Virtual Engine Calibration (VirCal)

Public report

Virtual Test Cell (VIRTEC)

Project within FFI Electronics, Software and Communication
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Content

1. Summary

Due to stricter emission regulations and more environmental awareness, the powertrain systems are moving toward higher fuel efficiency and lower emissions. In response to these pressing needs, new technologies have been designed and implemented by manufacturers. As a result of increasing complexity of the powertrain systems, their control and optimization become more and more challenging. Model-based development has become an indispensable part of systems engineering for design of the next generation powertrains. Model-embedded control and virtual test beds being integrated in powertrain development process and research and education activities. Virtual powertrain calibration can considerably reduce time and cost of product development process while increasing the product quality. Nevertheless, virtual calibration has not yet reached its full potential in industrial applications. Volvo Penta has recently developed a virtual test cell named VIRTEC, which is used in an ongoing pilot project to meet the Stage V emission standards. The integrated powertrain system includes engine, Exhaust Aftertreatment System (EATS), and Engine Management System (EMS). The objective of this project was to develop and test the essential aspects required to increase the contribution of virtual testing in powertrain calibration activities and practically implement it in a project. These aspects comprise the following: Hardware-in-the-Loop (HiL) system, simulation models, and working process for joint virtual and physical testing to facilitate efficient powertrain development process.

A novel simulation methodology for optimization and validation of control requirements has been developed, based on the combination of physics-based high-fidelity models and data-driven approach. Uniquely combining the best of two worlds and relying on minimum number of inputs from measurements and manufacturers, this methodology represents a powerful tool for development of the next generation powertrain systems. The simulation models are currently being validated by the VIRTEC team at Volvo Penta. In the model development branch, a Machine Learning (ML) model for engine simulations in the hardware-in-the-loop (HiL) environment was developed. The engine model, herein called ANN-engine, was built for a heavy-duty diesel engine, and directly implemented in the VIRTEC system.

2. Sammanfattning på svenska

Utvecklingen av drivlinor blir en alltmer komplex process. Antalet frihetsgrader ökar och därmed utvecklingstiden. För att korta utvecklingstiden med bibehållen (eller ökad) kvalitet, behövs s.k. modellbaserad utveckling tillämpas. Modellbaserad styrning och kalibrering är idag ett oumbärligt verktyg vid utveckling av framtida drivlinor. Dock har man inte nått den fulla potentialen i industrin. Volvo Penta har därför utvecklat en virtuell testrigg, VIRTEC som används vid utvecklingen för att uppnå de nya utsläppskraven

(Stage V) för off-road fordon. I detta system simuleras både motorn och avgasefterbehandlingssystemet (Exhaust AfterTreatment System, EATS) kopplat till motorstyrsystemet (Engine Management System, EMS). Av tekniska skäl är även viss hårdvara integrerat i systemet, s.k. Hardware-in-the-loop, HiL. Även själva arbetsprocessen för arbete med dessa system har utvecklats inom projektet.
I modelleringsarbetet, har även ny metodologi arbetats fram för att optimera och validera modellerna genom tillämpning av reducerade, fysiska modeller och en datadriven approach. Även maskininlärning har tillämpats mha s.k. Artificiella Neurala Nätverk (ANN) som implementerats och validerats inom projektet.

3. Background

Stricter emission regulations and more environmental awareness led to introduction of modern technologies in diesel powertrain systems–for example high pressure common rail, multiple injections, Exhaust Gas Recirculation (EGR), Variable Valve Timing (VVT) and Variable Geometry Turbine (VGT), as well as the aftertreatment components such as Diesel Particulate Filter (DPF) and Selective Catalytic Reduction (SCR). Introduction of these complex technologies could help to achieve higher fuel efficiency and lower exhaust emissions; however, the powertrain development complexities were transferred (although mitigated) to control and optimization of these systems. As a consequence, the Verification[1] and Validation[2] (V&V) of powertrain system (EMS, Engine and EATS systems) becomes increasingly challenging. The calibration efforts are further increased by the need to consider various operational modes, such as transients, cold starts and non-standard conditions, laying the burden on the Engine Management System (EMS). Each actuator adds an extra dimension in Design of Experiment (DoE) tests in order to calibrate and optimize a powertrain system.
The conventional calibration technique includes Design of Experiment (DoE), data acquisition, and determining the optimal lookup tables for an engine to identify the optimal balance of engine performance, emissions, and fuel economy. To perform high-quality calibration, enough data needs to be acquired for each operating point. The engine test bench is an expensive system, the number of measurements should be minimized to reduce time and costs of the calibration. Moreover, the conventional calibration does not make it possible for optimization during dynamic operation.

