Electrification for sustainable mobility –
Developing the fourth generation of the Toyota Prius

A Forward Leap for E-Volution

The Toyota Prius is internationally known as the pioneer in hybrid technology. To significantly increase not only the vehicle's efficiency but its overall product capabilities, Toyota optimized its entire development process. For this, the company also introduced a new model-based tool chain that includes the production code generator TargetLink from dSPACE and the test solutions of BTC Embedded Systems AG.

How can you maintain mobility without traffic excessively burdening humans and the environment in the long run? This question lies at the core of sustainable mobility, which is a fundamental development goal at Toyota. The new Prius can answer this question. In the JC08 test cycle, its fuel efficiency was improved to 40.8 km/l (95.97 mpg) or 2.45 liters per 100 km. At the same time, the vehicle's drive power was optimized to achieve an even more dynamic driveability.

A Leap Forward in the Evolution of the Prius 4th Generation

The powertrain concept of the vehicle is built on a unique combination of serial and parallel hybrid technology. The basis for this is a planetary gear called power split device (PSD), which connects an internal combustion engine with two electric motors. This allows for purely electric operation, energy recovery as well as serial and parallel operation of the electric motor and the combustion engine. Moreover, the PSD also serves as a continuously variable transmission (CVT). The powertrain is part of Toyota's new modular platform Toyota New Global Architecture (TNGA), which will form the basis of future Lexus and Toyota vehicle models. When the platform was introduced, all involved components were fundamentally re-engineered. This leads to impressive results for fuel consumption. The fuel efficiency of the fourth-generation Prius improved with regard to the country-specific test drive cycles: In Japan, efficiency improved by 26%, in Europe by 20%, and in the US by 14%.

Optimizing Control Development

With the fourth-generation Prius, the control requirements for improving vehicle performance have increased significantly compared to previous generations. Therefore, the optimization of the control structure plays a vital role in increasing development

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efficiency. For example, for the 4th generation Prius, motor control had to become highly responsive and capable of high-speed control to reduce the part size and enhance fuel efficiency. To be able to respond quickly to these new types of control requirements, and to be prepared for this and future technical innovations as well as vehicle deployments, Toyota thoroughly evaluated its overall control development. This included the ease of use and efficiency of the control structure, the development process, and the development tools.

Reconsidering the Control Structure

In a first step, the entire control structure was fundamentally reviewed. The goal was to establish a simpler and more coherent structure. This allows even less experienced employees to understand the control structure faster, facilitates control design, and saves time during debugging. Furthermore, combining the new control structure with code generating tools makes it possible to improve production code efficiency.

Reconsidering the Development Process

An efficient development process consists of the minimum amount of steps in order to ensure the desired level of quality. After reviewing its earlier development processes, it became clear that the number of steps for overall control development could be reduced by implementing model-based development (MBD), which would let Toyota automate the implementation of an all-at-once development process with optimal tools and save labor. Toyota also learned that implementing tools makes compliance with ISO 26262 easier and allows for efficient quality assurance. In addition to the conventional inspection process, Toyota wanted to be able to productively collaborate with suppliers at later stages of the development process.

Establishing a Model-Based Tool Chain

To reach the goals for a more efficient development process, Toyota is therefore trying to adopt a model-based tool chain that is based on the MATLAB®/Simulink® environment. The defined efficiency goals resulted in precise requirements for the tools that were considered to be suitable candidates at that time:

Improved development efficiency

Toyota chose the production code generator TargetLink® from dSPACE, which offers reliable automatic code generation and a consistent simulation concept from the model to the object code.

