Particle Reduced, Efficient Gasoline Engines

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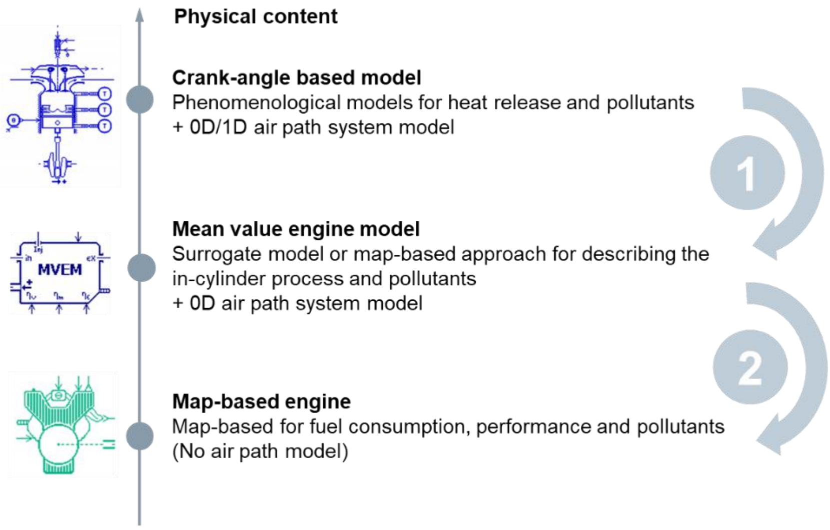
Summary

The report D1.8 presents the work completed by Siemens towards the extrapolation of local modelling approaches developed by partners in Work Package 1 (understanding of physics and detailed model development) to system approaches at the vehicle level. This report is an extension of the report D1.4 on "engine emissions predictions based on phenomenological combustion models", and highlights the research and development conducted by Siemens during the second part of the PaREGEn project. In the present report, Siemens gives some insight into its two main activities in the second part of the project, aiming at extending the works completed and reported in D1.4.

Firstly, Siemens developed models and methods towards a structured model reduction workflow to migrate crank-angle based models into mean value (MVEM) or map-based models, for analysis in a vehicle (model). Some aspects of the first step towards MVEM were documented in D1.4 and completed in the work reported here using multi-cylinder engine model considerations. The second step, switching from a MVEM to a map-based approach can be automated, as described in this report.



Secondly, the work completed in collaboration with LOGE (D1.4) in the first part of the project toward tool couplings and advanced emissions prediction capabilities was extended. Siemens developed another coupling strategy to combine the fast soot estimator from ETH and a complete powertrain/vehicle model in Simcenter Amesim, as an off-line validation step before the actual integration of the observer in an ECU.

Project constraints and the availability of data in particular, led to some adaptations of the initial plans of the assessment of the project demonstrator vehicles in a virtual environment using simulation. However, as agreed with partners of the project, Siemens focused its works on the development of tools and methods, using data from WP1 partners, public data and sample/template models available internally. Consequently, prediction of engine out particle numbers was demonstrated using faster than real-time simulation.

Siemens generated a set of workflows and methods, which supports model-based design implementation, allowing analysis from component to system and the combination of different software toward best-in-class prediction of engine/vehicle attributes.

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1 Introduction

The present report details modelling and simulation activities conducted by Siemens in the framework of the PaREGEn project. This report is complimentary to the report D1.4, which focused on the preliminary modelling works completed during the first part of the project, toward the reduction of crank-angle based combustion and emissions models for a proper integration in a vehicle context.

In this report, D1.8, the main modelling and simulation activities of Siemens on the following topics, according to revised plans, are highlighted:

- Model reduction from crank-angle based engine models to mean value engine model (MVEM) and map-based models. This is an extension of the work documented in D1.4 "Report on engine emissions predictions based on phenomenological combustion models".
- Integration and functional validation of the vGPS (PN) estimator from ETH in a virtual vehicle model. Since the capabilities of the vGPS (PN) estimator cannot be validated on the prototype vehicles (on-line), the WP1 partners decided to go for a virtual validation of the observer on a virtual powertrain model within the Siemens Simcenter Amesim software. This task demonstrated the capabilities of the estimator as if it were to be embedded in a real vehicle (a real time environment) and illustrated how the Siemens software can be used as an integration platform for control engineering and vehicle synthesis. These aspects are important for future vehicle development programmes.

2 Methods and results

2.1 Workflow for model reduction

2.1.1 Model reduction and "scalability"

The goal of this part of the work was to develop a specific engine model reduction workflow in order to be able to reduce a crank-angle based engine model to both a mean value model and a map-based model.

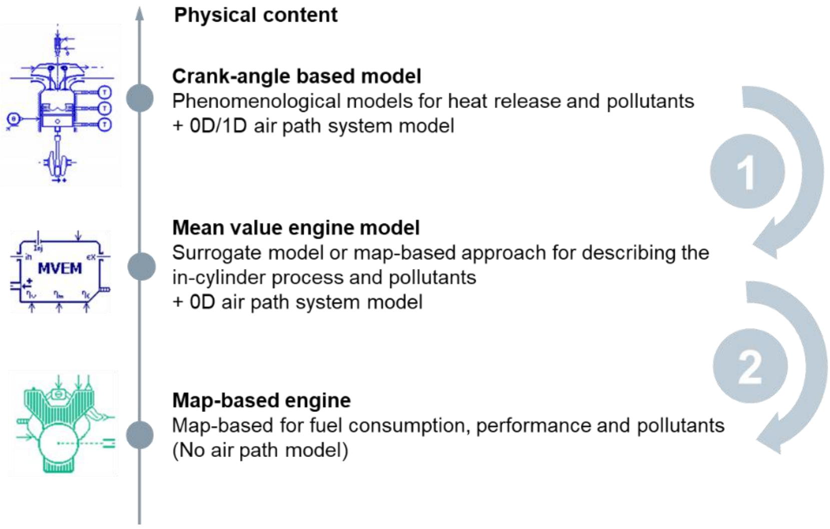


Figure 1 Scale of models involved in the workflow.

Each of these modelling levels are generally used by the industry depending on the simulation requirements. Having the possibility to rely on a well-structured workflow for downgrading a model to a simpler level can effectively support the engine and vehicle engineering processes, as illustrated in Figure 1.

- The first level is the crank-angle resolved approach, which describes the in-cylinder process details with the gas dynamics, the heat exchange, the combustion and pollutant formation. This is the level of model that is extensively used during the engine design process, when the sizing of the air path and the turbocharger matching are achieved. This level of model can be used for control engineers, as well when no test data is available in a new project, but decisions on actuator/sensor implementation must be taken. Finally, this approach is also required further in the development cycle for noise vibration harshness (NVH) analysis, as a predictive source of mechanical excitation on a powertrain/chassis model.

- The Mean Value Engine Model MVEM includes maps or surrogate models (neural networks and/or polynomial models) for the energy balance and engine-out emissions. It is combined with a physical model for the air path, which permits capture of the main engine transient response. This approach is delicate to deploy when a high number of degrees of freedom (axis) must be modelled. However, this level of model has the advantage, beyond the brief simulation times, of being able to be fed with data from crank-angle based models or directly from measurement data. The fast run times allow combining these models with exhaust system models to study the interaction between engine control, combustion and pollutant aftertreatment as well as with powertrain subsystems, such as the cooling or lubrication systems and driveline/vehicle models.

- The simple map-based approach leads to a functional model, which can be easily integrated in full vehicle models to predict the emissions over various driving cycles including WLTC and real driving cycles in the context of RDE, in seconds. This ability to handle seamlessly the driving conditions is a key advantage of this complementary map-based model.

This multi-level modelling strategy allows engine design options, new subsystems and auxiliaries to be evaluated. It contributes to improved and new generation of controls (model predictive controller (MPC), virtual estimators), and thus to more efficient and cleaner engines.

2.1.2 Model reduction – Step 1 – From crank-angle based to Mean Value Engine Model

Base data handling

On contrary to the crank-angle based models, which calculate the complete process in the cylinders including combustion heat release, the mean value model just gives a cycle by cycle estimation of engine outputs from mean inputs. The model provides, to its boundaries, a mean mass flow rate, a mean enthalpy flow rate and an indicated output torque as a function of pressure and temperature at its inlet/outlet, engine speed and injection quantity. The model is mainly governed by static equations and the in-cylinder process is described by means of look-up tables or surrogate models (polynomials and neural networks) for volumetric efficiency, indicated efficiency and exhaust efficiency.

The volumetric efficiency is a function of the air mass flow rate.

$$\eta_{vol} = \frac{m_{air}}{m_{ref}} = \frac{\dot{m}_{air}}{\rho_{ref}\, V_{cyl}\, \frac{N}{T_{cyc}}} \qquad \text{(Eq.1)}$$

With:

$$\begin{cases} m_{air} : air\ mass\ trapped\ in\ the\ cylinder\ [kg] \\ m_{ref} : reference\ air\ mass\ allowable\ in\ the\ cyliinder\ [kg] \\ \dot{m}_{air} : air\ mass\ flow\ rate\ [kg.s^{-1}] \\ \rho_{ref} : reference\ air\ density\ [kg.m^{-3}] \\ V_{cyl} : volume\ of\ cylinder\ [m^3.cycle^{-1}] \\ N : engine\ speed\ [rev.s^{-1}] \\ T_{cyc} : 2\ (4 - stroke\ engine)\ or\ 1\ (2 - stroke\ engine) \end{cases}$$

The indicated efficiency is the indicated work divided by the energy theoretically available in the fuel mass.

$$\eta_{ind} = \frac{W_i}{\dot{m}_{fuel}\, LHV} = \frac{\int p\, dv}{\dot{m}_{fuel}\, LHV} \qquad \text{(Eq.2)}$$

With:

$$\begin{cases} W_i : indicated\ work\ [W] \\ \dot{m}_{fuel} : fuel\ mass\ flow\ rate\ [kg.s^{-1}] \\ LHV : Lower\ Heating\ Value\ [MJ.kg^{-1}] \end{cases}$$

The exhaust efficiency is the part of fuel energy transferred to the exhaust gas.

$$\eta_{exh} = \frac{dh_{exhaust} - dh_{intake} - dh_{injection}}{dQ_{comb}} \qquad \text{(Eq.3)}$$

With:

$$\begin{cases} dh_{exhaust} : exhaust\ enthalpy\ flow\ rate\ [W] \\ dh_{intake} : intake\ enthalpy\ flow\ rate\ [W] \\ dh_{injection} : injected\ enthalpy\ flow\ rate\ [W] \\ dQ_{comb} : combustion\ heat\ release\ [W] \end{cases}$$

The aim is to generate, from a baseline crank-angle based model, proper files for the three main efficiencies listed above. Using the base approach for MVEM, the data files needed are: the volumetric efficiency, as a function of the intake pressure and the engine speed; the indicated efficiency, as a function of the total mass of air trapped in the cylinder; and the engine speed and the exhaust efficiency, as functions of the total mass of air trapped by the engine and the engine speed. The goal of the workflow is first to run the reference (crank-angle based) model, using a design of experiment (DOE) which covers the entire engine operating range, to generate the data set required to feed the maps. Then, the virtual test data are processed in order to create the efficiency maps required by the MVEM component. Interestingly, the same workflow can be used if actual test data from engine dynamometer are available instead of simulation results.

