ZURICH, MAY 19 – 23, 2025

# 2025 | 027

# Model-based development of a platform for large-bore medium-speed engines

Controls, Automation, Measurement, Monitoring & Predictive Maintenance


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## ABSTRACT

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In order to accelerate the coming new engine system development, the RCP (rapid control prototyping) and the HIL (hardware in the loop) are applied for the large-bore medium-speed engines.

MATLAB/Simulink is used to develop both the control logic and the engine plant model. The main advantage using Simulink is that the model is executable both on PC and the actual target hardware. The executable Simulink control logic on PC makes us evaluate the system validity before installing the software to the actual system.

From the development tool point of view, the tools which are commonly used in automotive industries are also suitable for marine engine development except the hardware I/O connection. Therefore, dSPACE MicroAutobox III is used as RCP, and SCALEXIO is used as HIL.

Recent development trends are handling different types of fuel, injection systems, actuators, and sensors. In that case, it is difficult to define the requirement for the system both hardware and software completely.

This paper describes how the model-based development platform enables establishing the engine control system basis flexibly and overcoming the major difficulty of the mechanical and electrical specification uncertainty.

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This paper describes how the model-based development platform enables establishing the engine control system basis flexibly and overcoming the major difficulty of the mechanical and electrical specification uncertainty.

# 1 INTRODUCTION

Delivering a new control panel with new components / devices, and new software is getting more complicated and important part of development of a CN (Carbon Neutral) fuel engine. The increase of the sensors, actuators and combustion control difficulty means directly increasing the number of I/O and wires and software complexity. The new fuel combustion approaches and cyber security makes the computer system even more complex.

Large bore medium speed engines specially for Gen-set have been historically left behind the technology evolution until LNG DF engine was upcoming. From the experience of LNG DF engine, control system has been gradually recognized as one of key factors for the successful CN engine development.

MBD (Model Based Development) has been started from aerospace industries and widely applied in automotive industries. Simulation technology helps the virtual development without actual target devices. The virtual model is not only plant model, but control model. These methodology fits large bore medium speed engines with some ingenuity. In this paper, control system development process including control panel hardware is discussed.

# 2 DEVELOPMENT PLATFORM FOR LARGE BORE MEDIUM SPEED ENGINE

V-model is well-known for MBD based embedded system development as Figure1. This typical V-model is mainly focused on the embedded software development for automotive industry or something similar. Reviewing large bore medium speed engine control system development, Daihatsu's MBD based development platform for large bore medium speed engine is as Figure2 which is modified for the specific industry's character.

SCE (Single Cylinder Engine) comes a top of the control system development process, as the combustion strategy and important device information can be obtained to figure out the basis of the system requirement.

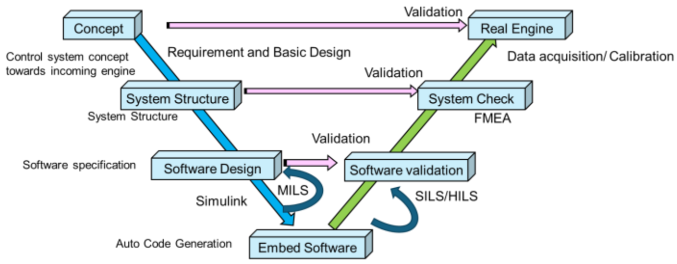



Figure1. V-Model

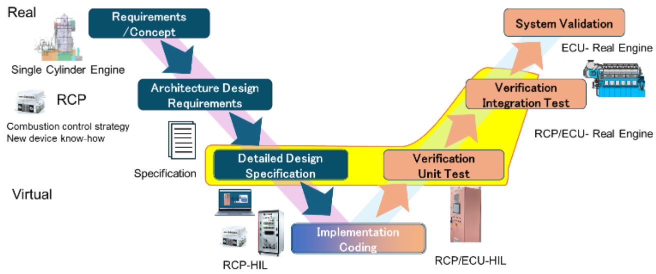



Figure2. Development platform for large bore medium speed engine for Daihatsu

Daihatsu's control software structure is based on AUTOSAR software architecture is shown in 2 ways (Figure3 and Figure4):

