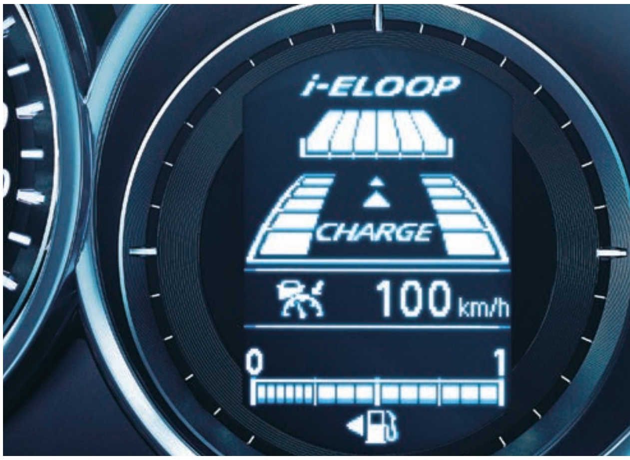
Aiming High

Mazda is pursuing two main goals for its automobiles: an enjoyable driving experience on the one hand, and outstandingly low fuel consumption and emission levels on the other. By 2015, the company plans to reduce consumption by 30 % compared with 2008. So Mazda launched the SKYACTIV program, designed to optimize all the components necessary for reaching these goals. dSPACE Simulators and the Automotive Simulation Models are playing a major role in this.

Function optimization and validation for management of gasoline engines with a compression ratio of 14:1



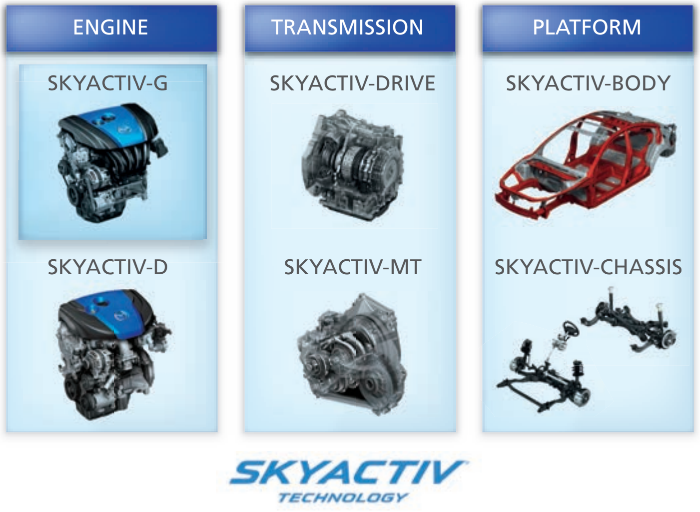
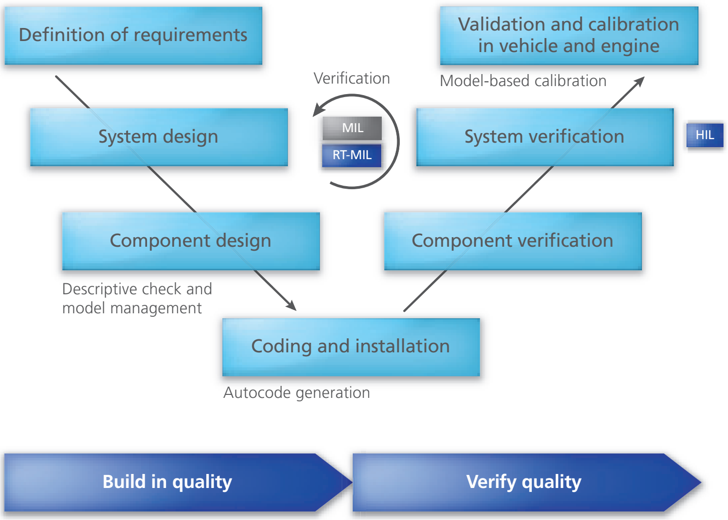


Figure 1: The MAZDA's SKYACTIV program aims at optimizing elementary vehicle components.