A "Reduction" tool is available in Simcenter Amesim to automate the data processing. It allows - from the equations described in an XML file - to run batch calculations to generate data sets and then files in the appropriate format for the MVEM.

Finally, the complete workflow is illustrated below, showing the link between raw simulation results and the efficiency data required by the mean value engine model and listed in the xml file.

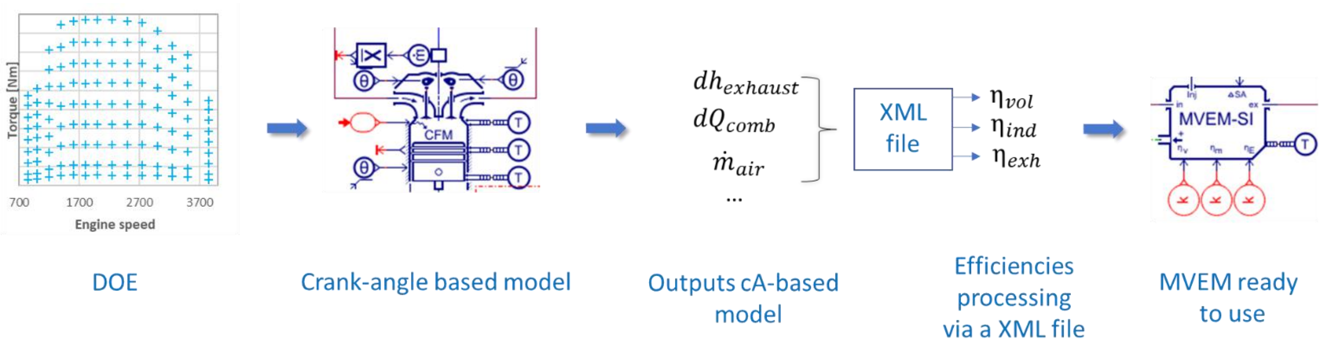


Figure 2 Crank-angle based reduction methodology

The parameters and variables needed for data processing are documented below. All the variables need to be retrieved from the simulations, which can be done easily thanks to the so-called "Study Manager" which handles the design of experiment data directly in the simulation software.

Table 1 Parameters & variables for volumetric efficiency computation

Volumetric efficiency	
Variables	**Parameters**
Air mass flow rate [kg/s]	Number of cylinders
Engine speed [rev/min]	Bore [m]
Intake pressure [barA (absolute)]	Stroke [m]
Intake temperature [K]	

Table 2 Parameters & variables for indicated efficiency computation

Indicated efficiency	
Variables	**Parameters**
Indicated torque [Nm]	Fuel heating value [kJ/kg]
Engine speed [rev/min]	Maximum combustion efficiency
Fuel mass flow rate [kg/s]	Stoichiometric air:fuel (A/F) ratio
Air mass flow rate [kg/s]	Number of cylinders
Exhaust pressure [kg//s]	Bore [m]
	Stroke [m]
	Maximum engine speed [rev/min]

Table 3 Parameters & variables for exhaust efficiency computation

Exhaust efficiency	
Variables	**Parameters**
Air mass flow rate [kg/s]	Fuel specific enthalpy [J/kg]
Fuel mass flow rate [kg/s]	Injection type (0: direct injection / 1: port inj.)
Exhaust temperature [K]	Fuel heating value [kJ/kg]
	Maximum combustion efficiency
	Stoichiometric A/F ratio

Once the simulation results are available, then the reduction tool can be used to complete the processing of the raw virtual test data. As previously mentioned, the data (and units) handling is achieved using equations and processing steps listed in an xml file. For the purpose of the project, a specific xml file is developed to fit with the engine characteristics: gasoline combustion, direct injection, turbocharged etc. A short extract of the file is given below to illustrate the way variables and units are handled:

```
<COMPOUND key="Voleff" unit="null" formula="4 * Pi * dMassAir / (N * nbcyl * Vcyl * rho)" title="Volumetric efficiency">
  <ARG key="N" unit="rad/s"/>
  <ARG key="dMassAir" unit="kg/s"/>
  <ARG key="Vcyl" unit="m**3"/>
  <ARG key="nbcyl" unit="null"/>
  <ARG key="rho" unit="kg/m**3"/>
</COMPOUND>
<COMPOUND key="rho" unit="kg/m**3" formula="Pin / (r_air * Tin )" title="Intake gas density">
  <ARG key="Pin" unit="PaA"/>
  <ARG key="r_air" unit="J/(kg*K)"/>
  <ARG key="Tin" unit="K"/>
</COMPOUND>
```

Figure 3 Example of equations included in the XML file for data processing

The benefit of this approach is the possibility to customize the processing to the studied case with its specific inputs/outputs.

Backflow data handling

In order to have good agreement between the crank-angle based model and the mean value engine models, it is important to take into account all the physical phenomena handled in the reference model. In particular, the baseline crank-angle based model is able to predict the gas exchange process through the valves including backflow phenomena. The backflow at the intake means hot burned gases can flow back into the intake runners and manifold, impacting its thermal state which influence the volumetric efficiency. The graph below presents an example on a sample model, of the backflow identified on the intake mass flow rate and the intake enthalpy flow rate.

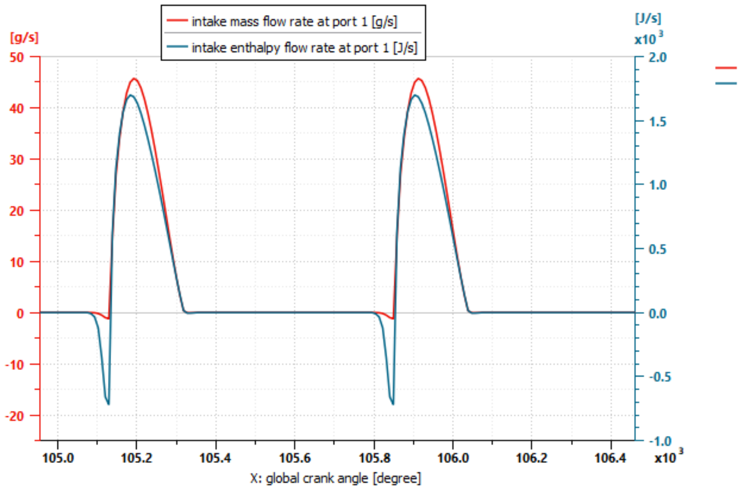


Figure 4 Intake mass flow rate and enthalpy flow rate

This backflow phenomenon is important to consider because burned gases are hotter than to fresh gases entering the cylinder. More precisely, the backflow increases the temperature of the gases in the intake manifold and has an important impact on the cylinder filling process. Regarding the reduction workflow, the main impact that needs to be integrated is this "thermal" effect. Indeed, the MVEM by default does not generate any backflow information, which makes the intake manifold colder than on the reference model and inducing a discrepancy on the actual volumetric efficiency.

The goal of the modelling work is to integrate the backflow effect in the MVEM in order to avoid deviations when compared to the crank-angle based approach. To do so, one first gathers from the initial model, the power or energy related to the backflow phenomena (see Figure 4), using a dedicated sensor component and filtering only the negative part of the signal. Then the energy signal is averaged over one engine cycle period to be handled in a mean value model context. The next figure shows the sketch use to get the energy backflow signal averaged on one engine period cycle.

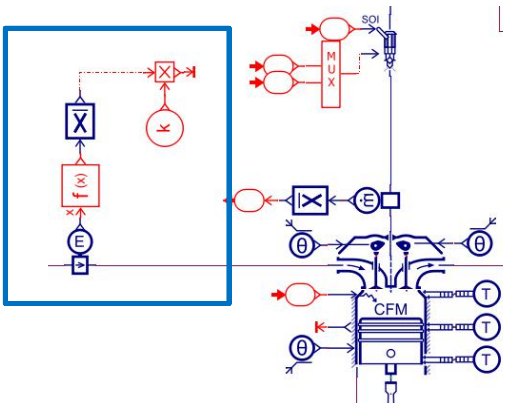


Figure 5 Backflow signal processing

The gain applied at the end is just here to multiply the signal by the number of cylinders.
Using the already presented DOE process, one has a backflow energy value for each of the simulated operating point. Then a table for the backflow energy flow rate as a function of the intake pressure and the engine speed is set and applied to the MVEM.

Exhaust pulsated flow handling

Another constraint when moving from a crank-angle based model to a MVEM is noticed in the air path modelling. In fact, during the operation of an internal combustion engine, the opening and closing of valves induces pulsated flows which cannot be modelled – by definition – by a mean value approach.

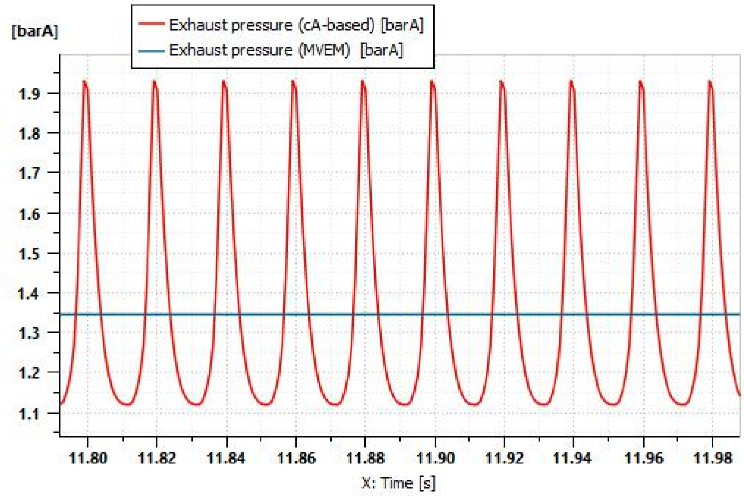
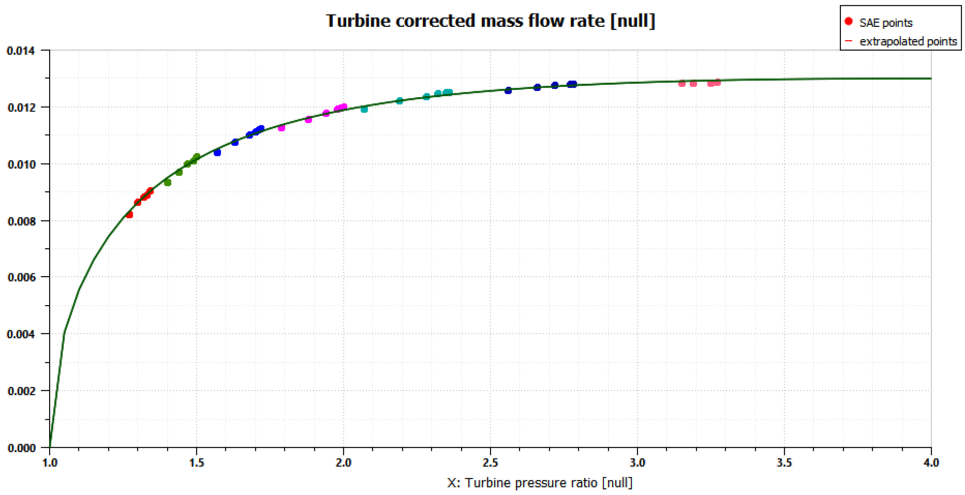


Figure 6 Pressure at the intake of the turbine for both model (crank-angle based and MVEM)

This pulsated flow propagates from cylinders to the inlet of the turbine and affects its performance. When doing simulations with MVEM, the turbine does see a mean flow and the model can show some significant deviations when compared to its crank-angle based counterpart. In particular, applying the same commands for the air path actuators could lead to different operating points (in particular at high loads when a lot of energy is transferred to the turbine).