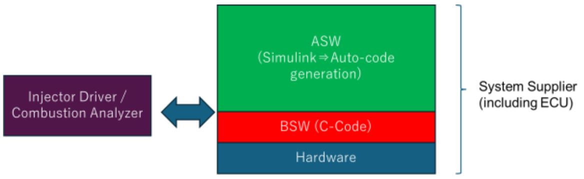
Senario1: Daihatsu issues the specification for the control system and the system supplier develops the whole system including ASW (Application Software). Once the software is provided by the system supplier, Daihatsu issue another specification which Daihatsu wants some modifications. Senario1 was the Daihatsu's past development method.

Senario2: Developing ASW part of the ECU software by Daihatsu. Other part of control system, BSW (Basic Software) and hardware are developed and purchased by the ECU Supplier. If Daihatsu has an enough capability to develop ASW, issuing specification of ASW part and to proceeding with Senario1 would also work better.

Senario1 is the easiest way to get the engine control system with minimum efforts in the beginning. But from this type of development process, Daihatsu learned following points which should be improved:

1. To improve the control system reliability and avoid a simple software bug, the ECU initial check on a virtual test bench is necessary before installing to the actual engine.

2. To shorten the software development period, any frontloaded job activity is beneficial.




Figuire3. Senario1 Software development

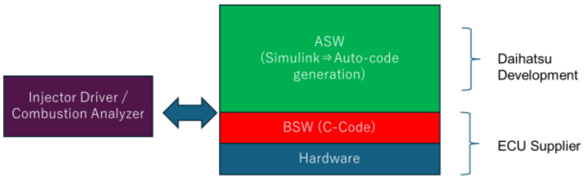



Figure4. Senario2 Software development

# 3 MBD PROCESS FITTING TO MARITIME LARGE BORE MEDIUM SPEED ENGINE

According to the difference between automotive and maritime, especially for large bore medium speed engine, which is related with mainly electrical hardware, to start the MBD based development, several countermeasures as table1 have been done from the beginning. Following countermeasure needs for the simulator to interface with the maritime controller.

Table1. Electrical interface difference

| | Automotive (Passenger car powertrain ECU) | Maritime (large bore medium speed engine) ECU |
|---|---|---|
| Analog Interface | 0-5V Voltage | 4-20mA Current<br>Self-Power / Loop Power |
| Digital Interface | 0-5V, 0-12V Voltage | 0-24V Voltage |
| Temperature measurement | Thermistor | RTD (ex. PT100) |

## 3.1 Analog interface

Due to the size of the engine, large bore medium speed engine' s wiring length is much longer than automotive wiring. Voltage drop cannot be acceptable level and instrumentation current 4-20mA interface is inevitable for large maritime analog interface. Many MBD related ECU test tools are designed for automotive applications and these interfaces are mostly voltage-based DAC and DAC systems. MBD tools availability become much wider when voltage- current and current-voltage conversion for all analog interface is taken care by Daihatsu itself.

## 3.2 Digital Interface

Digital interface is relatively easy to take care of.

Automotive (passenger car) electrical system is 12V battery powered and internal peripherals are mostly 5V. Maritime system voltage is mainly DC24V. Since automotive heavy-duty systems are 24V battery power system and automotive MBD tools usually covers passenger cars and heavy-duty vehicles, digital voltage does not become any big issue.

## 3.3 Temperature measurement

Temperature sensor characteristics is normally something that only sensor expert or ECU hardware specialist must take care of. For MBD development, all electrical signal interface must be simulated properly.

As Figure 5, characteristics of thermistor and RTD is completely different and in terms of resistance simulation, RTD is more difficult than thermistor. RTD simulator is anyway available on the market, but to prepare for ECU's all RTD simulation, cost, size, and resolution should be considered carefully. The easiest way to simulate RTD is, simply put a variable resistor, but with this solution, the resistance cannot be controlled by microprocessor.