Using model-based calibration, the behavior of complex engine system (fuel consumption, engine-out emissions, working temperatures) together with calibration settings is identified, based on fewer optimally distributed measurements and represented by simulation models.

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[1] The evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition.
[2] The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders.

The need for transferring part of the calibration activities into the virtual platforms were emphasized during the last decade. It is estimated that in automotive industries, number of actuators (degrees of freedom in DoE) increased from five in 1997 to twelve in 2014 and the calibration efforts (time spent on verification and validation of the system) are expected to double until 2020. As a result, the calibration should be rearranged from its current combination (Vehicle: 70%, test bench 25% and virtual 5%) to a more efficient combination (Vehicle: 40%, test bench 40% and virtual 20%). The 15% difference between the current estimated virtual testing in automotive industries and projected future share of virtual testing was the main motivation for the current project.
Virtual powertrain calibration helps divide the calibration efforts into two interconnected projects, introduced in this project as a joint virtual-physical process. The powertrain system under consideration consists of the engine, EATS and EMS.
Volvo Penta developed a platform for virtual powertrain calibration called **Vir**tual **Te**st **C**ell (VIRTEC) based on the requirements set in our initial investigation phase of the project. In that phase, different existing platforms were studies and the potentials and limitations of those systems were investigated. The platform was tested and verified in the pilot project concerned with the heavy-duty diesel engine meeting stage V regulations. In the present report, the term “platform” refers to the system consisting of a virtual test rig, simulation models and working process. The rig represents a HiL system, which is designed to resemble the actual test cell. The HiL system uses real-time models for engine and exhaust aftertreatment systems (EATS). The working process defines different quality gates and different working cycles.

4. Purpose, research questions and method

The main purpose of this project was to increase contribution of virtual testing in powertrain development by investigating and building the necessary elements within a pilot project. The requirements for fulfilling this purpose were identified based on the initial investigation phase and feedback from similar platforms in Volvo. Three main parts of an effective virtual powertrain calibration platform will be discussed here:

- Virtual rig: Low maintenance and user-friendly system
- Powertrain Models: Quality controlled, short lead time model development
- Joint virtual-physical working process: Efficient working process with buy-in from stakeholders

The main factor in setting requirements of the platform is ”the user” (customer) of the system. In the current study, the users are test/calibration engineers. The system should be as close as possible to a test cell (engine and EATS) while software (EMS) design is outside the scope of this system.
It should be noted that different targets (users and purposes) will lead to a different set of requirements and consequently a different solution for virtual testing.

5. Objective

The project objectives were to contribute to the **overarching FFI objectives** by:

- Promoting cooperation between industry and universities (Chalmers)
- Developing competitive research and innovation environments in Sweden
- Internationally interconnected research and innovation.
- Participation of subcontractors

Furthermore, the project contribute to the **sub-program objectives** by:

- Verification and Validation
- Go Green
- Strengthen Sweden and the Swedish automotive industry's competitiveness in a global perspective

The project specific objectives include:

1. Transfer 20% of the engine calibration activities from test cell into the VIRTEC system in a pilot project.
2. Creating a working process for joint virtual-physical engine calibration based the pilot project.
3. Faster Software development and shorter loops. Software checks and V&V can be performed earlier in the development work
4. Develop compatible model for VIRTEC system and designed for joint virtual-physical engine calibration process
5. One PhD student (for 2 years or a post-doctoral student) supported by the project.
6. Four Master thesis supported by the Project.
7. One PhD student internship
8. Publications of the research, both in scientific journals as well as conference publications e.g. SAE (Society of Automotive Engineers)
9. Use the system for the training of the new calibration engineers and new graduates at Volvo AB in order to reduce the learning curve of the engine Software for the new engineers.
10. Duplicating two systems at Volvo Penta for performing the current project
11. A VIRTEC system for Chalmers for future research and development of next generation of calibration engineers
12. VIRTEC system as an off-the-shelf solution at Volvo AB
13. Support similar projects in Volvo AB including duplication of the system, maintenance and knowledge transfer. Therefore strengthening Volvo AB competitiveness within the vehicle industry.

6. Results and deliverables

The main results divided into three parts: virtual test rig, models and working process. Human factors in communication and system usage has been discussed as well. At the end of this section, the deliveries will be checked against the objectives.

