Linking model predictive control (MPC) and system simulation tools to support automotive system architecture choices

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Abstract

Today's automotive industry must introduce advanced powertrain technologies as a consequence of the stringent environmental regulations and strong market expectations. This leads to the increase of vehicle variants and to the growth of the powertrain architectures complexity. Hence, the development of hardware and software can no longer be decoupled. Those activities have to run in parallel, starting from simulation and advanced engineering, continuing to the detailed engineering phase, and ending in validation and calibration. In the so-called Model-Based Systems Engineering (MBSE) approach, simulation models including both hardware and control systems are used to first make decisions on possible architectures. This paper presents a new MBSE approach that allows powertrain hardware selection to occur early during the simulation stages. The process combines Model Predictive Control (MPC) for the control system with a physical modeling software package for the hardware. This combination of MPC and physical modeling addresses several practical difficulties that typically hinder attempts at MBSE for hardware selection.

1. Introduction

Context

Today's automotive powertrains must delight customers with performance, reliability, and low noise while simultaneously meeting increasingly stringent regulations on CO_2 and other emissions, all at a competitive cost and fast time-to-market. Embedded software, electronics, sensors and actuators play a critical role and acts as a "glue" to make combustion systems, boosting systems, cooling systems, exhaust after-treatment systems, batteries, and transmissions perfectly integrate for optimal vehicle performance.

The development of the mechanical powertrain hardware and the software functions controlling them can no longer be performed independently. As a result, many automakers implement hardware selection processes where many powertrain variants are built. An electronic control system is then designed and calibrated for each variant. The variant that best meets system-level requirements moves to the next development stage. But this process is money and time-consuming and prevents manufacturers and suppliers to stay in the competition race.

Given the financial incentives, most automotive companies have tried some form of Model-Based-System-Engineering for hardware selection applying system simulation in particular. This implies to have access to the "right" models for both the hardware and the software.

Difficulties frequently encountered with MBSE for hardware selection

Models for the plant (engine, transmission, and vehicle) are generally available at the earlier stages of the product development process. Often generated during R&D and advanced projects, they are not necessarily well adapted to be applied for an innovative and efficient hardware selection process. In particular, the models generated in the with a powertrain subsystem design perspective are often too complex and slow to be combined efficiently with control tools. The present paper illustrates the requirements for getting the right modeling approach for plant model adapted to hardware selection and the implications for the deployment of models throughout the complete product development process.

On the other hand, when models of the plant are available, obtaining the corresponding control models is always a more difficult task. One of two methods is usually employed:

- Adaptation of existing production control approaches – This approach provides a path to the implementation on physical prototypes later in the process. However, simulation time can be slow because the production strategy block diagrams often include tens of thousands of elements. Personnel gaps are an even more serious issue. Hardware designers are usually experts in boosting, transmissions, or system-level simulation tools, but have limited skills in complex control strategy diagrams.

- Simplified custom controllers – A simplified control is created from scratch to cover the extra capabilities and degrees of freedom required for the new technology brick. This approach offers fast simulation times and understandable control models. But also come with disadvantages: the time and expertise required to build the controller from scratch is often substantial. Also, since it is often built quickly, controller performance can often be substantially different from that of a well-tuned production controller. As a result, controller tuning differences could be mistaken for hardware performance differences. Finally, the controller used in simulation is often a dead-end with no path to implementation on embedded computing platforms.

Novelty of the proposed approach

The process described in this paper improves on the second method by making it faster to develop custom controllers for new hardware: The novelty is to use physical models with MPC (Model Predictive Control), a systematic, easy-to-use requirement based controller design methodology. The focus of the approach is put on ease. Both Model Based controller Design (MBD) and optimal control are well established in the field of controls engineering but are under-applied in automotive due to the specialized knowledge required to apply them. A dedicated, easy-to-use MPC software package helps to overcome this difficulty and offers the benefits of model based and optimal control design to a larger community of engineers.