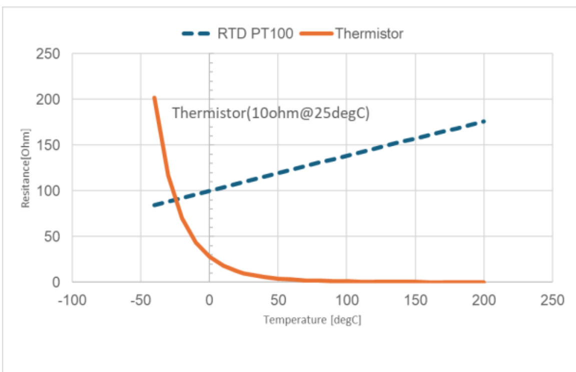
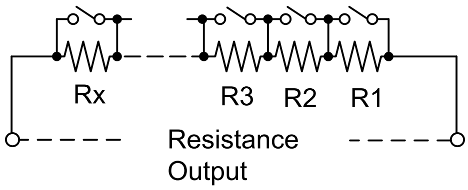


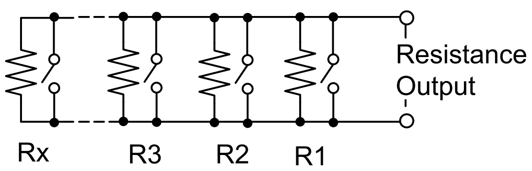

Figure5. Temperature sensor comparison

Figure6 shows the basic idea of two different types of temperature sensor simulation.

The series combination and the parallel combination are chosen to start the temperature sensor simulation circuit design according to the required resistance characteristics, resolution, and accuracy.




1. Series combination




2. Parallel combination

Figure6. Temperature sensor simulation

Using simple calculation with excel a parallel combination of resistors gets the good characteristics to simulate RTD. Though the resistor calculation is more complicated, the influence of contact resistance become smaller than the series combination. And the prototype developed RTD simulation board gets the good resolution and enough accuracy for HIL. Compared with the similar board on the market, the prototype is size-wise and cost-wise comparable.

### 3.4 RCP (Rapid Control Prototyping)

For CN engine, single cylinder engine testing is inevitable. Fuel used, fuel combination, fuel supply/injection system, and air system are surveyed to decide the engine strategy. Engine control system team should be involved in single cylinder engine test phase and share the concept and requirements of the engine overview.

Nonetheless many things are nothing to do with commercial system, there are also many information useful to get a clear overview for combustion concept what kind of control would be in the future required or possible.

Regarding electrical system point of view, the single cylinder engine test phase is good to know the required hardware specifications such as an injector power stage performance, boost voltage and current profile and so on.

Thus, Daihatsu put the single cylinder engine to the beginning of the control system development process.

RCP (Rapid Control Prototyping) is one of the key tools to connect the single cylinder engine testing and actual control system implementation phase. RCP is a kind of general-purpose ECU which user can make a prototype in short period including hardware and software. RCP is quite popular in automotive industry and Daihatsu has started to use RCPs with some external IO modifications like explained in 3.1.

The flexibility of the hardware and software make the prototype engine test extremely smooth to handle with.

Figure8 shows the RCP system set for Daihatsu's SCE test bench. With RCP, the common rail pressure control, crank angle detection, and fuel and gas injection are controlled.

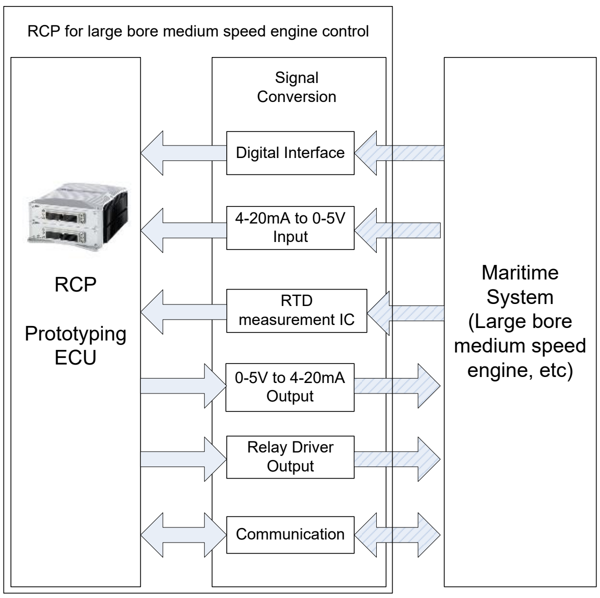



Figure7. Customized RCP for large bore medium speed engine control

There are a lot of difference between the single cylinder engine test facilities and the commercial control panel for the large bore medium speed engine.