Industrialized Virtual Rig

There are different solutions for virtual testing: Model-in-the-Loop (MiL), Software-in-the-Loop (SiL), and Hardware-in-the-Loop (HiL). These solutions can be real-time or faster/slower than real-time. If the design of the software is outside the scope of the rig, SiL and HiL are more suitable. SiL uses software, virtual EMS (vEMS), while HiL systems use physical EMS and a selected choice of engine hardware, e.g. throttle and EGR valve. The selection of SiL or HiL is case specific and might vary from company to company. HiL systems are more time-consuming to prepare for each powertrain calibration project and require some of the hardware. However, HiL system is the optimal solution as a virtual test cell since it closely resembles physical test cells and mitigates possible human errors in connecting vEMS. Also, the cost of vEMS maintenance is minimized. Since the physical EMS will be used, the system should be capable to operate in real-time (RT).

The system can be either hard real-time, with all the components being forced to run in real time, or soft real-time capable, i.e. as close to real time as required. If the models are compiled in a real-time apparatus, it is a hard real-time system. However, we have not seen any benefit in compiling the models in our real-time apparatus. However, the delays in the system need to be measured and ensure that the maximum delay does not exceed a predefined threshold.

The system should be user-friendly. This requirement implies that the interfaces of the system should be identical to those of the test cell so that the users should not need any extra software skills to run the rig. This is the most important factor in designing the system.

Another significant decision is the choice of hardware included in the rig. Including all the engine actuators will increase the rig setup time and complexities in changing the configuration. On the other hand, including the hardware components will minimize the fixes need to be added to the system due to including the simulated hardware. This will make the system to deviate from the test cells. There is a trade-off in including the hardware and it should be considered in designing the system.

A schematic of the VIRTEC system is shown in Figure 1. The system uses soft RT connection with the models, and it has the potential to switch to a SIL system, if required. However, HiL remains the principal solution since the main purpose of the virtual test cell is to emulate a test cell environment.

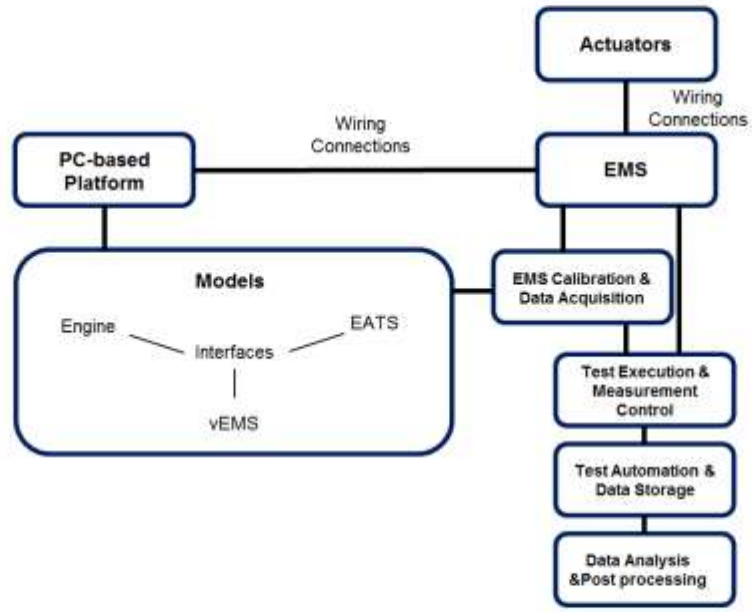

Figure 1. The schematic of the VIRTEC system

Three HiL systems were developed within the project and used extensively according to the plan.

Two Industrialized system was developed for Volvo Penta and one for Chalmers University of Technology in CERC to fulfill the deliveries of this project.

Powertrain Models

Different powertrain modeling choices are shown in Figure 2. Normally, the models with higher computational time have longer development lead time. Slower models, e.g. 3D CFD models typically include more physical details and can be used earlier in the powertrain development. The models with higher computational time are mainly adopted for component simulation, e.g. turbo simulation and these models need less test data for tuning of the model. In contrast, faster models have shorter development lead time; with more empirical adjustments; typically used later in the development process; can be used for system level modeling; however, more test data are required for development of these models.
Detailed 3D CFD models are too slow for HiL applications with current computational power. In addition, the creation of 3D models is very complex and time consuming, which is another constraint for their usage, as it will be discussed below. Computationally demanding 1D detailed model cannot be used in HiL applications either. Simplified 1D models and empirical models (0D) are the main choices for a virtual calibration platform. The empirical models have high accuracy, but they are not physical. The models cannot be reused if the powertrain configuration has been slightly changed; however, the empirical models are beneficial when the powertrain configuration has been confirmed. Some level of generalization outside the measured data is required, so the table-based

empirical models should not be used. However, machine learning tools might be beneficial by providing good interpolation with some levels of extrapolation.