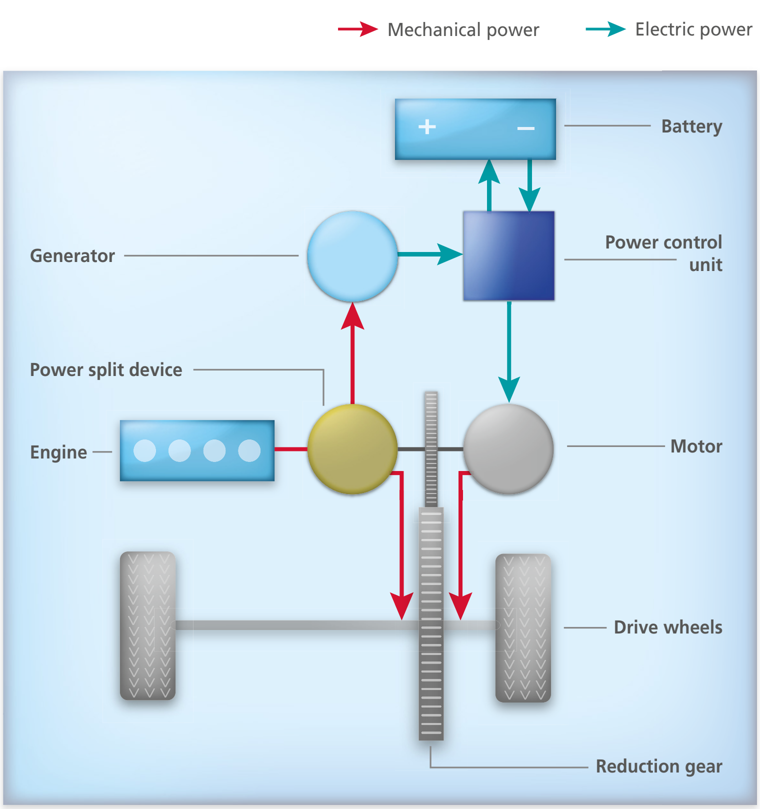
Securing quality that can stand up to actual implementation

Toyota uses the test tools BTC EmbeddedValidator and BTC EmbeddedTester from BTC Embedded Systems AG for quality assurance. They ensure that TargetLink models and generated code can be checked at the implementation level in fixed processes at the early stages of development.

Defining and applying modeling guidelines

The model-based Simulink/TargetLink development environment is suitable for structure-compliant modeling. The work of developers can be reduced by incorporating predefined modeling guidelines into the guideline checker MES Model Examiner® and thus automating the checks of steps. Furthermore, highly efficient production code

The power split device distributes the torques of the internal combustion engine and electric motor to the wheels and the generator.