Figure8. Customized RCP for a single cylinder engine test bench (dSPACE Micro Autobox II + Rapid PRO)

### 3.5 HIL

HIL (Hardware in the Loop)

For control system development HIL is a very important tool because otherwise frontloaded system development is almost impossible.

HIL is a substitute of the real engine system. All the electrical signal inputs and outputs are simulated and connected to the ECU, so that the ECU can behave as if the engine is connected. Dependent on the purpose of the check and validation, Daihatsu is preparing different types of HILs.

#### 3.5.1 Large HIL

Large HIL is developed to intend to execute the comprehensive software validation and closed loop control tests as Figure9. As basic concept of HIL is similar to RCP, signal conversion maritime system is necessary. The large HIL itself is based on dSPACE SCALEXIO HIL system and with dSPACE Japan support, whole system was completed. All I/O are simulated and the plant model is developed to behave dynamically as the real engine. All the sensor value and digital signals are automatically changing according to the plant model calculation.

Since plant model development is one of the difficult tasks and the most important thing is that a large HIL availability before the software implementation is finished and the real engine test starts, in the beginning phase, first acceptance level was the basic dynamic behavior enough to run the closed loop control logic and there is no diagnostic fault detection by the ECU. To improve the plant model behavior, 1D GT-Power engine plant model is developed in parallel. Using GT-POWER-xRT solution, a real time engine plant model which is basically the same as the GT-POWER engine model for CAE analysis in terms of plant model inputs and outputs necessary for the control system information can be run on the HIL or SIL (Software in the Loop) on PC.

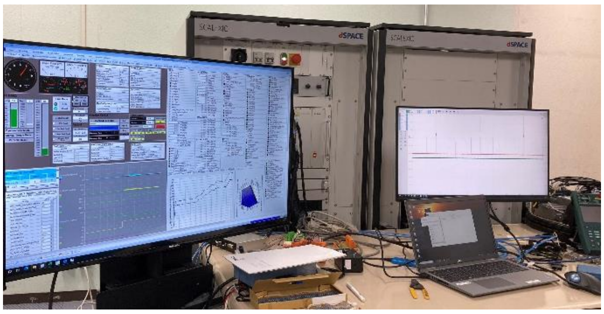


Figure9. Large HIL (dSPACE SCALEXIO)

Large HIL hardware system is as Figure10. Similar to RCP, specific signal conversion is necessary in order to utilize automotive oriented dSPACE HIL to maritime engine controller.

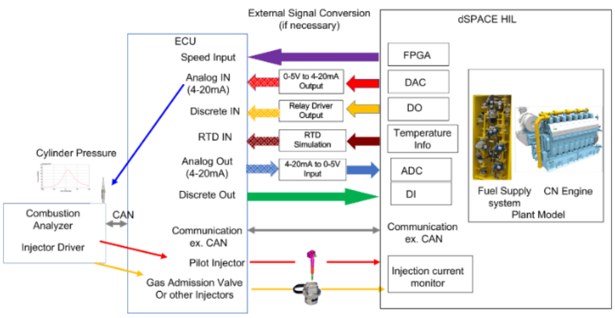



Figure10. Large HIL System structure

After ECU testing with a large HIL and debugging is completed, most of the problem caused by the wiring, software bugs, and electrical devices can be eliminated.

#### 3.5.2 Small HIL

There are many software modules in the ECU which does not require the dynamic behavior of the real engine, such as communication, simple sequence control, and many HMI display control.