The tool approach also offers the possibility to port MPC directly from numeric simulation to embedded software, which can actually run on physical hardware such as Electronic Control Units. Finally, as MPC yields nearly optimal control, tuning is generally of good quality, making it less likely that control tuning choices will mask differences between mechanical hardware.

Methodology

This paper presents a new Model-Based Systems Engineering (MBSE) approach based on the application of existing tools interfaced in order to generate a fast and efficient workflow that allows powertrain hardware selection. The approach is structured around four main stages:

- Development of a non-linear physical plant model for the studied system
- Processing of the model in order collect linear models applied for the design of a MPC controller
- Validation of the controller using a Model-In-the-Loop environment including the baseline plant model
- Evaluation of the system potential using the plant with controller regarding relevant criteria

The present paper illustrates how this combination of MPC and physical modeling addresses several practical difficulties that typically hinder attempts at MBSE for hardware selection.

The application and benefits of the approach are illustrated on a use case from RENAULT with the benchmarking analysis of gasoline air path systems using a tool chain including LMS Imagine.Lab Amesim combined with the Honeywell OnRAMP Design Suite.

2. Application of system simulation (Existing tool)

Commercial CAE software is a critical lever toward the management of system complexity and limited development times. This is why it is widely deployed in automotive industry from the early stages of development to the final stages before SOP, where system simulation is applied to validate system integration.

The hardware selection process in the early stages of an innovative product development process can take advantage of the existing deployment of CAE environments and more importantly, its usage for system simulation. The capability to evaluate numerous technical options in a limited time gives a competitive advantage compared to conventional iterative process with real prototypes.

General requirements for system simulation

The application of a simulation based decision process also raises three major challenges in terms of tooling capabilities:

- Integration in a larger MBSE process
  System hardware selection is located early in the development process. In this so called system pre-design phase all system component specifications have to be detailed. The system hardware selection process must be supported by models generated upstream in the V-cycle, which can include an additional level of complexity linked to the poor availability of data. The direct application of high fidelity plant modeling (1D software) is often not appropriate as this can jeopardize the trade-off between prediction capabilities and run times.

- Diversity of hardware selection topics
  One of the challenges for the system simulation software is to offer the capability a high level of versatility to address different levels of modeling to fit with the variety of systems and sub-systems that must be investigated by car manufacturers. This is why a high level of flexibility and scalability is required from simulation software. For example in the selection of the right air path architecture for a given engine the details of the intake and exhaust flows and their impact on the combustion process have to be known in a precise way while the rest of the vehicle can be modeled in a simple way to study vehicle attributes like fuel consumption or performance. Another example is the development of a hybrid powertrain in which all related powertrain subsystems have to be detailed with high precision but in which the air path system can be described in a simple way.

- Interfacing with control development environments
  Since hardware models must ultimately be combined with the software model, a common approach is to apply co-simulation technics. Most of the simulation tools offer this kind of interface with Simulink or even with C codes. The problem with co-simulation is that it often has an over-cost in terms of run times. That is also in favor of the application of 0D models compared to high fidelity 1D modeling approaches.

Application with LMS Imagine.Lab Amesim

The 0D models in the LMS Imagine.Lab Amesim (LMS Amesim) software package provide sufficient fidelity to be used in hardware development while remaining simple enough for its use in control design. The 0D lumped parameter approach, which is used in LMS Amesim, offers a good compromise between high level vehicle simulation tools, which are often too simple, and full 1D software that is often too complex. High level software are able to predict the full vehicle attributes over driving cycle but do not allow going deeper into sub-systems details. 1D software is well-suited to engine design, but runs slowly when linked to control environments.