Visions for Combustion Engines

In conventional internal combustion engines, 70 % to 80 % of the fuel's energy is "lost" even before it reaches the wheels. Mazda is taking on this unpleasant fact and aims to make the combustion process more efficient by reaching ideal combustion at the highest possible compression ratio. By 2015, the efficiency of the Mazda fleet should be increased by 30 % compared to the levels in 2008. These goals are defined in SKYACTIV-G, a research and development program dedicated to optimizing gasoline engines (figure 1). Not only active engine improvement but also further consumption-reducing measures such i-stop (idling stop system) and i-ELOOP (capacitor-based energy regeneration system) will all contribute to increasing efficiency.

Figure 2: HIL simulation is a key component of quality assurance. MIL simulation opens new possibilities for early function verification.



Optimized Engine Management

A high compression ratio considerably improves thermal efficiency. The compression ratio of current gasoline engines is around 10:1 to 12:1. If the ratio is raised from 10:1 to 15:1, the thermal efficiency theoretically increases by about 10 %. Increased torque loss due to higher knocking is one of the reasons why this is difficult to achieve in reality. Knocking is abnormal combustion during which the air-fuel mixture ignites prematurely. It is caused by the effects of high temperatures and pressures. Improvements in combustion engines therefore require comprehensive engine management measures. To achieve the best management possible, the engine ECU software had to be completely revised and expanded to include many new functions. Improved control strategies were developed to deal with knock, ping and possible misfires. This required that the variable valve timing (VVT) system has an optimal control for the intake air and exhaust gases.

Optimizations in the Development Process

Because the complexity of the functions to be developed is increasing, the software development process also needs to meet the new development requirements. Mazda therefore decided to switch to a fully model-based development method. This involves specialized tools, appropriate processes and enormous engineering know-how. The benefits of this are evident in several areas.

Model-Based Function Development and Validation

There are established methods for

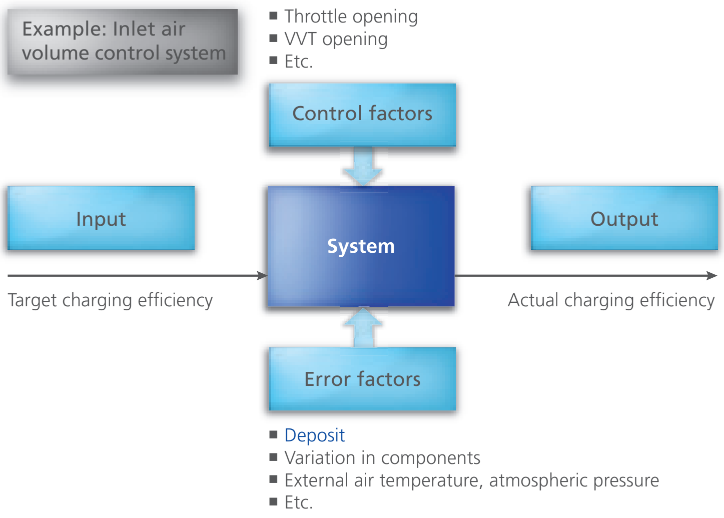


Figure 3: Values influencing the charge of a combustion engine.

validating the quality of functions developed by model-based development. In the V-cycle, each development stage has a corresponding test phase. Proven test methods include procedures such as hardware-in-the-loop (HIL) and model-in-the-loop (MIL) simulation (figure 2). Both of these methods were used for the SKYACTIV program. dSPACE simulators equipped with Automotive Simulation Models (ASM) were also incorporated. The testing potential of simulators goes much further, though. They can also be utilized for function optimization. To implement the objectives of SKYACTIV-G, clear concepts and approaches were outlined. For the targeted compression ratio of 14:1, it was necessary to improve the cylinder charge level. The throttle valve and the position of the VVT valve are the influencing factors here. However, there are also interference factors whose effects need to be known and accounted for, such as deposits, component tolerances, and the ambient temperature and pressure (figure 3).

> "By using dSPACE systems right from the design phase for controller algorithms, we were able to use the same test scenarios throughout the whole development process."
>
> *Satoshi Komori, Mazda*

Function Analysis and Optimization with HIL

As an interference factor, deposits are a prime example of how HIL simulation can be used to investigate and optimize functions. Deposits are caused by combustion residue that settles on valves and valve seats and obstructs the flow of the gases. They have the greatest impact at a low valve opening. In previous function developments without a HIL simulator, investigations were performed with real components, and just preparing the parts and vehicles was expensive enough. Ever since HIL simulators have been available for this, these investigations can be performed through simulation (figure 4). The plant model used for this simulates the mass flow