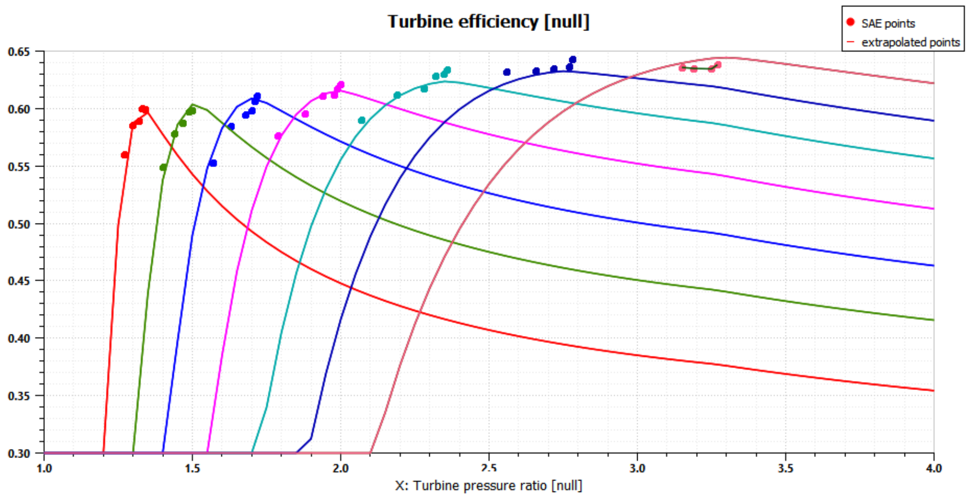


Figure 7 Turbine maps: corrected mass flow rate and turbine efficiency in function of the pressure ratio

The pressure ratio is defined as the ratio between the exhaust pressure and the turbine inlet pressure. Assuming a constant exhaust pressure (~atmospheric pressure), the turbine pressure ratio depends mainly on the turbine intake pressure. As it is visible in the figure above, the corrected mass flow (Dmc) and the turbine efficiency (η) are not linear. Then the average of the instantaneous flow and efficiency considering evolutions of the pressure ratio does not match mass flow and efficiency values for an average ratio:

$$Dmc\ (\tau_{moy}) \neq \frac{1}{T}\int_0^T Dmc\ (\tau)\ dt$$

$$\eta(\tau_{moy}) \neq \frac{1}{T}\int_0^T \eta(\tau)\ dt$$

This could induce some deviations between the crank-angle based model and the MVEM as soon as the oscillations are coupled with high transferred energies. In the framework of the project, a new approach to tackle this issue has been tested. The main idea is to integrate gains (α and β) to correct the reading in the data in the turbocharger characteristics maps:

$$Dmc = \alpha\ Dmc_{map}$$

$$\eta\ = \beta\ \eta_{map}$$

These gains (α and β) are evaluated using an iterative method and can be directly integrated in the turbocharger component models when used in combination with MVEMs.

2.1.3 Model reduction – Step 1 – Validation

The goal of this part is to show a practical application of the method detailed in the previous paragraphs. The crank-angle based model used here is a sample model directly available in Simcenter Amesim which corresponds to a gasoline engine with 4 cylinders, turbocharged, with direct injection including a 0D airpath model, so as to match with the applications covered by the project. The combustion model provides the combustion heat release using a predictive model (Coherent Flame Model CFM by IFP Energies Nouvelles [4]).

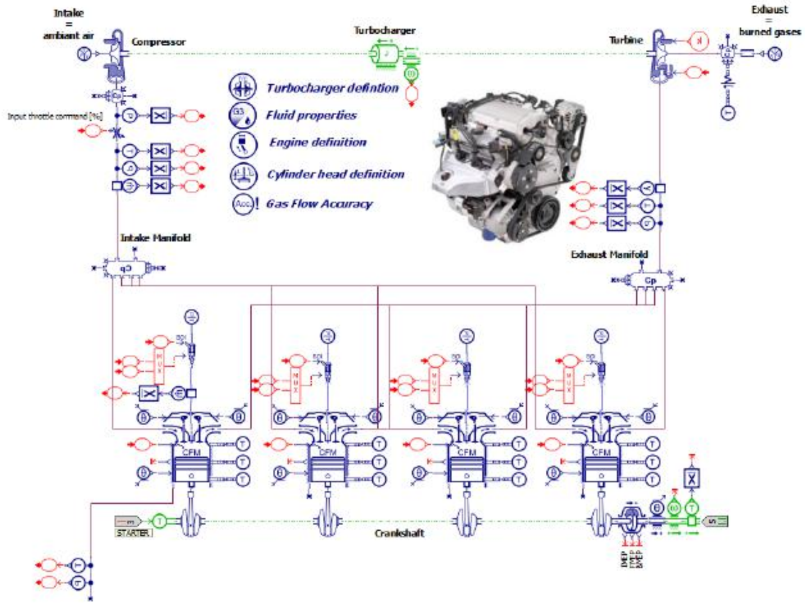


Figure 8 Crank-angle based model

The first step is to create the DOE in order to cover most of the engine operating conditions. The control of the engine set point is a function of the engine speed [rev/min] and the acceleration command [0-1] (which represents the torque [Nm]). The completed DOE includes 22 engine speeds (800 rev/min to 6000 rev/min) and acceleration command from 0 to 1 (with step of 0.1), which represents 220 simulated points.

Variables calculated and required by the workflow are:

- Indicated torque [Nm]
- Air mass flow rate [kg/s]
- Fuel mass flow injected [kg/s]
- Intake temperature manifold [K]
- Intake pressure manifold [bar]
- Exhaust temperature manifold [K]
- Exhaust pressure manifold [bar]

Then, after running simulations (over the 220 points), the Reduction tool processes the three maps needed by the MVEM and the backflow data. The Figure 9 gives an idea of the volumetric efficiency as a function of the engine speed and the intake pressure. The Figure 10 is the indicated efficiency as a function of the engine speed and the air mass. Finally, the exhaust efficiency as a function of the engine speed and the air mass is shown in Figure 11.

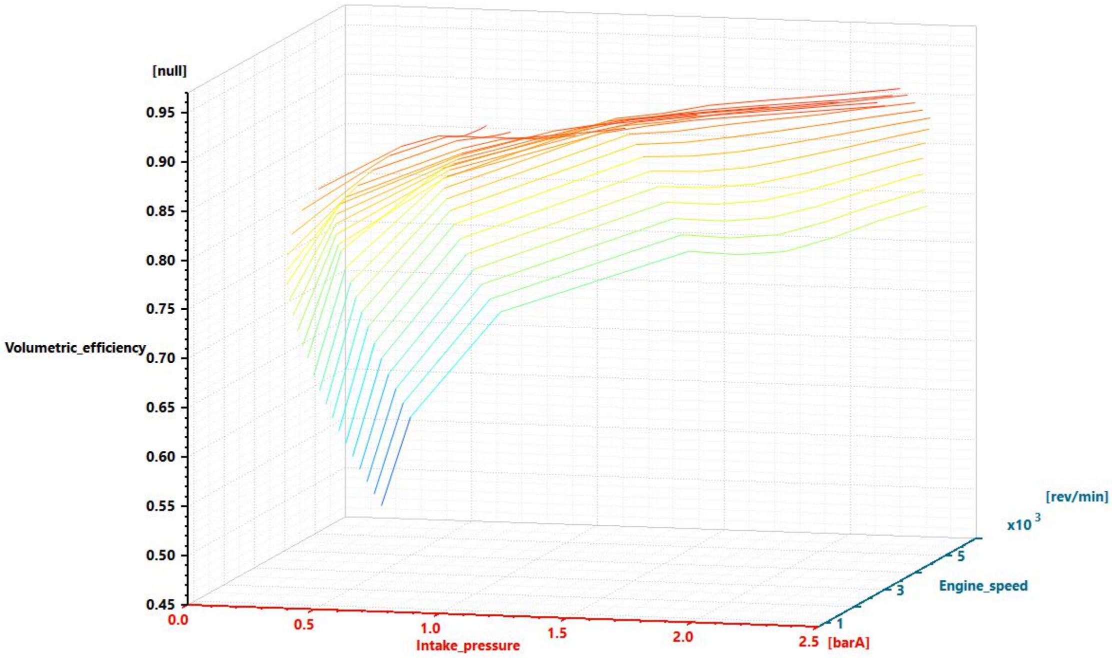


Figure 9 Volumetric efficiency in function of the intake pressure and the engine speed

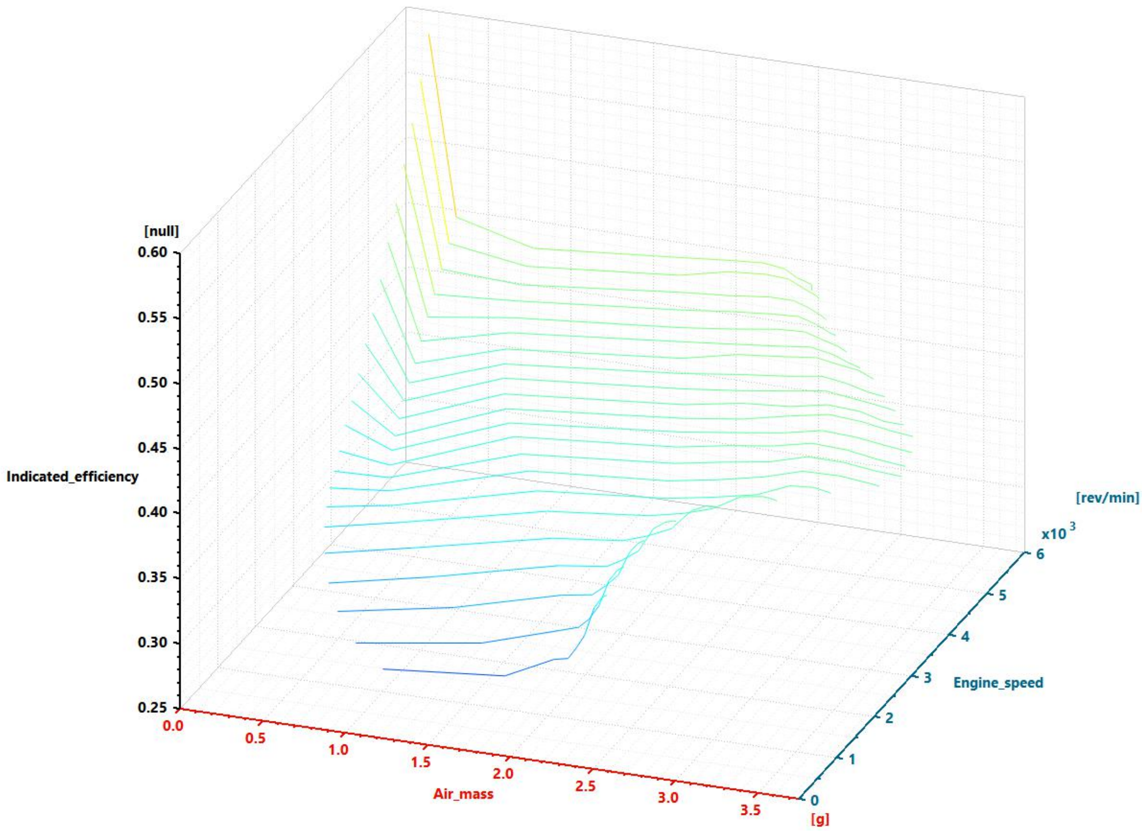


Figure 10 Indicated efficiency in function of the intake pressure and the engine speed