Taking advantage of this flexibility of the LMS Amesim software, RENAULT has progressively adopted it as standard tool for system simulation and plant modeling. It is currently deployed for advanced engineering, vehicle planning phase and supports the full control development cycle from design to MIL to HIL. RENAULT’s large plant model database includes detailed engine models, transmissions, actuator models, and a full hybrid vehicle model, and is updated continuously with each new vehicle or powertrain program. RENAULT’s controls engineers use these models for system simulation and software validation and calibration

LMS Amesim’s scripting capabilities and its ability to automatically produce a linearization of full plant models are of special interest for the hardware selection process described in this paper. Both features were used to establish a connection to the MPC control design suite HONEYWELL OnRAMP. On one hand, LMS Amesim is an open software that is delivered with scripting APIs (Matlab, Python…) that ease its integration in processes and application oriented workflows. Hence, scripts were developed in order to pilot remotely the LMS Amesim core, to get the plant model description (definition of I/O, units, ports…), to gather a linear model for a given operating point and to launch non-linear simulations to check the validity of the linear model and validate the designed control function. On the other hand, the 0D software package is able to extract from a physical non-linear model a linear model at a given operating point, which is possible thanks to the use of ordinary differential equations (ODE). Indeed, the numerical methods applied to solve physical equations in CFD1D or 3D software do not support this feature. The automatic creation of linear models from an existing non-linear 0D model is the inbuilt LMS Amesim core capability that made it possible to create the interface with the HONEYWELL MPC design software.

3. User-friendly MPC control design tool (Existing tool)

MPC (Model Predictive Controls) has been a preferred controls methodology in process industries for several decades thanks to its rapid, systematic approach. Over the past decade, its use has significantly increased in the automotive controls community due to theoretical advances which reduce processing time, and due to the increased computing power of the ECUs themselves. At RENAULT several powertrain control innovation projects are already using MPC in a quasi-industrial context. Other automotive OEMs are also active applying MPC to automotive problems including traction control, vehicle stability control, and exhaust system control.

For the MPC part of this work, RENAULT selected the HONEYWELL OnRAMP software toolset. OnRAMP™ Design Suite is a software tool for modelling and design of advanced control algorithms for a wide range of automotive applications. There are many aspects to consider when evaluating such a tool: certification, compatibility, controller performance, footprint in the ECUs, calibration and documentation. OnRAMP addresses these as a package.

Advanced control toolboxes from academia or the commercial sector often offer significant flexibility and advanced features for MPC design. However they often require advanced knowledge from the user and offer limited support for wide spread deployment within an organization. OnRAMP offers a GUI-driven workflow and automatic tuning algorithms to facilitate the design, tuning and performance evaluation of the MPC controller. The OnRAMP workflow delivers C code that run on more than 15 OEM target environments.

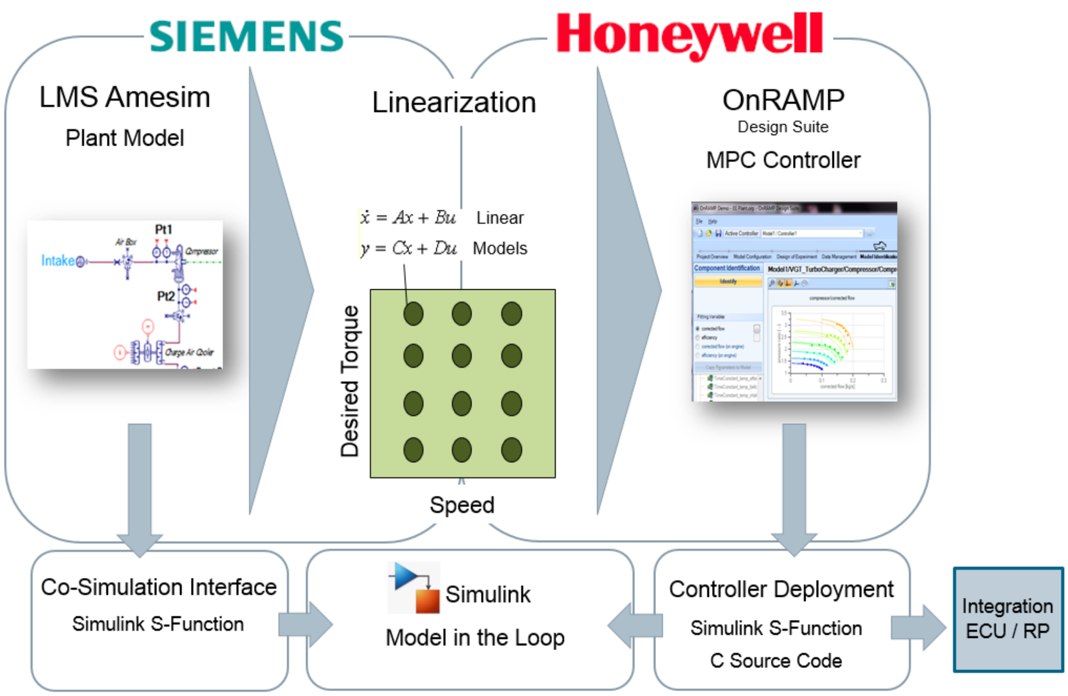
Thus, OnRAMP is targeted at automakers and suppliers who would like to benefit from MPC by making it fast and easy to use for a wide audience including engine calibrators, controls generalists, and MPC controls specialists. The tool proposes a systematic workflow and automates model building and tuning tasks, which are tedious, or that require specialized MPC knowledge.