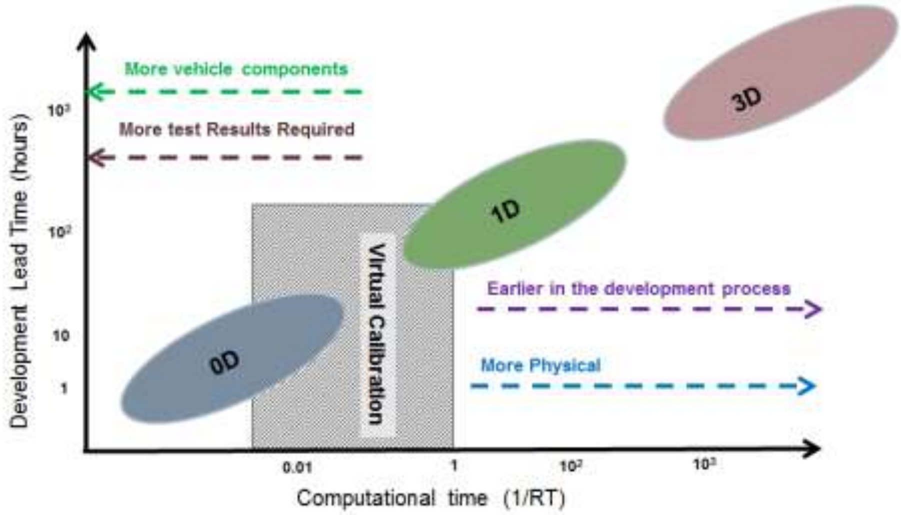

Figure 2. Modeling choices for virtual powertrain applications.

The model development time should also remain short enough so that the models can be effectively used in calibration projects. Model development loops should be shorter than software or powertrain hardware modification loops, so that the models can be delivered at the right time to the project. Otherwise the physical calibration project will move forward without any contribution from virtual testing. This is a practical issue with using virtual calibration in powertrain development as previously noted in other platforms. A high level of collaboration between model suppliers and virtual team is required along with the selection of the right methods for model development.

The models provided for virtual calibration are different from the models used in simulation systems, e.g. component level analysis of the turbo system; although a strong connection between the models is recommended. The connection between the models can be improved by using the same platform, same model input/output and scalable computational time. The main difference between simulation models and virtual models is the computational time. The RT models used for virtual testing should be shared with software design and EMS engineers in order to synchronize the activities. Figure 3 illustrates the concepts of virtual testing and simulation. The simulation tool is typically used in the early stages of the powertrain development process, for component simulations, and can be slower than real-time. The simulation engineer is a connection between simulation tool and the project, and the combination of simulation engineer expertise and software tool will provide inputs to the projects. In virtual platforms, on the other hand, the models are used directly by the powertrain calibration projects. Therefore, an extra step in model quality control is essential. Validation of powertrain simulation models, herein called acceptance testing, constitute an integral part in model quality assurance. This was also mentioned in literature as an important step in model integration. A standard tool is required to measure the quality of all the models with the same method.

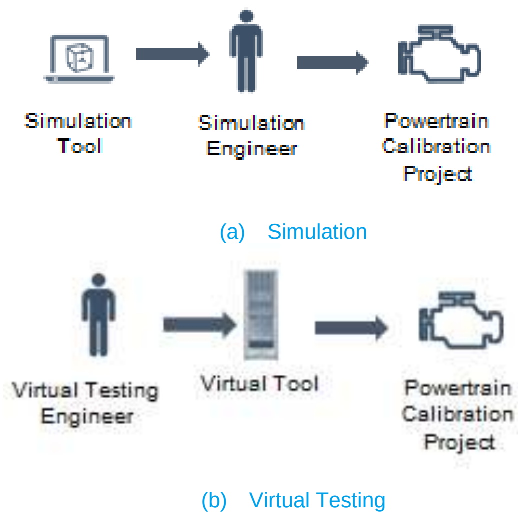

Figure 3.Comparing Simulation and Virtual Testing.