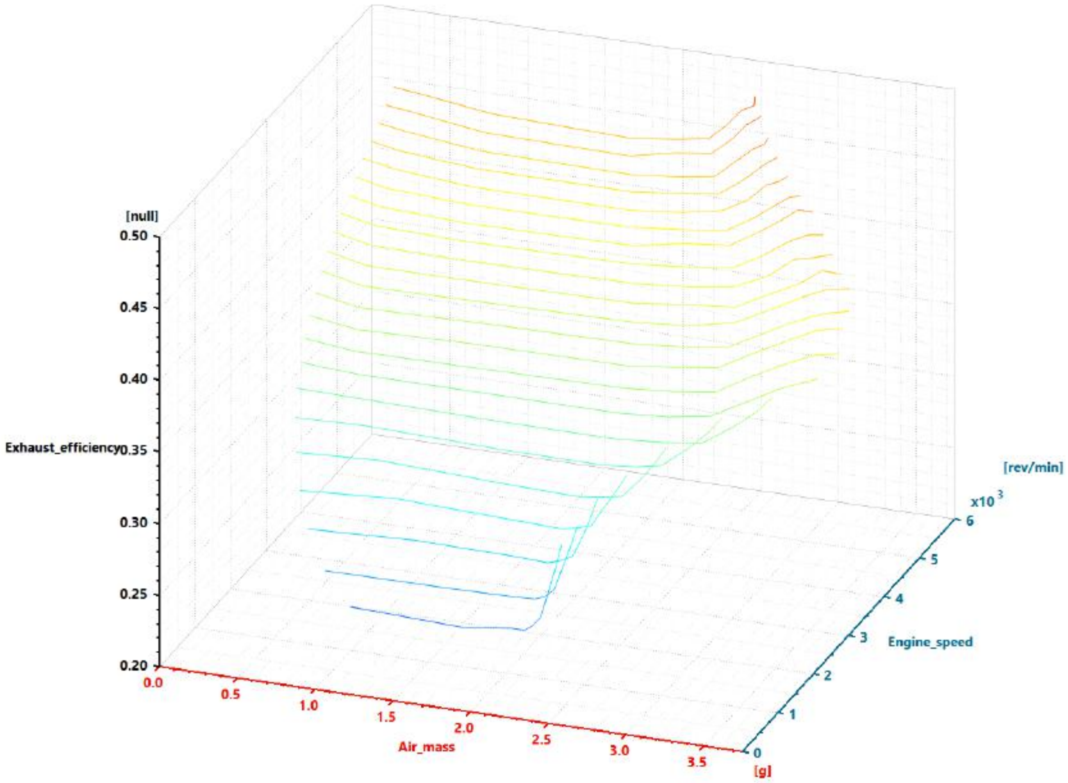


Figure 11 Exhaust efficiency in function of air mass and the engine speed

The same DOE is used to compute and generate the backflow table (backflow energy flowrate as a function of the intake pressure and the engine speed).

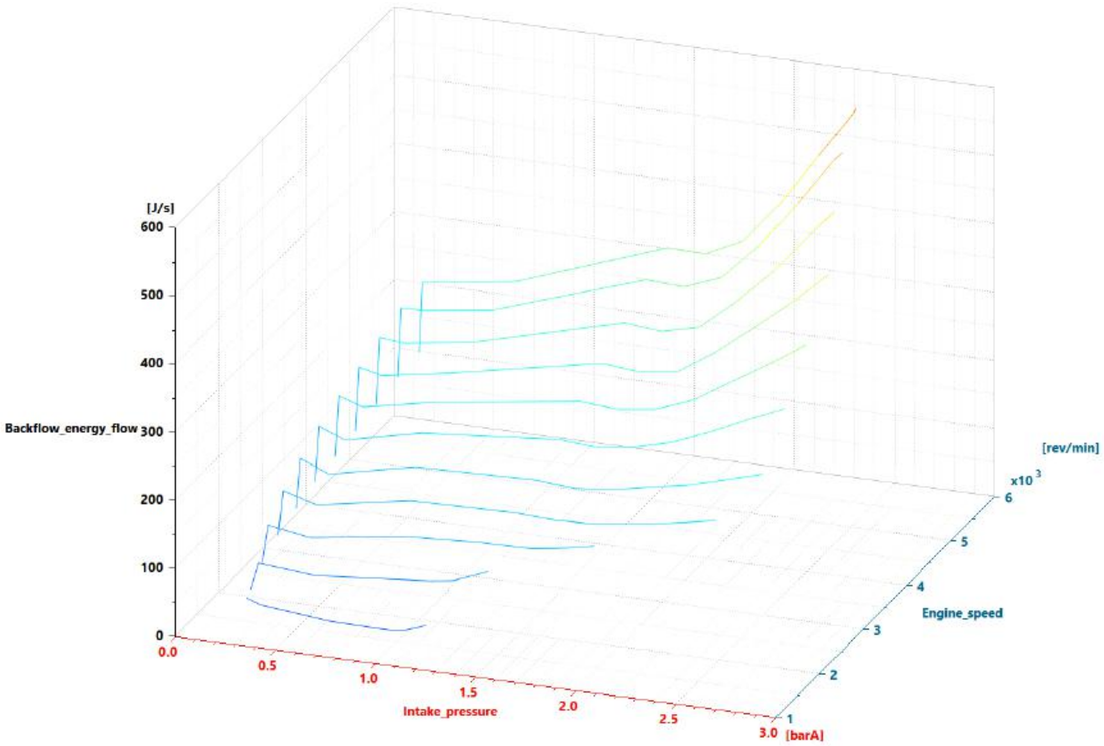


Figure 12 Backflow energy flow in function of the intake pressure and the engine speed

The next paragraphs present the impact of considering the backflow phenomena on the MVEM prediction (in comparison to baseline model). Figure 13 presents the conditions at the intake manifold: the red dotted line represents the crank-angle based model results, the blue curve is the one with the backflow handling and the yellow one is the one without backflow. It is clear on the graphs that considering the backflow is important to achieve a good level of accuracy.

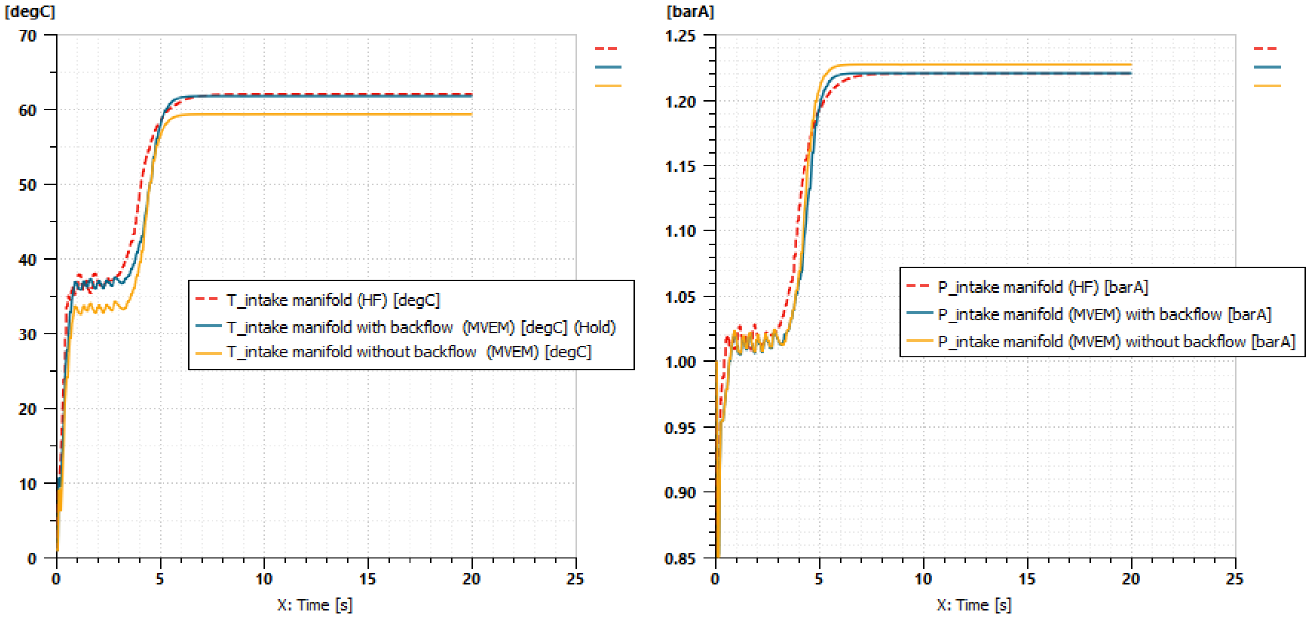


Figure 13 Intake manifold conditions comparison with backflow handling and without backflow

Once all the data needed to run the MVEM are created, the next step is to build the sketch with the MVEM component as a core. The airpath is the same as for the reference model (see Figure 8); the 4 cylinders components are removed and the MVEM component is put on the sketch.

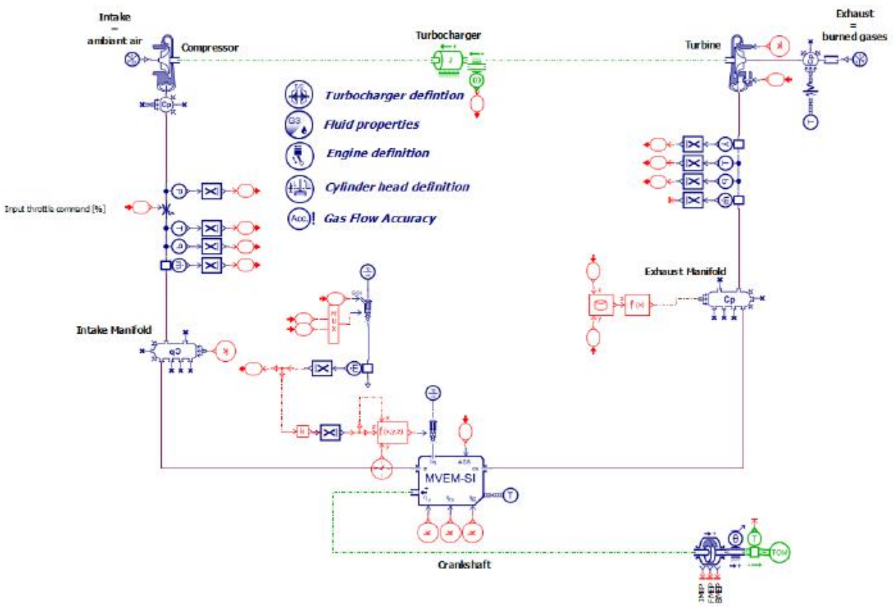


Figure 14 MVEM model sketch

Then we achieved a first comparison between the crank-angle based model and its reduced mean value model. The graph below shows the results for the intake manifold condition on the running point: 3500 rev/min and acceleration command equal to 1 (full load) that represents BMEP equal to 18.4 bar.