In that case, a large HIL is a kind of too much and it requires a lot of places to settle. Usually, many HILs as virtual test benches are necessary at the same time to proceed the software validation test in short period.

Daihatsu developed a small HIL more for software development less concerned with the closed loop combustion engine control.

The developed small HIL consists of minimum plant behavior model for debug convenience and electrical circuits which simulates the signal of inputs and outputs between the ECU and the engine. The user should know how the engine system works and control the sensor and digital signal value as the real engine. There are hundreds of parameters to check for HMI and most of the parameters can be checked with a small HIL. Final confirmation is done by a real engine.

Figure11 shows the developed small HIL.

Figure11. Small HIL (with RCP)

## 4 MODELLING APPROACH

Plant model is necessary for any simulators to check and validate the ECU with implemented software.

### 4.1 Nonphysical simple model

For many software module testing are engine physical, dynamical behavior is not important. In this case, plant model can be simple and software engineer can prepare simple executable (real-time) plant mode to proceed the software validation process.

### 4.2 0D physical model

If the engine plant model should behave more dynamically the same as the real engine, a 0D physical model would be an answer as Figure12.

Simulink based 0D physical model consists of acausal model which is combinations of physical equations and maps. For real-time calculation and simplicity for the model preparation, 0D model is sufficient for most of the embedded control system development.

Daihatsu has been working on the dSPACE ASM based 0D plant model. dSPACE ASM (Automotive Simulation Models) is various Simulink simulation plant model open libraries designed for automotive application. Since the Simulink block is open, Daihatsu can modify the base model and apply to large bore medium speed engine.

One of the benefits of simple 0D model is, it is much easier to customize or modify the plant model for different engine as far as the basic engine structure is similar. Since the essential behavior of the plant model is combination of air system and combustion model, continuous plant model improvement activities are possible with basic knowledge of the engine model.

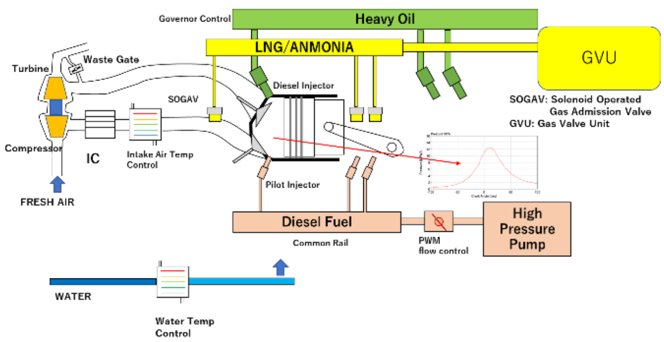



Figure12. 0D engine plant model concept

### 4.3 1D physical model

Once HIL is ready and used by the control system development, the expectation to expand the utilization increases. The 0D engine plant model is good enough for the control system development in functionality point of view, but it is not for calibration, because the plant model is calibrated by the real engine test result.

To utilize HIL for the calibration purpose, 1D simulation plant model such as GT-POWER would be a candidate. The original GT-POWER model is too heavy to run faster than real-time for HIL purpose. But with the GT-POWER-xRT solution, the engine plant model can be calculated more than 10 times faster than the original GT-POWER model.

For SIL (Software in the Loop) usage case, calculation speed is important, but not critical. But for HIL usage, the plant model must be some how modified until the calculation speed become fast enough to run on HIL processor.

Figure13 shows the example of LNG DF GT-POWER-xRT model for HIL.

It is joint work with the control system and CAE department to enable 1D engine model as a part of real time simulation model for HIL or SIL. A GT-POWER engine model is usually created by CAE team because they must estimate engine performance by 1D simulation. The engine model created is normally limited to the important part of the engine for performance calculation. However, ECU needs all the inputs and outputs connected to the engine. Therefore, many 0D plant model parts remain even after receiving a GT-POWER-xRT engine model from CAE team and if more 1D plant model is necessary to improve the plant behavior, then additional 1D plant model development should be done.