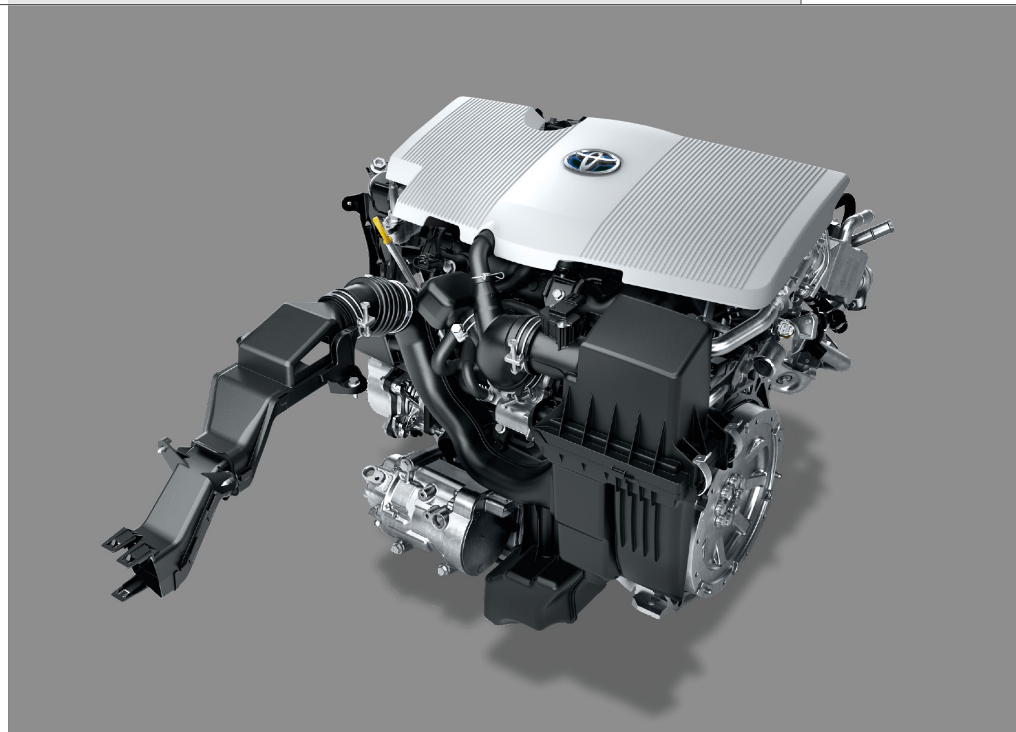


can be generated that sustains consistent modeling and is compliant with MISRA C.

Together with BTC, dSPACE supported the introduction of the new workflow at Toyota by providing comprehensive seminars and workshops that are immediately applicable to actual practice, in addition to engineering services. Toyota pursued a development process that was based on the ISO 26262 reference workflow for TargetLink and BTC EmbeddedValidator and EmbeddedTester.

Experiencing the New Tool Chain

The evaluation of TargetLink in combination with the test tools from BTC found that total man-hours can be reduced during the development process, including conventional inspection processes. Subsequently, this helped achieve the goal of quickly and accurately developing new functions. Toyota's system developers especially appreciate the fact that TargetLink operation flows can be automated relatively easily. Using this environment not only makes producing implementable code simple, it also supports Toyota's detailed needs for applying implementation information settings to an entire model block with, for example, a single click of a button. Moreover, while both Toyota and its suppliers each had processes for developing and inspecting code in the past, automating the implementation code generation and carrying out inspections using TargetLink and BTC EmbeddedTester reduced supplier man-hours as well. This made developing functionality in cooperation with suppliers easier.



The combustion engine of the Toyota Prius. It connects directly with the electric machines and the power split device.

The power control unit controls all hybrid driving functions.

Complete Validation

Although Toyota's conventional testing methods also adequately ensure code quality, they require a high number of man-hours. The formal verification used by BTC EmbeddedValidator automatically and completely verifies the consistency between specifications and models. The following examples are used to prove mathematically and conclusively that requirements are not violated:
Confirm that the following situation can be applied without exception to all combinations of input signals:

- In case a situation occurs where the battery cannot be used for some reason,
  - the vehicle invariably migrates to a drive mode that does not use the battery.

BTC EmbeddedValidator creates all possible value combinations for this

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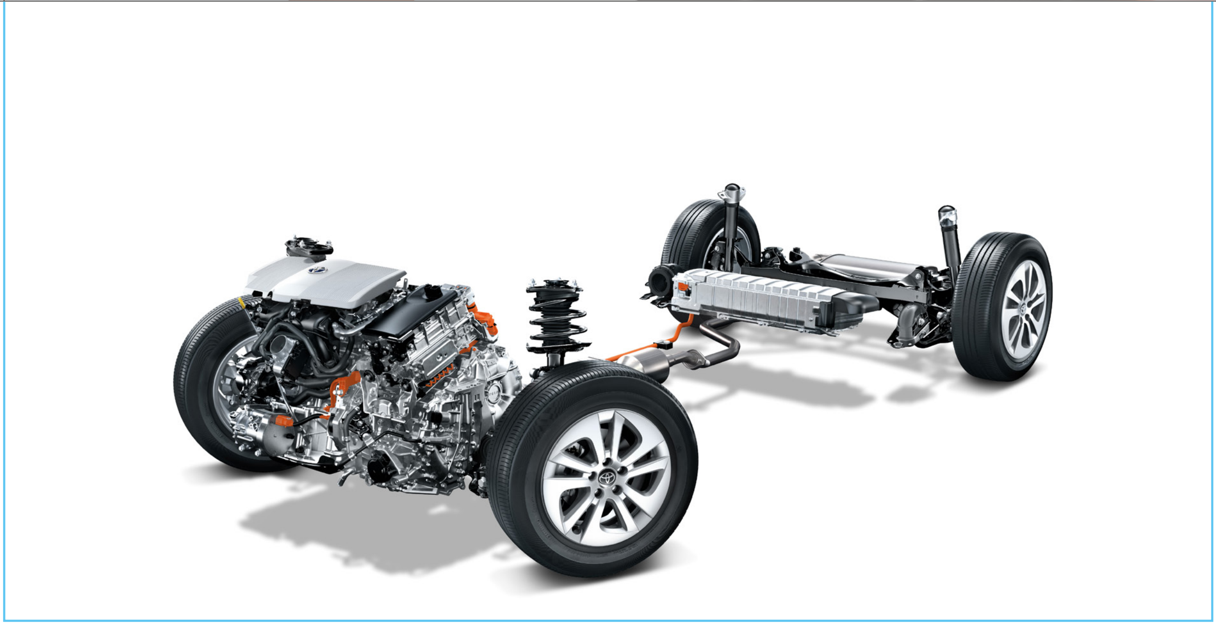