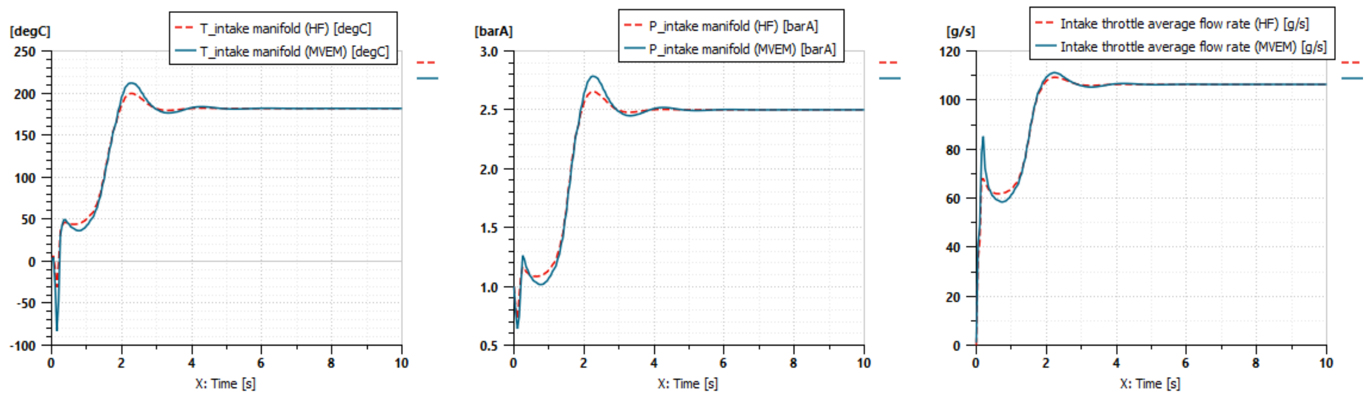


Figure 15 Intake manifold conditions comparison between HF and MVEM model

The same graph have been plotted for the exhaust manifold conditions.

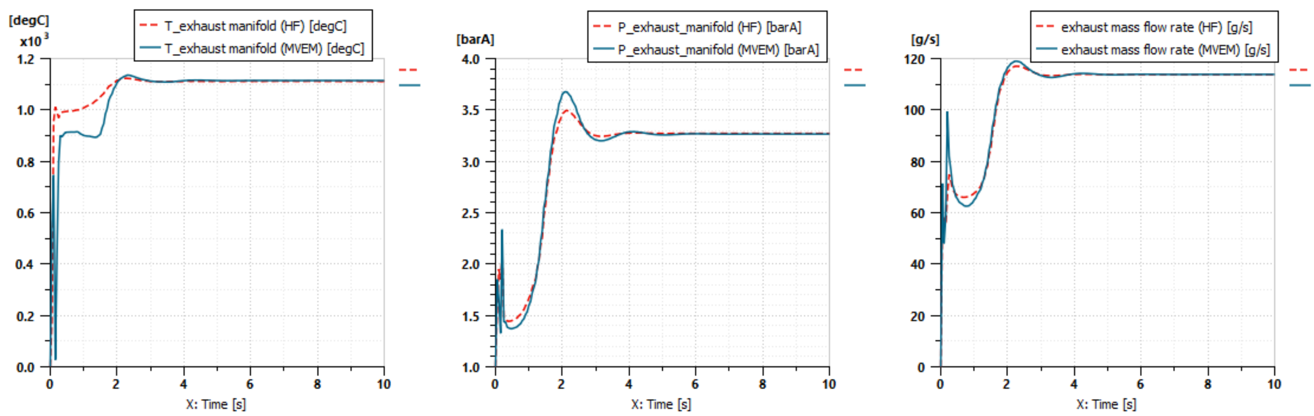


Figure 16 Exhaust manifold conditions comparison between HF and MVEM model

Others variable are plotted in order to compare the two models: the boost pressure (means the pressure at the exit of the compressor) and the indicated torque.

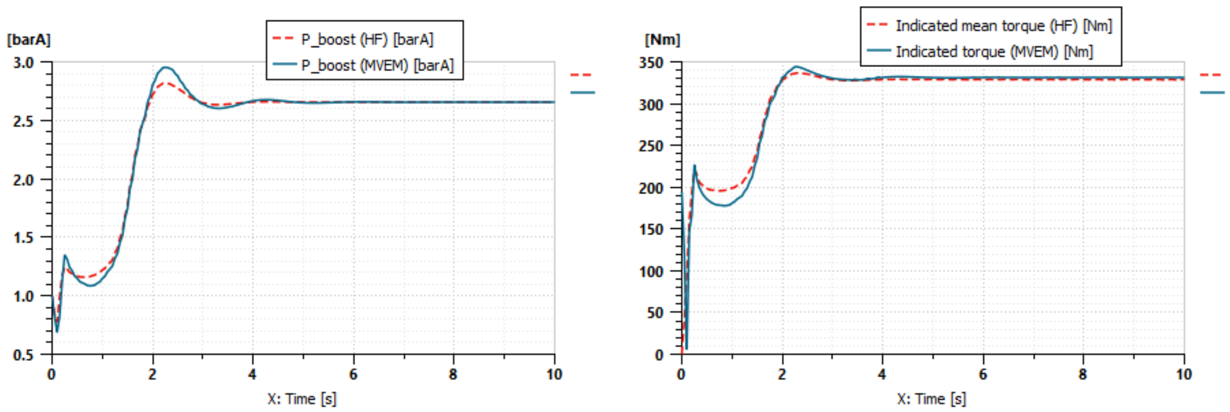


Figure 17 Comparison between HF and MVEM model for boost pressure and indicated torque variables

The main observations here are that the static performance of the system is properly represented by the MVEM (the final steady-state operating point is accurately predicted) and the transient performance is also well represented. This is mainly due to the fact the air path system model is not changed when migrating from the reference to the mean value engine model.

2.1.4 Model reduction – Step 2 – From Mean Value Engine model to map-based model

In a pure map-based approach, the engine model makes use of data files and maps only (no physics). The approach is however useful to simulate fuel consumption, emissions, vehicle performance, with brief simulation times during planning phase investigations for instance.

Table 4 Data files required to feed the engine map-based model

Application	Datafile required
Torque & fuel consumption & exhaust	Torque or BMEP Fuel consumption CO, HC, NOx and soot emissions Equivalence ratio Exhaust gas temperature FMEP

The method to create a map-based model from a MVEM is to generate the data to feed files as required by the target model. The list of datafiles is given in Table 4. Most of the maps depend on engine speed and the engine torque (or BMEP). To generate these maps, one runs a DOE (covering the maximum of engine operating points) using the validated MVEM model. Then, the results obtained are formatted to create maps, directly read by the map-based engine model.

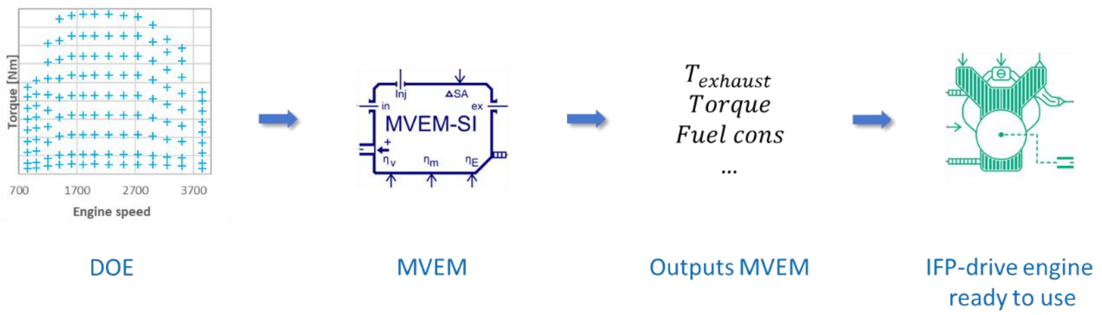


Figure 18 MVEM reduction methodology

The reduction tool (described in the previous chapter) can be used to automate the process for the maps and files creation. Hence, a new xml file is developed in order to explicit the relationships between the MVEM outputs and data required to set the maps for the simple engine model.

2.1.5 Model reduction – Step 2 – Validation

Here the MVEM generated by the workflow for step 1 as a baseline is used to illustrate the actual reduction to a map-based model (step 2). As mentioned above, the maps are generated using the "reduction tool which makes use of a new xml file specifically developed for this second reduction process.
To define the DOE, the study manager in Simcenter Amesim is fed with the following variables:

- Inputs: engine speed and acceleration command
- Outputs: exhaust temperature [degC], BMEP [bar], thermal efficiency, FMEP [bar], equivalence ratio, specific fuel consumption [g/kW/h], torque [Nm] and possibly pollutants emissions [g/kW/h].

The goal is to vary the engine speed and the acceleration command in order to complete an engine mapping. It is important in the DOE to have the maximum torque and the minimum torque points to generate the corresponding torque files required by the map-based engine model.

Finally, the Reduction tool generates nine tables as a function of engine speed [rev/min] and BMEP [bar] which are:

- Exhaust temperature [degC]
- Wall heat losses
- FMEP [bar]
- Equivalence ratio
- Fuel consumption
- CO, HC, NOx and soot emissions [g/kW/h]

Note that, in the example values for emissions, are not available. Since the XML file is generic, these additional capabilities can be developed afterward.