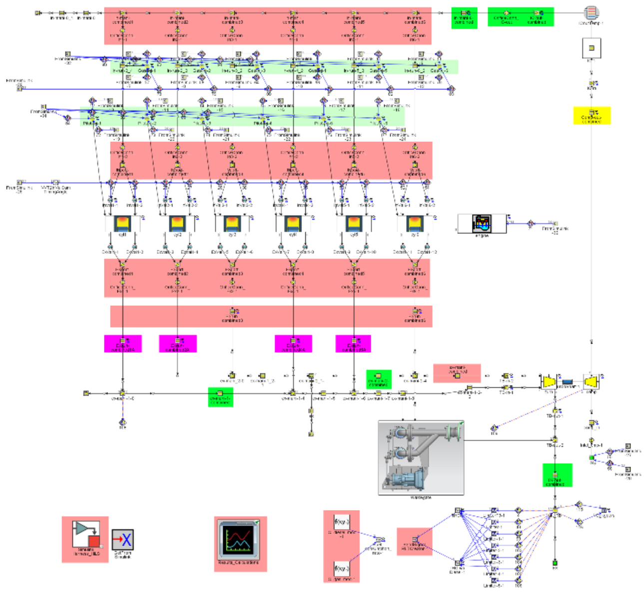


Figure13. LNG DF GT-POWER-xRT model

## 5 THE PROGRESS OF THE PROCESS INTRODUCED

Utilized MBD technologies and development process is frontloaded, many tasks can be finished before the actual ECU debug and the engine test.

Figure14 shows a subjective image of the development process comparison from past development experiences.

The development contents themselves do not decrease the number of jobs and handling MBD tools are sometimes not easy at all. But it is much better to do any debugging in advance than to do everything at the same time. The idea of front-loaded working process is to avoid overflow of the workload and decrease the control system's big reworks after starting the actual engine tests.

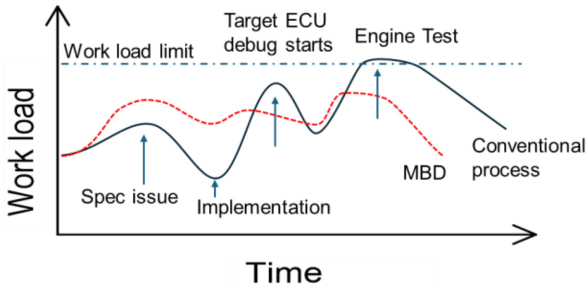



Figure14. Empirical comparison of conventional process and MBD

Since MBD process has been introduced to the development of large bore medium speed engines for CN fuels, software troubles caused by minor bugs are found during HIL test, and software debug with the actual engine is almost eliminated before starting the controller test with the actual engine. Figure15 shows an example of comparison between the MBD process and the traditional process for software development for the engine testing.
Software debugging phase with HIL is very important because there is no risk to damage the engine or human injury, and energy consumption / emission is much lower than the real engine for operation. If the real engine is used for initial phase of software debugging, engine operation range is limited for safety reason. Though the HIL is good enough to validate many parts of the software, there are still not a few parts which the real engine is necessary, our idea of the software development is increasing the virtual testing part unless the real engine is not necessary.

