig. 7. Evaluation of MVM and FRM based on selected criteria

As summarized in Fig. 7, depending upon the targeted use case, different levels of model characteristics can be prioritized by the selection of one approach rather than the other. Generally, the boundary conditions of the project remain the main discriminant factor to prefer one approach rather than the other. The study focuses on the following criteria:

1. Flexibility for HiL-based systems:

Previous works showed that the RT capability is achieved in both models. Unlike the MVEM where it is still possible to do online tuning of parameters, when the compiled FRM is integrated in the simulation frame, it behaves like a black-box.

2. Model training data:

Both models require the same amount of data, such as steady-state mapping data, with and without EGR.

3. Model adaptability:

On one hand, the FRM could be improved by modular functions and each cylinder could be controlled independently for the implementation of new strategies; on the other hand, the Simulink-based engine model consists of adaptable sub-models that allow high adaptability in short transition periods, but a calibration is required for every new modification.

4. Consistency across cycles:

Both models have strong points and weak points, but the overall response is optimal for both models.

5. Overall model accuracy:

For the MVEM, the only consideration for the calibration is the accuracy, for the FRM the model accuracy is one side of the coin in a trade-off with RT capability. However, a well-calibrated predictive combustion model ensures enough extrapolation capability and transient accuracy thanks to the physics-based characteristic of the model.

6. Model training effort:

For each submodule in the MVEM, steady-state engine mapping or local DOE data are required for the calibration process, while the procedure to create a FRM could be simplified in a “one-click” procedure when a detailed model is available. No training is really required due to the physics behind the solving process in each time step.

5.1 Outlook

HiL simulations with RDE cycles in defined test cases are ongoing. Furthermore, a software for RT emission prediction based on detailed chemistry will be integrated into the FRM. A functional mock-up interface will be developed for this purpose and the models will be validated in both MiL/HiL environments (RWTH research project 2019).

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