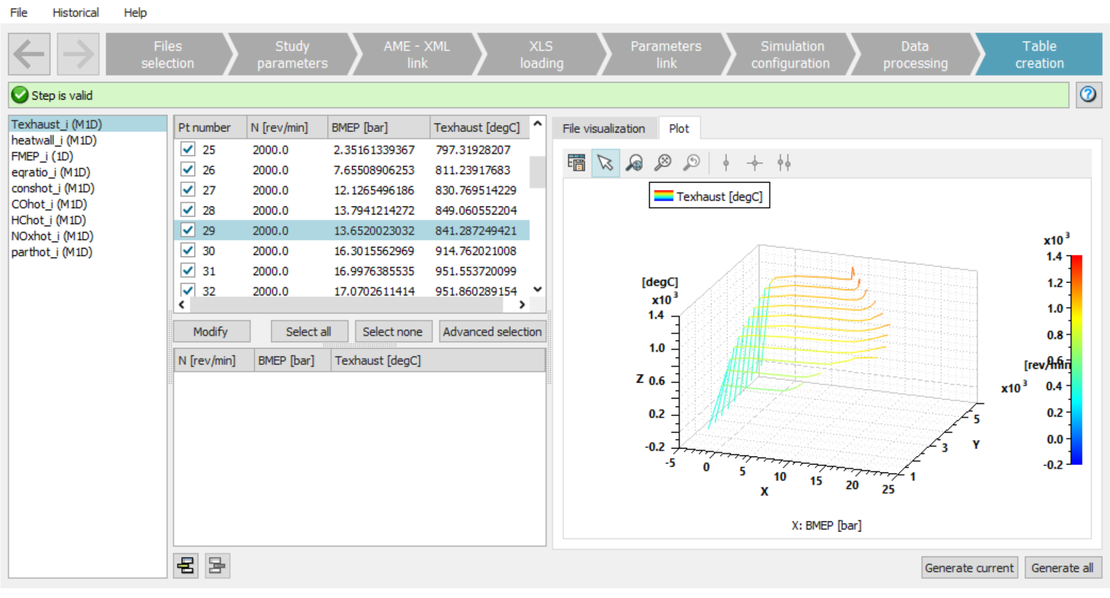


Figure 19 Reduction tool final step: Table creation for a map-based engine model

The definition of the turbocharger lag and other air path time responses is specific and cannot be done using the Reduction tool. To determine the turbocharger time response using the MVEM model, a simulation with a step change on the accelerator command (set at 0.2 to 1) has been completed. Thus, the turbocharger lag time corresponds to the time taken to reach 95% of maximum load.
A second file is used to set the BMEP at which the turbocharger response lag is used. This BMEP value represents the engine load threshold which leads to an actual activation of the turbocharger.

Once all the engine maps and data are produced, a model for a complete vehicle (running over a driving cycle) is created, see Figure 20.

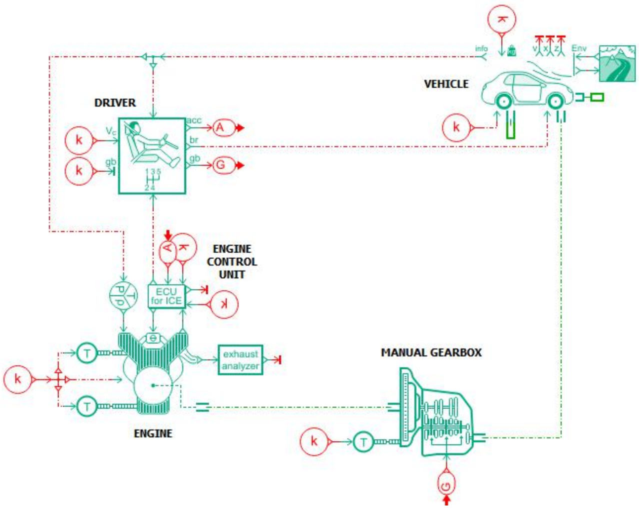


Figure 20 Complete vehicle model sketch

On this sketch, five main components are represented: the engine, the engine control unit (ECU), the gearbox, the driver and the vehicle. The engine is the map-based model filled with maps generated from the MVEM. The engine control unit ensures the right link between the driver requests and the engine control signals (combustion mode, idle speed regulation, maximum speed regulation, fuel resume speed etc.). The manual gearbox has five speeds here. The vehicle definition (mass, aerodynamic parameters, wheel characteristics etc.) are from a sample vehicle. The driver controls the acceleration, the braking and the gear shifting.

At this stage, it is challenging to compare results from MVEM and map-based model without a fine control model for the MVEM in order to complete driving cycle simulations. A functional comparison test is, however, achieved on a performance test where the MVEM is evaluated at full load and the map-based model runs in a vehicle performance scenario.

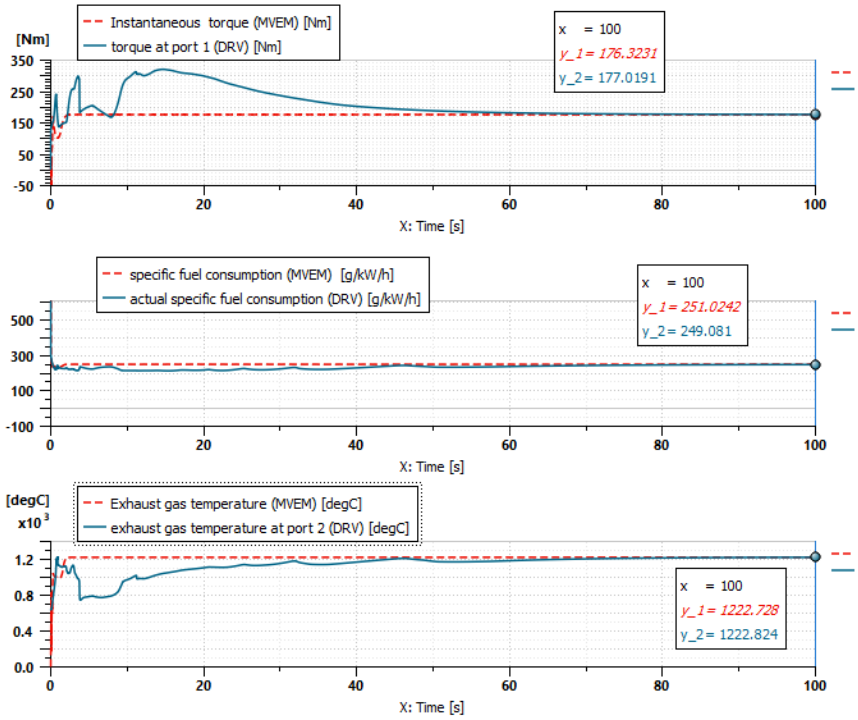


Figure 21 Comparison between MVEM and map-based models

To compare results, three variables are plotted above: the instantaneous torque [Nm], the specific fuel consumption [g/kWh] and the exhaust gas temperature [degC]. The error between models at the end of the simulations is less than 1%.

Once the map-based approach is validated, it is possible to run the vehicle over driving cycles to get information such as fuel consumption and CO_2 emission, as illustrated below for a WLTC.

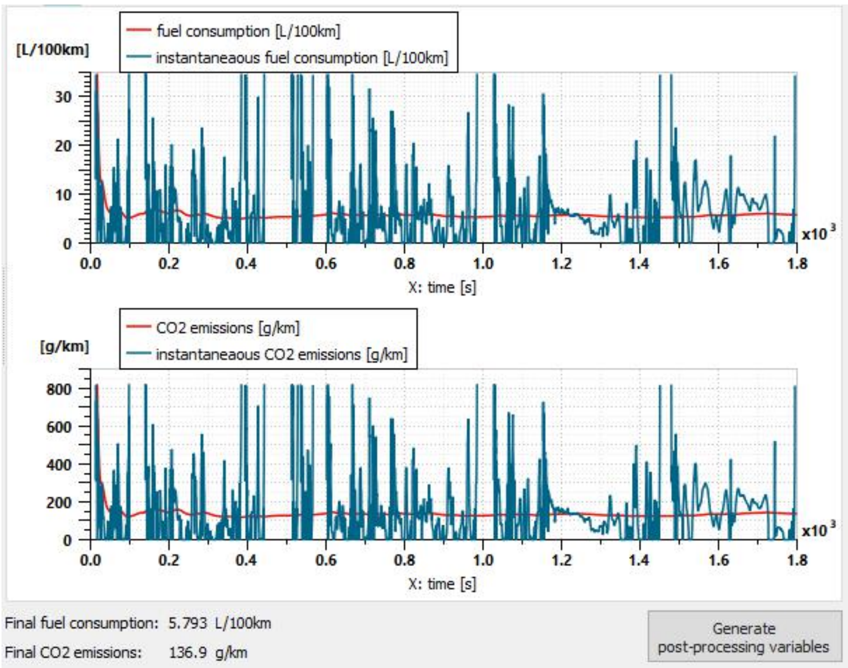


Figure 22 Fuel consumption and CO2 emission over a WLTC

To conclude on the reduction workflows, one can give an idea of the benefits in terms of simulation times, which is one of the main benefits of the migration to lower level models. The results are wrapped-up in the following table, expressed as a speed up ratio compared to real time.

Table 5 Comparison of simulation times (speed-up factor with respect to real time)

Crank-angle based model	MVEM	Map-based model
0.75:1	4.5:1	253:1

The map-based model calculation time on a standard laptop computer is 253 times faster than real-time, the MVEM is 4.5 faster and the crank-angle based model is 1.3 slower than real time (with neither simplification nor model optimization). This confirms the benefits related of the model reduction.

2.2 Integration and off-line line validation of the virtual gasoline particle sensor vGPS

While report D1.4 highlighted the synergies and coupling of the Siemens Simcenter Amesim software with the SI-SRM from LOGE for prediction of the combustion and emissions, the present report focuses on simulation capabilities toward a virtual validation of developed concepts at the system level. In this framework, full powertrain and vehicle models have to be developed in order to allow the assessment of attributes including fuel consumptions and emissions of prototypes over driving cycles including RDE. They also offer a strong support to control engineers in charge of the design and validation of the control logic.
In this context, the Amesim engine/vehicle model offers an appropriate way to test and validate, in a virtual environment, new estimators and observers as the vGPS (see report D1.12). Indeed, they can be seamlessly

integrated in a model which can deliver settings to emulate on-line simulation on ECU or on real-time targets and providing all the required I/O to apply realistic stimuli to the virtual sensor.

2.2.1 vGPS integration in Simcenter Amesim

A dedicated tool is available in the Siemens Software to create specific sub-models called the "Sub-model Editor". The Sub-model Editor enables various types of user coding. The sub-model requires the model inputs and outputs and generates a C code skeleton to include the user code. To integrate the vGPS, first, the source code had to be adapted to fulfil the requirements for inputs and outputs, as well as the C code generation. The workflow used is the following:

- Update the source code to generate a function with ECU inputs, parameters as arguments and the PN estimates returned by the function as outputs
- Use the Matlab coder to generate the source code in C files
- Create a specific Simcenter Amesim sub-model which calls C functions and creation of a specific interface for the sub-model

The source code main function depends on 13 variables, which are typically available in a standard ECU:

- The exhaust temperature [degC]
- The intake temperature [degC]
- The intake pressure [kPa]
- The exhaust pressure [kPa]
- The engine speed [rev/min]
- The intake mass flow [kg/h/cyl]
- The start of injection [°]
- The injection duration [ms]
- The ignition timing [°]
- The air to fuel ratio [-]
- The coolant temperature [°C]
- The intake valve closing time [°]
- The injection pressure [bar]

The source code lists 11 parameters to describe the engine geometry and fuel characteristics:

- The bore [mm]
- The compression ratio [-]
- The rod [mm]
- The stroke [mm]
- The Lower Heating Value [MJ/kg]
- The air fuel ratio [-]
- The injector centre offset [m]
- The nozzle spray line angle [°]
- The discharge coefficient [-]
- The nozzle diameter [m]
- The nozzle hole number [-]

In addition, the code contains six model parameters, which are supposed to be calibrated engine specifically. A detailed description of the parameters and calibration is available in the report D1.12. The model parameters for this generic engine setup are adopted from the JLR demonstrator vehicle.

The Sub-model Editor allows to create a component with a specific icon and a specific sub-model associated. All sub-model in- and output ports can already be specified and are then predefined in the generated C code skeleton.