OnRAMP includes its own modeling libraries. However, the present work seeks to leverage RENAULT's large database of existing physical plant models in LMS Amesim format.

4. Combining the MPC and system simulation tools into a new MBSE workflow

Since the missing piece of MBSE for powertrain hardware selection is a fast, convenient controller synthesis, it seems natural to link a system simulation tool like LMS Amesim with a MPC control synthesis tool like OnRAMP. RENAULT engineers have championed this work because they believe that MPC can fill the controls gap in MBSE.

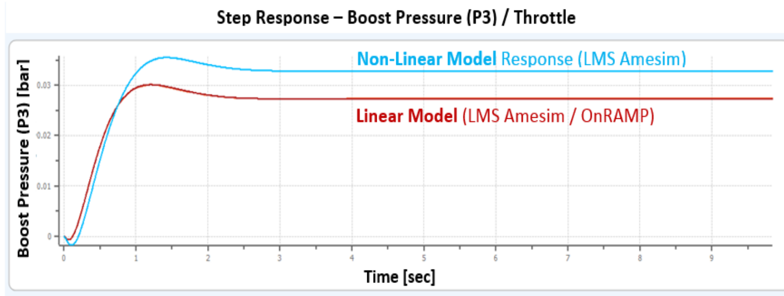
As aforementioned, linking the two tools together is enabled by, first linearization capabilities and secondly by the scripting features of the Siemens PLM Software system simulation platform. The Figure below illustrates the process applied for the design up to the validation of the MPC controller.



The first step of the process is to identify inputs, outputs, disturbances and scheduling variables to the controller. This is determined thanks to a modeling convention in LMS Amesim. In practice, the interface between the two tools is concretized by an interface block included in the plant model which defines the actual control I/O.

The second step of the process is steady-state model analysis and feed-forward design. OnRAMP sends, through the API, actuator positions to the LMS Amesim model with the objective of controlling the plant to satisfactory steady state operating point. LMS Amesim responds with the plant's steady state response, as well as with linear state space models ($dx/dt = Ax + Bu$, $y = Cx + Du$) that approximate the behavior of the plant at the proposed actuator positions. OnRAMP then adapts its proposed actuator positions, using information from the A, B, C and D matrices to search in the right direction. Consequently the feedforward actuator positions are found achieving desired set-points while respecting constraints. The non-linear model is then linearized at these feed-forward actuator positions by LMS Amesim. The generated linear models are then processed further in OnRAMP for scaling, order reduction and discretization.