As mentioned above, model quality control (see Figure 4) is an essential step toward an effective virtual calibration. In a virtual calibration platform, the details of the model interface, e.g. inputs/outputs (IO), units, consistent naming and defining shared IO among projects are as important as model accuracy. Simulation models, like any other products, should be quality controlled, and their quality should be improved continuously.
Nevertheless, for many applications in powertrain calibration highly accurate models are not required, e.g. OBD or software logic checking. The model design and requirement settings should be backward based on “what should be the model specifications to perform the task”. This approach is related to George E. P. Box quote: “Essentially, all the models are wrong, but some are useful”.

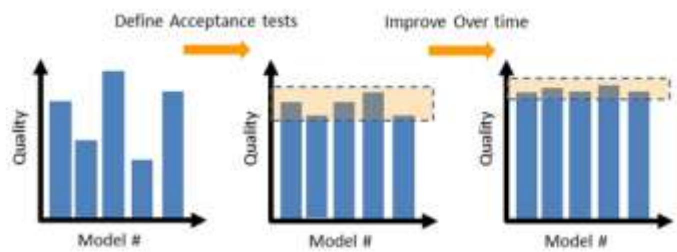

Figure 4. Model quality control concept.

Quality of measured data is also an important factor in ensuring an effective virtual testing. Measurement accuracy needs to be strictly monitored. Some extra testing might be required, but it should be minimized to guarantee low operational costs of the system.
Since legislations are based on transient drive cycles, powertrain models should also be validated using dynamic drive cycles. This task might be more difficult for table based empirical models.
Scope of modeling in virtual testing needs to be defined as well. The task of further model development will be carried out in academic environment and/or R&D. The focus of virtual team should be on providing application specific models.

GT-POWER FRM model was developed as a part of the pilot project. Steady-state part load map (PLM) data was provided as training data and Non Road Transient Cycle (NRTC) was provided for the purpose of validation. PLM data represent torque and engine speed parameter sweeps to cover the entire engine map, and include 160-200 points in total. The NRTC test is a transient driving cycle for mobile non-road diesel engines developed by the US EPA in cooperation with the authorities in the European Union (EU). The FRM model is real-time capable from the beginning (not simplified from detailed model) and optimization toolbox in GT-POWER was used to calibrate the model based on PLM data. Using semi-automated calibration of model constants helps to keep the model development time sufficiently short.
The second model developed in this pilot project was a data-driven model. ANN modeling approach was used in the pilot project and trained on NRTC and PLM data. A custom transient cycle was used for validation of the model. Matlab® machine learning toolbox was used for simulation of the signals. The model consists of two layers: the first layer models engine temperatures and pressures. The temperatures and pressures are then used as inputs in the second layer which predicts exhaust emissions concentrations. All the verification and validation tests were performed on the HiL system.

The quality of the models has been monitored for a period of six months. The results are validated in closed loop system in VIRTEC against the validation data (NRTC cycle).

Further development of the FRM model was performed in close collaboration with Gamma Technology including calibration of turbine system using first principles physical models. The development will be implemented in the next version of GT suite.

Within ANN modelling, extensive methodology assessment was performed to evaluate the choice of data set for calibration, testing and validation. By analyzing the variability at each step, a better understanding of the model performance was obtained. Also, a variety of modern machine learning tools was applied and assessed including Feed-forward and NARX. Modelling of the EATS was attempted through a series of MSc thesis, mainly focusing on the modelling methodology. The single channel approximation was scrutinized and has resulted in new research activities at Chalmers.

Working Process

The virtual calibration brings together calibration engineers, software engineers (responsible for design of EMS software), simulation engineers, and project managers. Since strong collaboration between these engineering groups is necessary, the working process is one of the most important parts of virtual testing system. Yet, there is no universal formula for an efficient working process, since organizational structure and departmental relations vary in different companies. It should be defined based on a specific work culture of the establishment that the platform was implemented. The working process should be designed to keep the entire virtual operational cost low enough to stay beneficial based on our experience.

The Communication Channels (CC) with other processes needs to be defined; those include simulation models, statistical analysis, calibration project, software, and Project Management Engineering (PME). The CC are listed below and shown in Figure 5, not necessarily in sequential order. A description of the extra steps needed for incorporating virtual testing into the company is described.