The vGPS sub-model icons has been created with two ports: the first one on the right is the output of the sub-model (particle number estimation) and the second one on the left is the ECU inputs (13 inputs described above). Since the model has not been calibrated under cold start conditions, an unused input (Figure 23) has been reserved for coolant temperature.

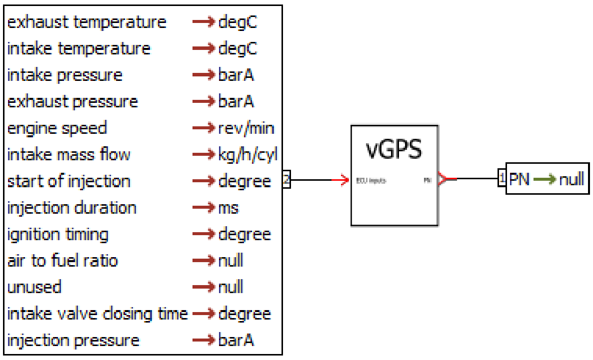


Figure 23 External variables (I/O) of the vGPS in Amesim

Parameters of the vGPS model have been included directly in the place provided for this purpose in Amesim to easily modify them depending on the application. Once all variables and parameters have been set in the sub-model editor, it automatically generates a C code skeleton.

This template C code has been updated with calls to the C functions generated by the Matlab Coder. This includes call to the vGPS "main" function which computes the particle number. Finally, a modification of the code has been performed to prevent code execution every time step, but only once every engine cycle, respectively every time period selected by the user.

2.2.2 vGPS off-line validation

To validate the integration of the vGPS in Simcenter Amesim, the newly developed sub-model has been tested using a sample demonstrator for a MVEM vehicle model. This example represents a conventional gasoline engine vehicle with a MVEM, a clutch, a gearbox and basic controls, evaluated on a NEDC in warm conditions. This demonstrator can run with standard variable time step solvers and fixed time step solvers (up to 0.5 ms) as well.

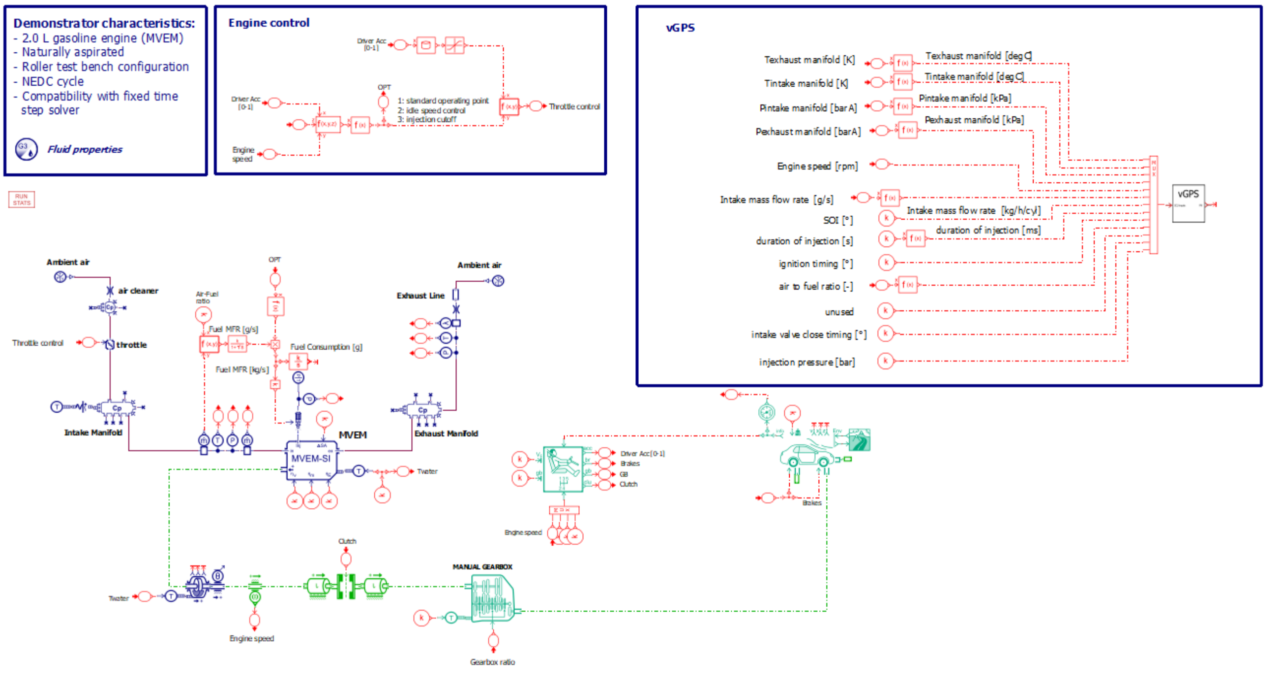


Figure 24 Coupling of a MVEM vehicle model with vGPS

The simulation is performed over a NEDC (1180s).

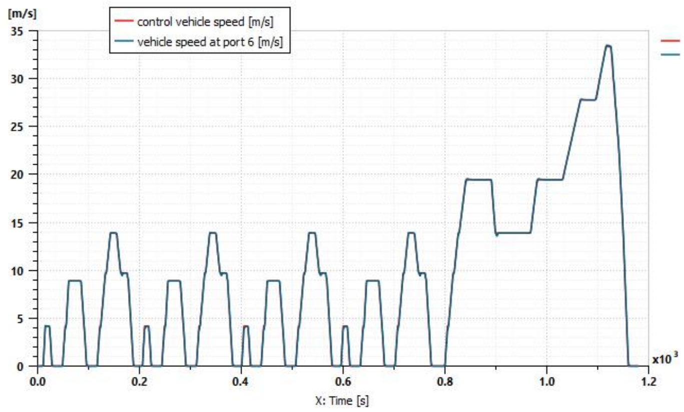


Figure 25 Vehicle speed simulation (NEDC)

The results of the vGPS computation in terms of particle number (PN) are presented on the graph below.

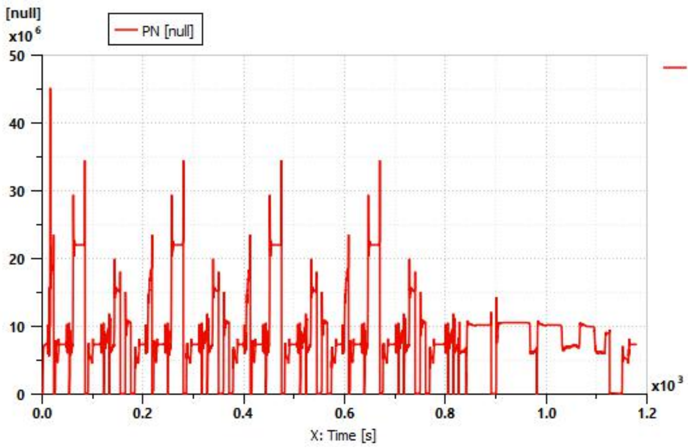


Figure 26 Results of the vGPS in terms of PN (Particle Number)

Since the vGPS targets on-line applications (when integrated in a real time environment or embedded in an ECU), a special focus is put on the CPU performance of the model.

Table 6 presents the simulation times for the studied model including the full vehicle and the vGPS. Both, a fixed-time step and a variable time step solver are used here. The values are obtained with a call of the vGPS every 10 ms. The time step used by the fixed-time step solver is 0.1 ms (to ensure compatibility with the dynamic content of the physical powertrain model).

Table 6 Simulation times including vGPS calls (every 10ms)

	Fixed-time step	Variable-time step
Simulation time [s]	150.1	154.2
Speed-up Ratio to real-time	7.9:1	7.6:1

The simulation times are quite similar in the two cases, at around 150 seconds for the execution of the NEDC cycle. This represents a speed-up ratio of 7 or 8:1 compared to real-time. These demonstrators can be seamlessly exported in a real time environment (for Hardware-in-the-Loop validation for instance).

In practice, the simulation times can be even reduced by generating less calls to the soot estimator. It could be interesting when applying the vGPS, as we do, to assess - off-line - soot emissions over driving cycles. For instance, if the synchronisation period is raised to 100ms, one obtains reduced CPU times as reported in Table 7, without any significant change in the results. A time-saving benefit when using the variable step solver which can take bigger steps, is observed.

Table 7 Simulation times including vGPS calls (every 100ms)

	Fixed-time step	Variable-time step
Simulation time [s]	103.6	24
Speed-up Ratio to real-time	11.4:1	49.2:1

The vGPS has been tested on an additional scenario. IDIADA, in charge of independent testing in the project, applies an in-house RDE driving cycle to assess the performance and other attributes of the developed vehicles. To do a parallel real and virtual testing using simulation, Siemens has also implemented this cycle for vehicle model evaluation.

In Simcenter Amesim a specific tool is developed based for the systematic evaluation of the criteria detailed by the Real Driving Emissions norm. The tool calculates the 20+ criteria and is then able to deliver a RDE-compliance assessment. From a velocity and altitude data set, the graphical user interface gives the user several types of information. In the figure below, one can see on the right-hand side of the window, a preview of the velocity and altitude profiles as a function of the time or displacement. On the left-hand side, a list of the criteria is given with the related evaluations. Then, a flag is displayed (green/red) which determines if the data loaded do correspond to a RDE cycle.

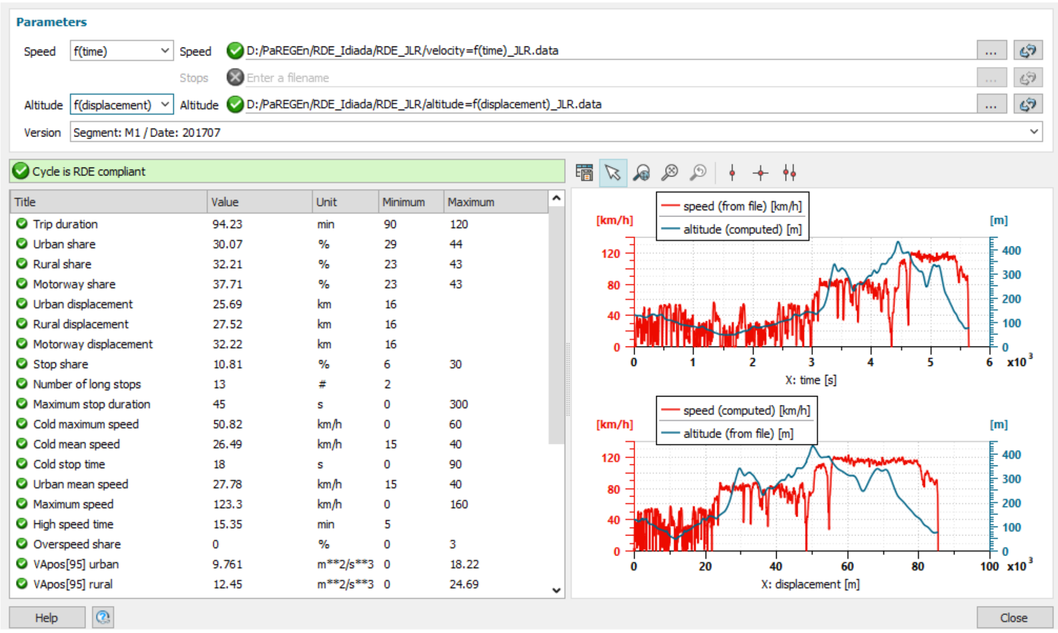


Figure 27 RDE cycle checker

Once vehicle speed and altitude profiles have been checked, they are used by the driver model which is responsible for the application of the commands to the vehicle (acceleration, brake, clutch etc.). The graph below shows the control vehicle speed (i.e.: the profile given by IDIAIDA) and the actual vehicle speed computed by the model.