Setup of the electric drivetrain of the Toyota Prius 4.

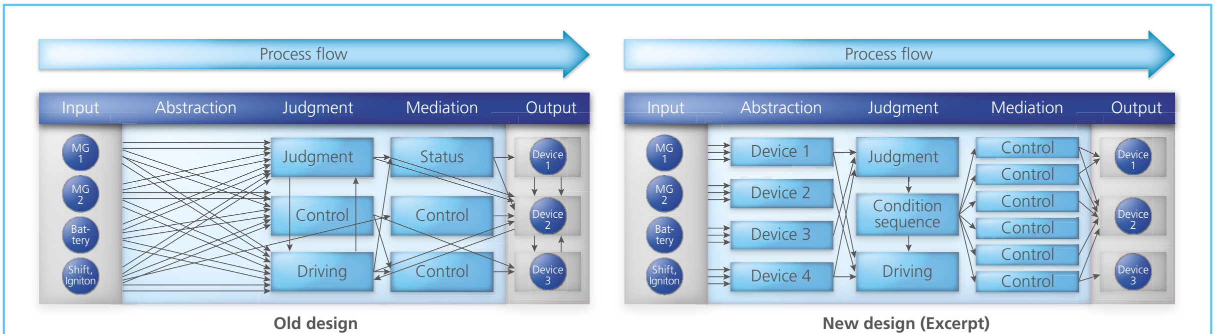
> "We established a basis for improving the efficiency of the entire development process, including inspection, by using TargetLink, BTC EmbeddedValidator, BTC EmbeddedTester, and related tool chains in conjunction with automation mechanisms."
>
> *Naoki Ishikawa, Toyota Motor Corporation*

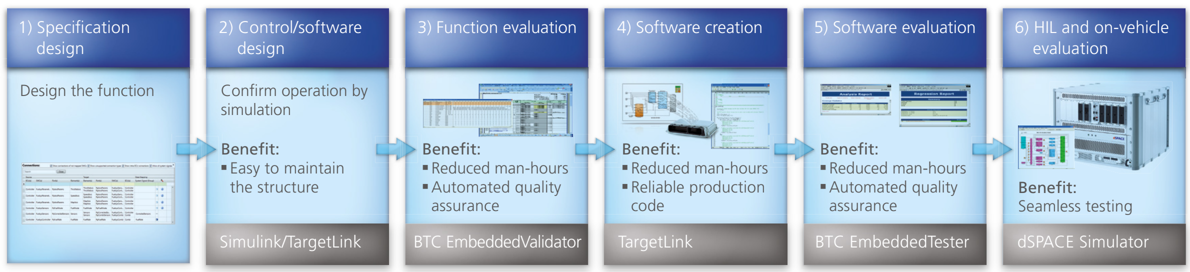
requirement and confirms and proves whether a counter example exists. Moreover, BTC EmbeddedTester offers fully automated back-to-back testing between Simulink/TargetLink models and the production code and automatically generates MC/DC code coverage test cases. In addition, the tool detects all problems in the code, such as value range violations and division by zero. The results include all produced vectors and can be confirmed using an automatically created report. During back-to-back testing, the target microprocessor (hardware) and the cross compiler (object code) are also incorporated in the tests, and provide a final validity confirmation. In doing so, TargetLink and BTC EmbeddedTester are combined to execute the processor-in-the-loop (PIL) simulation using the actual target microprocessor. This test step leads to more efficiency for ISO 26262-compliant validation.