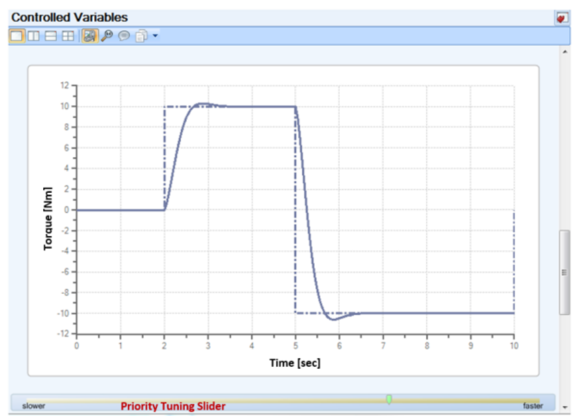
Furthermore the non-linear and linear models step responses are visualized and checked within OnRAMP. This is actually one of the key steps for successful design of MPC feedback control later. Figure on the right illustrates this.



The third step is scheduled linear MPC feedback design. The standard MPC cost function consists of penalties for actuator movement, tracking error and soft constraints. This is outlined in the optimization problem shown in the equation below.

$$\min_{U_{N_u};\,\varepsilon_1} J(U;x(k);v(k)) = \sum_{j=0}^{N_y} \|e(k+j|k)\|_2^Q + \|\delta u(k+j)\|_2^R + \|\rho_1 \cdot \varepsilon_1\|_2^2$$

Important part of feedback control design within OnRAMP is automatic tuning algorithm to achieve user defined requirements on robustness and bandwidth. This is an essential feature to enable generic design for a wide variety of plants. The user requirements are used to formulate the robust stability condition and OnRAMP then manipulates weighting matrices (e.g. for Q and R in the above) of the MPC cost function such that this condition is satisfied. The controller tuning then consists mainly of adjusting controller bandwidth, relative weights of controlled and manipulated variables and choice of prediction horizon. This leads together with earlier model checks to systematic and intuitive design and tuning of a MPC feedback control.



Finally, the controller designed within OnRAMP is tested in a closed-loop environment, using co-simulation methods. Indeed, the OnRAMP tool can generate the C code for the control and the associated data that can be either exported in Simulink. At this stage, the MiL environment is define as a co-simulation between LMS Amesim and Simulink or can be set in the Siemens platform by importing the Simulink model directly into the LMS Amesim GUI.

5. Application to hardware selection – engine air path systems

RENAULT engine portfolio already includes gasoline engines that comply with the Euro 6 emissions standard. Engineers are already in the process of upgrading current engines to fit with the upcoming regulations involving new driving cycles like the Worldwide harmonized Light vehicles Test Procedures (WLTP) and Real Driving Emissions (RDE). An update of the control logic and calibration will not be sufficient to fulfill these requirements. As a consequence, new mechanical hardware must be selected.

RENAULT selected a set of candidate suppliers for 10 candidate hardware components, or “technology bricks.” The standard implementation would require to build 10 prototypes and to run test programs to benchmark every component. The resulting costs and time would not be acceptable for RENAULT.