- CC1: Virtual team receives structured statistical data and starts building empirical models (0D). The structured data means that the unreliable measurements are removed and organized data are stored systematically.
- CC2: In this part, models are ordered and requirements are set by virtual team; based on the purpose of the virtual activities in calibration project. Models are received and validated.
- CC3: This is outside the scope of the virtual team work, but by adding virtual testing to the organization this channel will be added as well. The powertrain design specifications need to be simplified to be applied to real-time models, e.g. accumulated volumes, average diameters, average lengths, manufacturers' maps etc.
- CC4: Timeline and type of activities planned for virtual platform need to be communicated; virtual team needs to monitor the planning activities on virtual platform. The Verification and Validation (V&V) matrix of activities needs to be followed by PME and a base V&V template should be used for all the projects.
- CC5: The control software in EMS is normally transferred to calibration project for testing. This channel will add an intermediate step to test, as well as (roughly) calibrate and optimize the software (including the calibration data setting) first in virtual platform by calibration engineers. This step can be automated.
- CC6: Testing on virtual platform needs to be monitored by virtual team. This includes servicing the system, help calibration engineers to run their tests, provide guidance on the right applications for the platform, and gather feedback and issues and transfer it to HiL setup. Any issue in the quality of measured data should be reported by virtual team. Here virtual team should provide information on the tasks that cannot be performed on the system, e.g. durability and combustion hardware design.

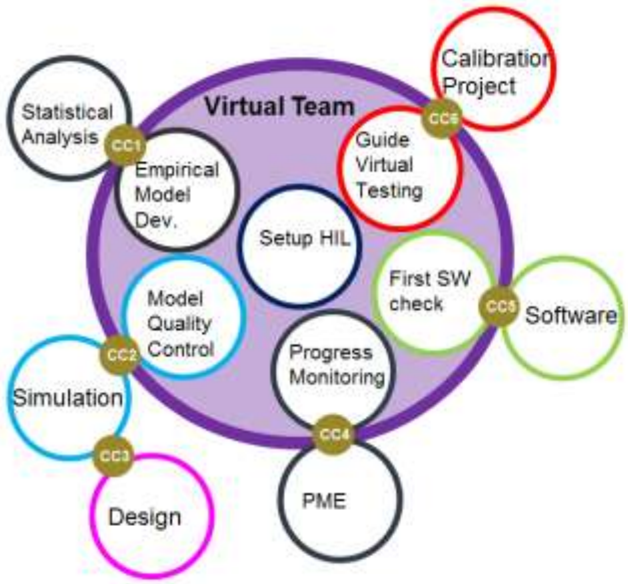

Figure 5. Virtual team in contact with other processes.

Working process is the part of the virtual calibration that can only be achieved by practicing over time, while project management and communication between different teams play the key roles.

The working process was divided into three loops: Powertrain Model development, Development environment and Industrial environment. In the powertrain model development loop, the model is developed or modified (if it already exists from previous loops). In the development loop, HIL is prepared for the calibration project, the issues are resolved, and the system is quality assured. The industrial loop is the process of using the platform for engine verification and optimization activities. The full loops has been discussed in our published paper (2018-01-0007)

Human Factors in Communication

Human factors and different working processes are important elements in communication. The Software and HiL setup teams are normally working based on a scrum methodology (an iterative and incremental agile framework), while the powertrain development projects are based on waterfall methodologies (linear, non-iterative sequential design approach). Besides working methodology, different teams are focused on different aspects of powertrain technology. Due to these differences, it can happen that the teams are almost speaking different “languages”. This potential issue needs to be addressed by imposing working processes for different stages with special focus on defining interfaces between the teams and acceptance criteria. This factor has been mentioned, as “silos of engineering”, in other virtual platforms as well.

Usage of the Platform

In the pilot project, a two-weeks-in two-weeks-out working system was defined to further develop the platform, while it was under testing and verification. The system was used for pilot project for over 2500 hours for testing/validation. The system was offered as an optional method; however, the powertrain calibration activities were closely monitored. The system was booked 50% of the time and we estimate our service time (maintenance, troubleshoot and help to run the system) about 10% of the time.

The main applications of the platform included the following: On Board Diagnostics (OBD), Back-back software check, Engine Protection, Soot model in EMS, SCR control. Figure 6 shows the distribution of applications on the system. The system was mainly used for software (including data setting and calibration) validation, since the accuracy requirements are less strict and also to ensure the good performance of the system at the beginning. Beside the software, the system was used for calibration (optimization), hardware testing, as well as for learning the test cell applications for new test and calibration engineers.