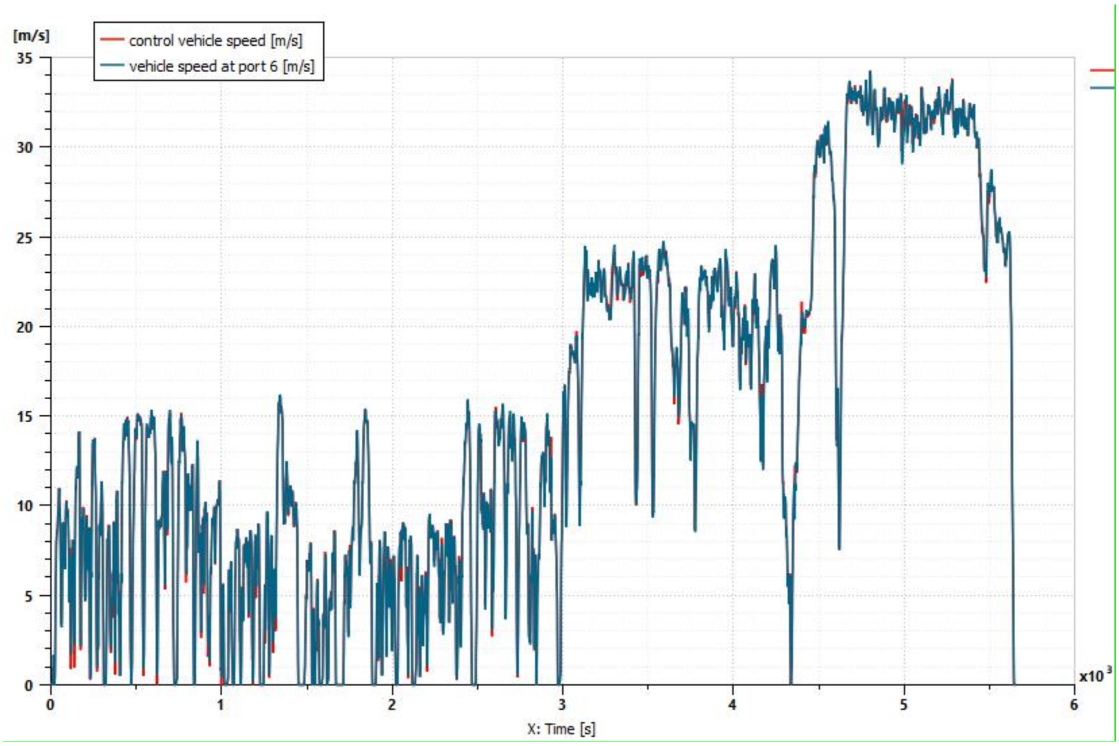


Figure 28 Actual vehicle speed vs target over the RDE cycle

The results of the vGPS computation in terms of particulate number (PN) are presented on the graph below.

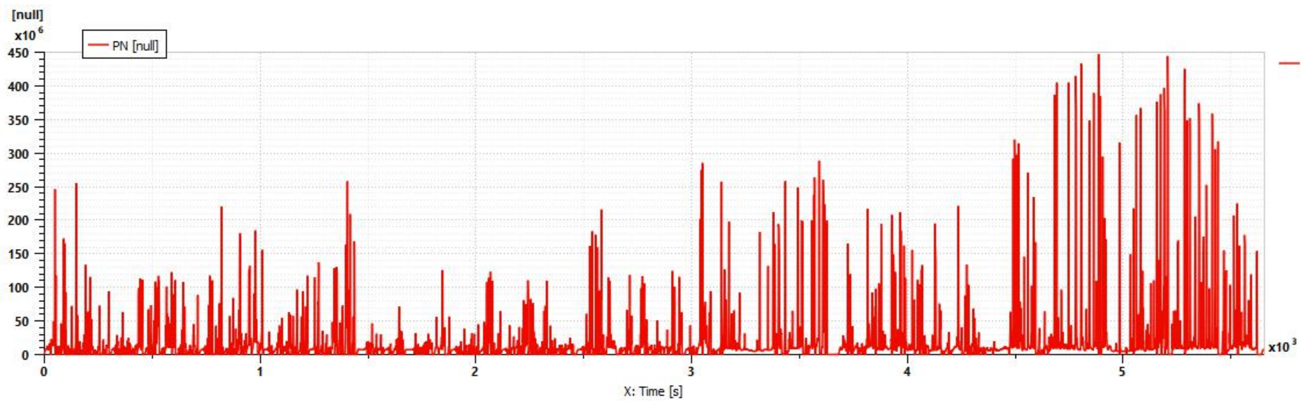


Figure 29 Results of the vGPS in terms of PN (Particulate Number) on the RDE cycle

The RDE cycle being more dynamic than the NEDC, the higher level of soot emissions is as expected. A clear increase of the particle number on the last part of the cycle is also observed. This behaviour is due to the profile of the vehicle speed who increase as well. The cumulated number of particulate over the RDE cycle is 1.12×10^{11} and represents 1.31×10^{9} #/km.

As a conclusion, the vGPS observer has been integrated in the Simcenter Amesim software and offers a way to get estimates for soot emissions off-line. The coupling has been performed using a Mean Value Engine Model which provides all the required inputs to the vGPS and has shown excellent CPU performances. That is a very significant validation step for the vGPS toward its integration in a real ECU (on-line).

3 Discussion and Conclusions

In order to compensate the limited availability of validation data Siemens revised the original plan keeping an objective toward the research and development of modelling approaches and methods aiming at extending the analysis from a local perspective (combustion, spray and soot formation) to a system perspective (in-vehicle evaluation) where the system simulation software brings more value to engineering projects. In practice, this led to the work, illustrated in the present report:

- Development of models and methods to support engineering workflows and to offer the capabilities required to extend the analysis and findings of partners at the component level to a system approach (from details and local analysis to vehicle system analysis).
- Development and validate software coupling strategies in order to combine existing capabilities in Simcenter Amesim with expert tools like the SI-SRM by LOGE (D1.4) and the vGPS soot estimator by ETH (D1.12).

In conclusion, Siemens was able to develop new models and methods to support model reduction and support engineering activities related to vehicle system analysis and evaluation. Simcenter Amesim was demonstrated as an integration platform, able to be to coupled with third party software, which is a strong requirement by the industry in a model-based-development context.

The simulation results show that, given sufficient data, the modelling techniques used can estimate the PN emissions much faster than real-time, such that a vGPS will be feasible in practice.

4 Deviations

The initial scope of the research and developments targeted by Siemens for the second part of the project (D1.8), was to complete the research and development of methodologies and modelling capabilities in order to reduce crank-angle based models into approaches more adapted (faster) to in-vehicle evaluation. Then, the scope was to validate the developed workflows with partners data generated from prototype engines and vehicles.

The actual Siemens achievements present some deviations in comparison to initial plans, mainly due to project constraints with data availability and release timing, and follow a revised plan resulting from discussions and decisions taken in agreement with the project partners (Work Packages 1, 4 and 5).

Indeed, applying and validating simulation method requires large sets of data from the partners including component to system characteristics for modelling tasks and test data sets for identification and/or validation purposes.

The access to data is a critical aspect in simulation projects. This is specifically complex in the case data related to prototype engines and vehicles and this was actually identified as a risk and found to be a challenge faced within PaREGEn:

- Engine prototypes are the results of design iterations, which makes it difficult to get consolidated data before their operation on the engine dynamometer.
- Engine prototypes integrate innovative technologies delivered by suppliers, thus full characteristics and operation generally cannot be disclosed to third parties.
- Prototype engines are run on the engine dynamometers at a few engine operating points in order to validate their main attributes, whereas simulation tools need to be feed with broader set of data (extrapolated by simulation to cover any kind of operation experienced on a driving cycle in our case).
- The hardware being set, the control strategies are generally finalized very late in the projects and the full details cannot be easily shared nor disclosed with third parties.
- The prototype vehicles are generally available very late in projects for the final testing campaign and assessments.

In practice, the main sources of data in the project are the BOSCH prototype engine (see D1.4), the JLR engine (single cylinder and multi-cylinder) and DAI engine. However, this DAI engine was operated on the engine test bench at very few points, which were not enough to feed the modelling and simulation approaches proposed by Siemens, which aim at covering various operating conditions as experienced on real driving cycles.

The JLR data for the multi-cylinder engine were delivered when Siemens had to finalize parallel modelling work, including completion of works in collaboration with other partners in Work Package 1 (integration of vGPS soot estimator by ETH). Siemens engaged the combustion simulation works in the last weeks of the project and the results were not ready for insertion in the present document. Hence, they will be added to the final project reporting.

It should be noted, also, that details related to the JLR engine simulations are confidential and cannot be disclosed here.

5 Nomenclature

BMEP	Break Mean Effective Pressure
CFM	Coherent Flame Model
CO	Carbon monoxide
CPU	Central Processing Unit
DOE	Design Of Experiments
ECU	Engine Control Unit
FMEP	Friction Mean Effective Pressure
HC	Hydrocarbons
HF	High Frequency
MPC	Model Predictive Controller
MVEM	Mean Value Engine Model
NEDC	New European Driving Cycle
NOx	Generic term for the mono-nitrogen oxides (nitrogen dioxide and nitrogen oxide)
NVH	Noise Vibration Harshness
PN	Particle Number
RDE	Real Driving Emissions
SI-SRM	Spark-Ignited Stochastic Reactor Model
vGPS	Virtual Gasoline Particle Sensor
WLTC	Worldwide Harmonized Light Vehicles Test Cycle

Appendix A – Acknowledgement

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners:

#	Partner	Partner Full Name
1	RIC	RICARDO UK LIMITED
2	DAI	DAIMLER AG
3	JLR	JAGUAR LAND ROVER LIMITED
4	BOSCH	ROBERT BOSCH GMBH
5	FEV	FEV EUROPE GMBH
6	JM	JOHNSON MATTHEY PLC
7	HON	HONEYWELL, SPOL. S.R.O
8	JRC	JOINT RESEARCH CENTRE – EUROPEAN COMMISSION
9	UNR	UNIRESEARCH BV
10	IDIADA	IDIADA AUTOMOTIVE TECHNOLOGY SA
11	SIEMENS	SIEMENS INDUSTRY SOFTWARE SAS
12	LOGE	LUND COMBUSTION ENGINEERING LOGE AB
13	ETH	EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH
14	UDE	UNIVERSITAET DUISBURG-ESSEN
15	RWTH	RWTH AACHEN UNIVERSITY
16	UFI	UFI FILTERS SPA
17	UOB	UNIVERSITY OF BRIGHTON
18	Garrett	GARRETT MOTION CZECH REPUBLIC SRO

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