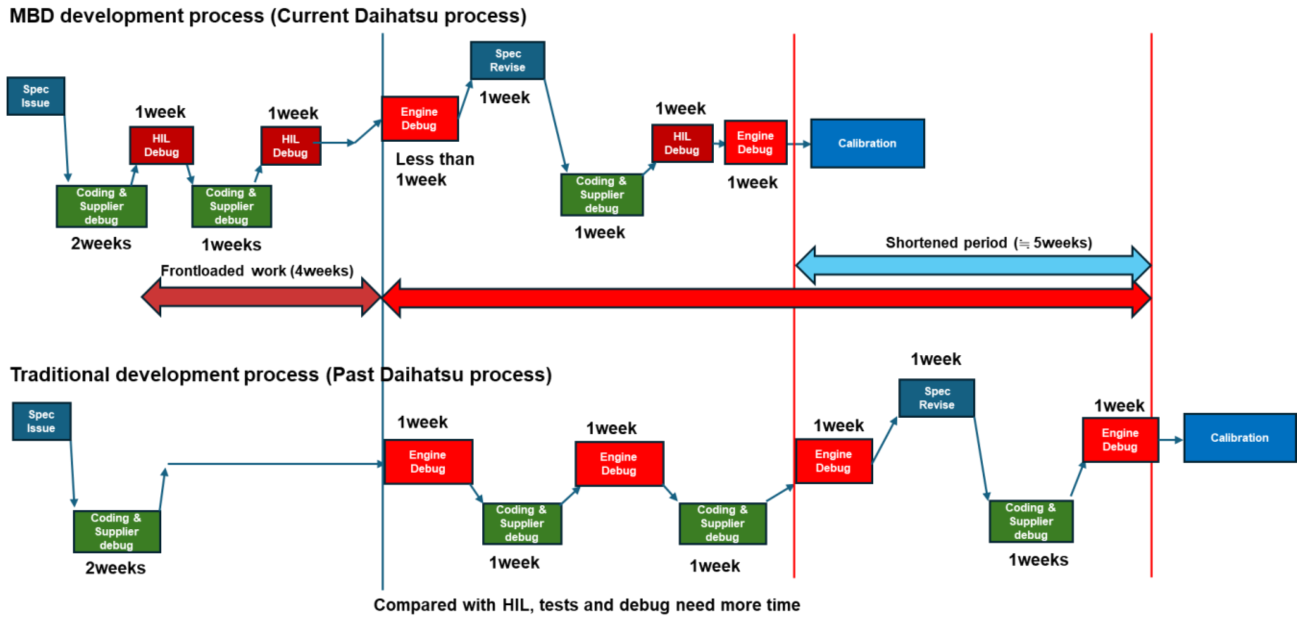



Figure15. Typical example of comparison between the MBD process and the traditional process from spec issue to engine calibration

## 6 SUMMARY & CONCLUSION

The main purpose of MBD based development platform is to shorten the development period without losing the quality of the control system.

Using simulation technologies, majority of the controller development can be frontloaded without using actual engine. Specially for large bore medium speed engine, the opportunity to use the actual engine is limited even after the test engine is assembled due to the low number of test engine build. Specific features regarding large bore medium speed engine development:

- SCE as a part of development process
- Automotive oriented MBD tool (RCP / HIL) modification to fit the maritime engine control system
- Using different types of HILs for efficient work
- Expand RCP usage to accelerate software development

CN fuel engine development requires not only intensive efforts for fuel and combustion design but also control system. With proposed development platform, flexible and fast controller development is on the way to launch. It is possible to concentrate on the inevitable test which the actual engine must be used. A lot of software part which the real engine is not necessary are being developed using the virtual test bench. Table2 shows the assumed future wok lists and challenges. Because CN fuel knowledge and handling itself is challenging issue, in terms of MBD development process, the concept and requirement phase of the V-flow would be the most important part of the development process.

Table2. Future work and challenges

| | Subsystem | Parts | Challenge | L |
|---|---|---|---|---|
| 1 | Additional unknown I/O | Injectors, Exhaust gas sensors, etc. | Electrical system interface preparation | N hi |
| 2 | Fuel supply system | Liquid or gaseous fuel supply and purge system | Plant modelling, simulating the necessary behaviors | N hi |
| 3 | Combustion system | Fuel type, property, injection type, combustion type | For control system development, simple combustion model is preferred. But it is difficult to prepare CN engine combustion model because even prototype engine does not exist in the beginning. | V hi |
| 4 | Exhaust gas aftertreatment system | NOx, N2O, NH3, H2 etc. | Many unknown information to develop | H |

## 7 DEFINITIONS, ACRONYMS, ABBREVIATIONS

CN: Carbon Neutral

MBD: Model Based Development

RCP: Rapid Control Prototyping

HIL: Hardware in the Loop

HILS: Hardware in the Loop Simulation

MIL: Model in the Loop

SIL: Software in the Loop

RTD: Resistance Temperature Detector

HMI: Human Machine Interface

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