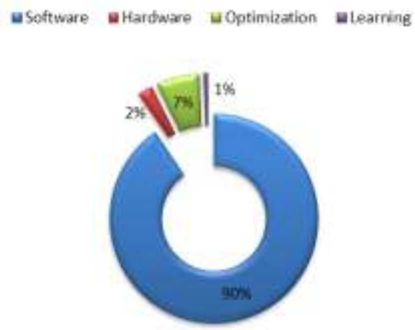

Figure 6. Distribution of activities on VIRTEC system based on the task type.

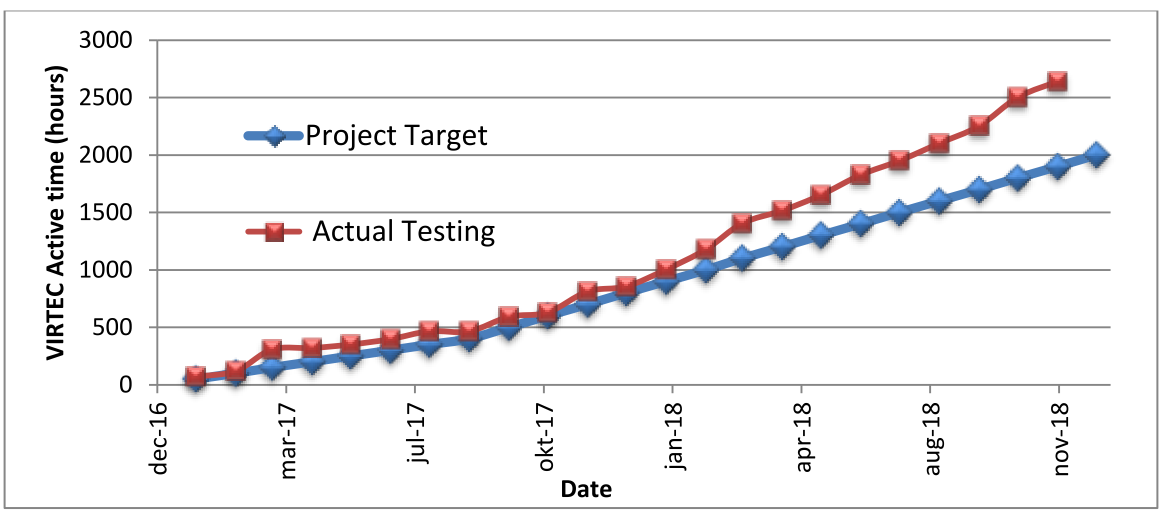

Figure 7. Distribution of activities on VIRTEC system based on the task type.

Deliveries and Objectives

Here we check the deliveries of the project against the initial objectives

1. Transfer 20% of the engine calibration activities from test cell into the VIRTEC system in a pilot project.
   The original planning was 2000 hours of testing while the system has been used over 2500 hours in product development.

2. Creating a working process for joint virtual-physical engine calibration based the pilot project.
   A suggested working process for joint physical and virtual development was presented here and evaluated in pilot project.

3. Faster Software development and shorter loops. Software checks and V&V can be performed earlier in the development work
   One of the main usage of the system was back/back testing of the Software for engine before physical testing and this application has been noted as one of the main benefits of the system.

4. Develop compatible model for VIRTEC system and designed for joint virtual-physical engine calibration process
   Two different modeling methods have been tested and verified in the system. Fast running model (1D/0D models) and Machine Learning models.

5. One PhD student (for 2 years or a post-doctoral student) supported by the project.
   A post-doc researcher was recruited for performing this project at Chalmers.

6. Four Master thesis supported by the Project.
   Six master students and two course-project were defined to support this project at Chalmers.

7. One PhD student internship
   One PhD student worked for 6 month from NSERC Network of Canada.

8. Publications of the research, both in scientific journals as well as conference publications e.g. SAE (Society of Automotive Engineers)
   The list of publications is included in the next section.

9. Use the system for the training of the new calibration engineers and new graduates at Volvo AB in order to reduce the learning curve of the engine Software for the new engineers.
   One of the important usage of the system was training new calibration engineers.

10. Duplicating two systems at Volvo Penta for performing the current project
    Two Industrialized systems were developed for performing this project at Volvo Penta.

11. A VIRTEC system for Chalmers for future research and development of next generation of calibration engineers
    A system were developed and placed at CERC for future research collaborations

12. VIRTEC system as an off-the-shelf solution at Volvo AB
    The system has been announced internally and currently being used outside Penta within Volvo group as well.