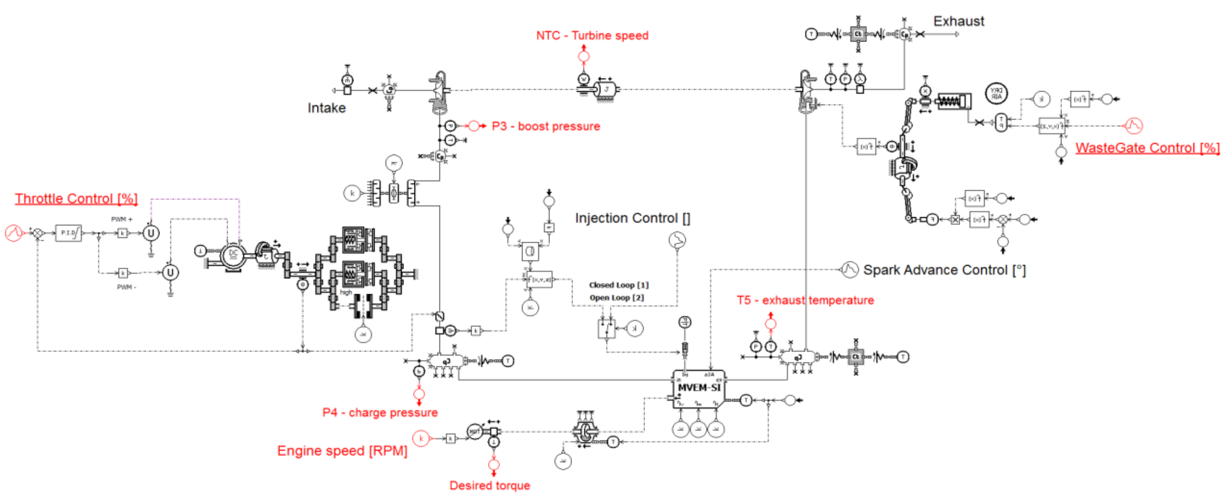
As a consequence, RENAULT decided to apply MBSE and to build 10 virtual prototypes to determine the optimal combination of technology bricks while keeping the associated costs under control. This required building 10 Model-In-the-Loop platforms coupling the plant models with their control models. This can be seen as a very complex, time-consuming task requiring highly skilled engineers for both the plant model and control model development or adaptation. Actually, the process applied by RENAULT does permit to tackle these challenges by taking advantage of:

- LMS Amesim with its well-balanced 0D modeling approach,
- OnRAMP with its fast and systematic control design workflow
- The coupling of two software one for the design of the other for the controller design and the set-up of the MIL environment

Illustration of the application of the tool chain

The workflow detailed in the paper is illustrated on a simple use case related to the evaluation of hardware for a gasoline air path system. Indeed, downsized turbocharged gasoline engine attributes are strongly dependent on the air path and charging technologies and the associated control. Many different hardware and related architectures are proposed by suppliers, from the common waste-gated turbocharger, to electrical driven compressor and dual-stage devices and the engine manufacturer needs to evaluate their technical versus cost potential.

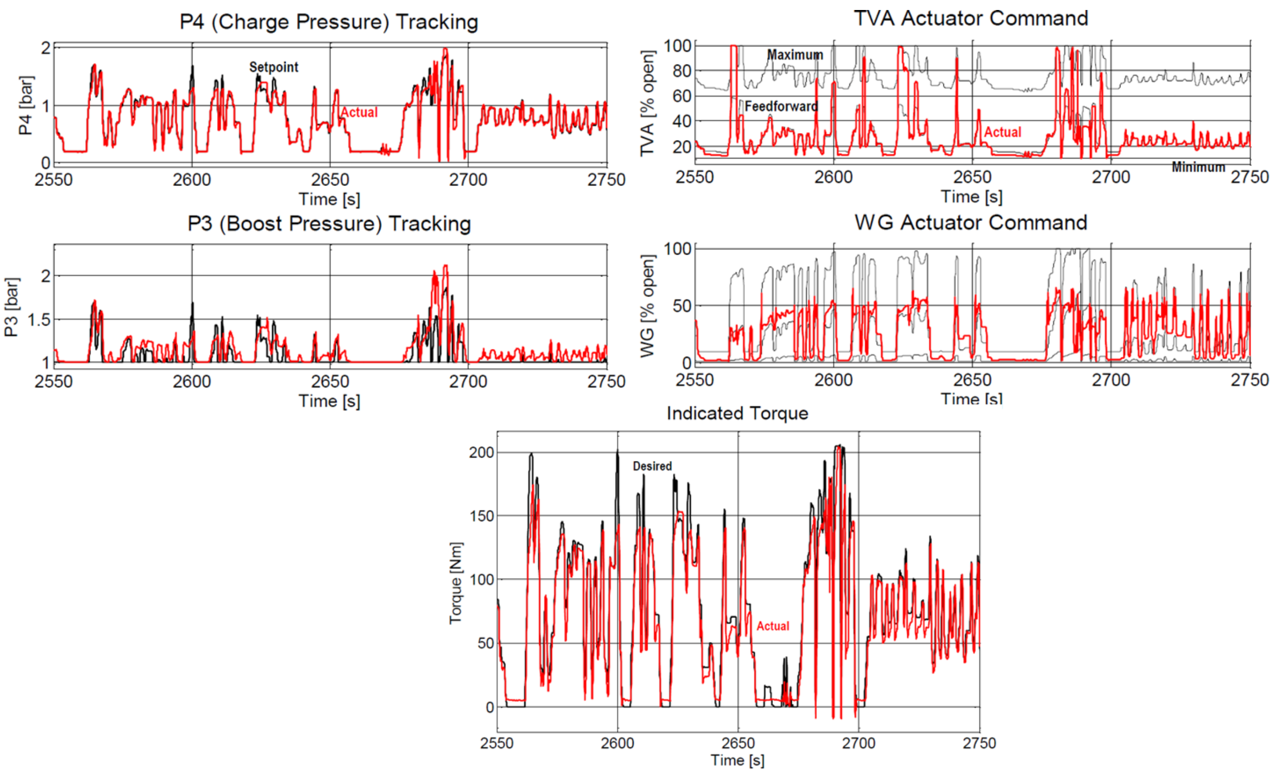
As a starting point, the tool chain is applied to a standard air path configuration including a turbocharger with a waste-gate and a throttle valve. A physical model for this baseline engine is developed in the LMS Amesim platform, its inputs and outputs are properly set according to the control problem and for the interfacing with OnRAMP. In practice, since the purpose of this engineering task is to define the potential of the system for steady-state and transient operation, models for the actuators were also included in the model as below so as to get an accurate prediction of the real system time response.