Challenges and Future Prospects

Toyota implemented a variety of tools and environments, including an all-at-once development process, new processes, and automated mechanisms in parallel with the vehicle development. However, initially man-hours increased more than anticipated. It thus became clear that a proper process management had to be put in place that continuously monitors and optimizes the process. Further improvements to the efficiency of the development process and the tool chain as well as the development environment are planned for the future so that their merits become even more obvious to developers. For example, Toyota is investigating the intensified use of controller models in the early stages of development (virtual simulations with dSPACE VEOS®), the continued im-

The control structure before and after the optimization.





Advantages of each process and tool used in the development process during model-based implementation.

> "By applying the tools, we succeeded in paving the way for promoting more efficient hybrid vehicle development."
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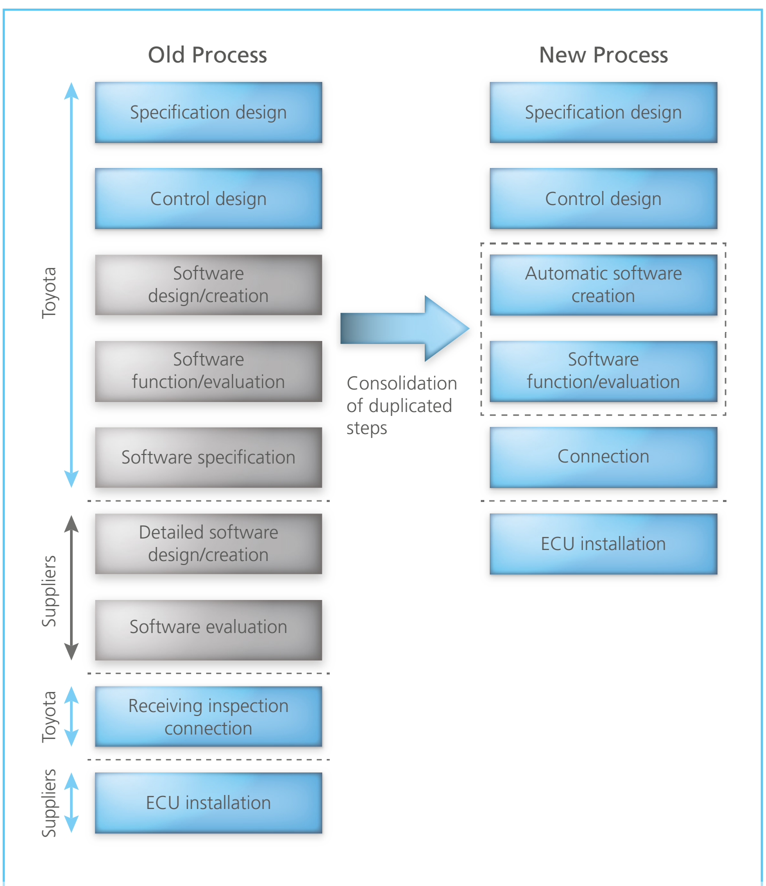
> *Shinichi Abe, Toyota Motor Corporation*

provement of the control development environment (e.g., component re-use, including test patterns, parameters, and models (xILS plants) using dSPACE SYNECT®), and the improved usability of the environment itself. ▪

Shinichi Abe, Naoki Ishikawa
Toyota Motor Corporation

The optimized development process is reduced to the minimum number of process steps and thus improves development efficiency.



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