13. Support similar projects in Volvo AB including duplication of the system, maintenance and knowledge transfer. Therefore strengthening Volvo AB competitiveness within the vehicle industry.
    The project stayed open for internal collaborations and knowledge transfer through the length of this project.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Publications, student projects and internal initiatives. A system was developed at Chalmers for future use
Be passed on to other advanced technological development projects	X	Some parts of this project will be used for other related projects, specifically modelling techniques
Be passed on to product development projects	X	The current project is integrated in the product development, although here are room for improvements
Introduced on the market		Only for internal applications and product development
Used in investigations / regulatory / licensing / political decisions		NA

7.2 Publications

Conference papers:

- Andric, J., Sjöblom, J., Sediako, A. D., Faghani, E., & Schimmel, D. (2018). *Development and Calibration of One Dimensional Engine Model for Hardware-In-The-Loop Applications*. SAE Technical Paper Series, 1, 1–8. https://doi.org/10.4271/2018-01-0874
- Faghani, E., Andric, J., & Sjöblom, J. (2018). *Toward an Effective Virtual Powertrain Calibration System*. SAE Technical Paper Series, 1, 1–11. https://doi.org/10.4271/2018-01-0007
- Sediako, A. D., Andric, J., Sjöblom, J., & Faghani, E. (2018). *Heavy Duty Diesel Engine Modeling with Layered Artificial Neural Network Structures*. SAE Technical Paper Series, 1, 1–10. https://doi.org/10.4271/2018-01-0870
- Sjöblom, J., Andric, J., & Faghani, E. (2018). *Intrinsic Design of Experiments for Modeling of Internal Combustion Engines*. SAE Technical Paper Series, 1, 1–9. https://doi.org/10.4271/2018-01-1156

Master thesis projects:

- Erlandsson, A. (2017). *Fast Running 1D model of a heavy-duty diesel engine*. Chalmers University of technology.
- Almqvist, F. (2017). *Combined Empirical and 1D Modeling Approach for Exhaust Aftertreatment System for Heavy Duty Diesel Engines*. Chalmers University of Technology.
- Cen, H. (2018). *Calibration and validation of a 1D Model for Exhaust Aftertreatment System in Heavy Duty Diesel Engines*. Chalmers University of Technology.
- Hagentoft, Elias and Isanka Dabarera, M. M. (2018). *Online Model Based Engine Calibration using Gaussian Process Regression*. Chalmers University of Technology.
- Narayanan, B. (2018). *Semi-Physical Modelling Approach for Exhaust Aftertreatment System of Heavy Duty Diesel Engines*. Chalmers University of Technology.

Master Student projects:

- Grimm, D., Sathyan, S., Holm, V., & Kumar, S. (2018). *Recalibration of Heavy-Duty Diesel Engine for Marine Application*. Chalmers University of Technology.
- Ilisei, S., Dwarakanath, S., & Joshi, H. (2017*). Virtual Calibration using Parameter Estimation for Fast Running Model of Diesel Engine*. Chalmers University of Technology.

8. Conclusions and future research

In this report, the results and deliveries of the project for developing an effective virtual powertrain platform were described. The requirements are divided in three categories: virtual rig, simulation models and working process. Volvo Penta's Virtual Test Cell (VIRTEC) was described as a platform that is in line with the requirements. The powertrain models fit the application not only in terms of accuracy but also lead-time development, quality control and input data. A working process designed specifically for a joint virtual-physical testing was developed. The effectiveness of the platform has been tested and verified in the pilot project. Finally, applications and performance of the system in the pilot project have been discussed. Currently, the main applications are related to software verification; however, using the modelling techniques developed in the current project, should open up more opportunities for optimization of the powertrain system in a virtual testing environment.

Future research include Fast running model and machine learning model development at Chalmers. In respect to the conceptual graph of generalization-accuracy, the new model will be flexible enough to adapt quickly for the application while the state of the art model will be selected. The effectiveness of working process needs a major validation.
The platform for virtual powertrain calibration should be more mature as the engine project moves forward from concept phase to certification. The biggest contribution of VIRTEC is where experimental testing is more difficult, e.g. weather box (high altitude and extreme environmental conditions). When the engine is certified for a general application, VIRTEC can be the back-up for aftermarket and service based on customer data.
It also should be mentioned that virtual testing boundaries and requirements discussed in this report are not powertrain specific. Therefore, by improving the technologies (diesel, gasoline, hybrid or electric), the virtual testing would still be effective as a connection between EMS and powertrain testing.

9. Participating parties and contact persons

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