The control problem is expressed here in terms of tracked control inputs (sensor signals) – boost and charge pressure, outputs (actuator commands) – throttle and waste gate and constraints – turbocharger speed and exhaust temperature. The controller is evaluated by applying a given engine speed and boost and charge pressure setpoints and analyzing the results in terms of charging pressure and torque production.

The design of feedback MPC controller consisted of 30 operating points and the controller was designed to heavily prioritize the charge pressure tracking for torque delivery.

Some typical results generated using the MiL environment including the plant model and the MPC controller are given in the followings. The controller performance is good enough to match the charging pressure requirements using a combined control of the waste gate and throttle, and at the end, insures the right shaft torque production even during the highly transient phases of the ARTEMIS cycle.

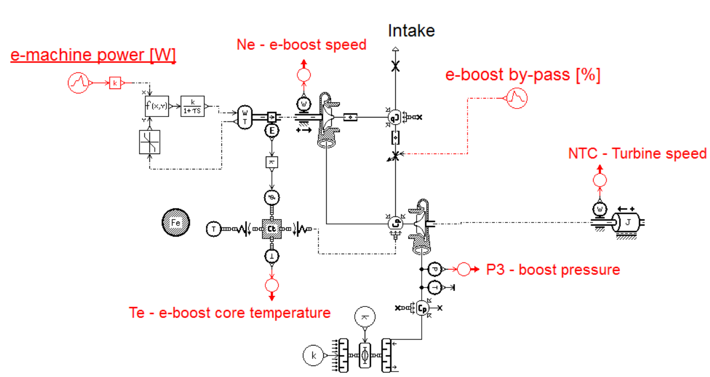


Since the final goal is the introduction of new technology bricks to address future emissions standards (Euro6c and Euro7), from the baseline configuration presented above, RENAULT introduced the electric supercharger technology (e-boost) to evaluate its potential for increasing the engine performance attributes during transient phase of the cycles in particular. Actually, the combined LMS Amesim-OnRAMP approach permitted to rapidly assess several engineering options:

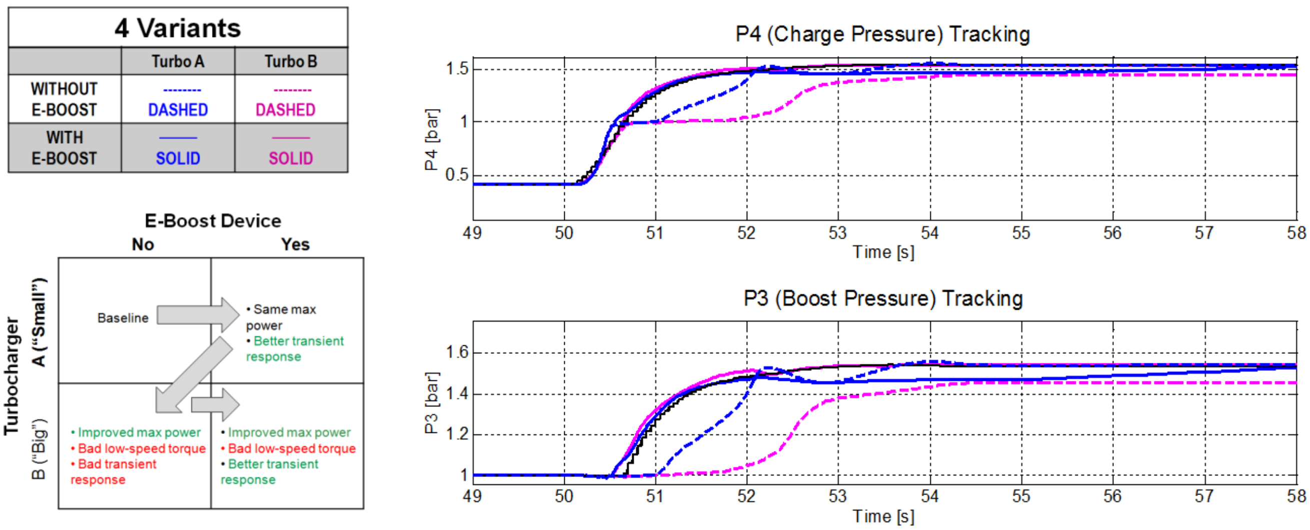
- Architecture: e-boost can be mounted upstream or downstream the main compressor, can be associated to an additional heat exchanger...
- Sizing: power of the e-boost electric machine as a function of the engine performance requirements, e-boost can be combined with an upgraded turbocharger...
- Pollutants: impact on emissions (NOx, HC, CO) on driving cycle and three-way catalytic converter activation time...

Starting from the baseline air path system, the plant model is upgraded including the e-boost machine.

The e-boost device is added to LMS Amesim engine model upstream of the main turbocharger. The control problem is then changed to take into account this additional actuator and new constraints like the thermal state of the electrical machine or its maximum speed.



The figure below shows some results given by the workflow evaluated on four hardware variants – with and without e-boost device and with two version of the turbocharger. This kind of analysis achieved in a couple of hours demonstrates the efficiency and the potential of the tool chain for the selection and pre-sizing of hardware.



Thanks to this approach where MPC is coupled with the plant models, RENAULT is able to complete these numerical studies in a very short time and select the best settings for each project milestones.

6. Conclusion

Two complementary software suites, one for physical modeling and the other for MPC control design, were linked into a new workflow that supports automotive mechanical hardware selection. The workflow allows engineers in charge of advanced engineering and pre-design to investigate in a very short time the potential benefit of a new sub-system--a significant step towards "design-right-the-first-time."

Looking ahead, the same systematic calibration approach and scalability that make MPC attractive for pre-development hardware selection problems, should naturally lead to deployments in production ECUs. RENAULT is currently leading several initiatives in this direction where Renault is evaluating MPC with the use of OnRAMP Design Suite to face scalability and maintainability concerns with production controllers.

Renault is still analyzing how to use MPC on real hardware and industrial application of MPC in powertrain control at Renault remains an open question. Issues yet to be understood better are its impact on ECU metrics and the required changes of the industrial process. Nevertheless, MPC is about to be used for Model based system selection in advanced projects within the company.

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