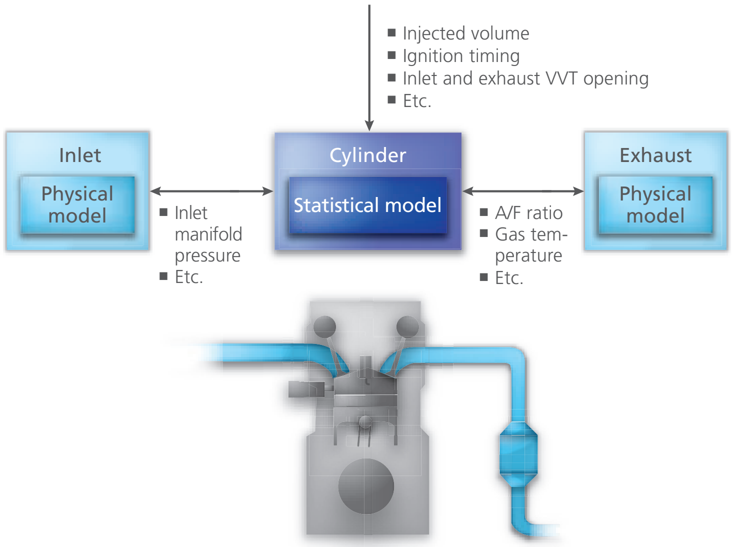


Figure 4: Combining physical and statistical models creates precise simulation models that are easy to handle.

Conclusion and Outlook

For the SKYACTIV program, Mazda relies on MIL and HIL simulation with the dSPACE Simulator and used dSPACE Automotive Simulation Models (ASM) for fast, efficient setups. The test equipment is used for function optimization and validation. Overall, Mazda was able to revise the individual components, such as the engine ECU and the complex electrics/electronics (E/E) system network, and validate them completely and comprehensively. The particular benefits of HIL testing are the automated and reproducible test runs. Initial experience has shown that early testing and test reusability have enormous potential for increasing efficiency. This method has proven its worth in vehicles like CX-5 and Mazda 6, which all benefit from superb SKYACTIVE-G gasoline engines with a compression ratio of 14:1. The testing processes and systems will be optimized and expanded for future developments. It is already clear that they are essential for the further development of E/E systems and will be given additional roles in the development process.

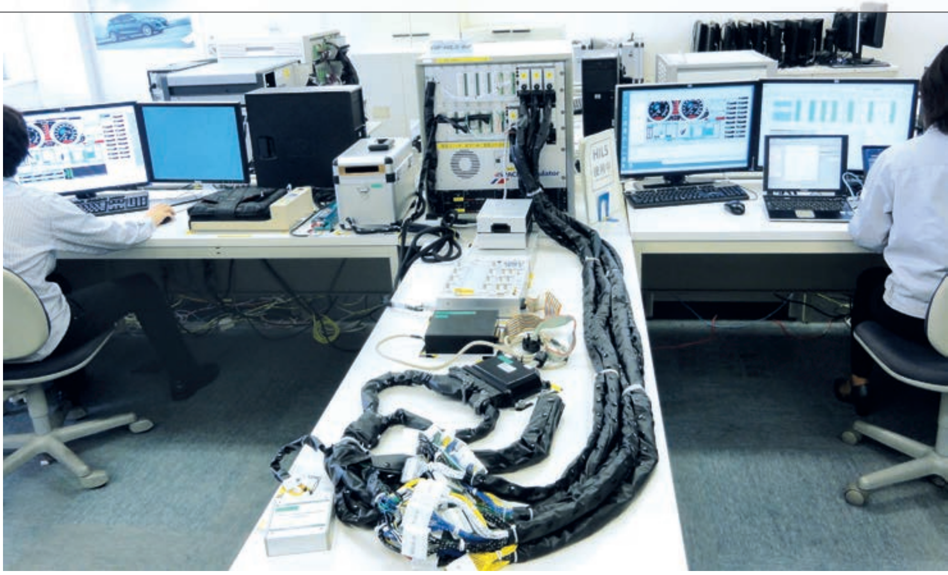


Figure 5: Test bench for the SKYACTIV-G ECUs.

through the valves and the combustion process in the cylinder with a high level of accuracy. To account for the effects of deposits, a new additional model component was implemented and integrated into the plant model. The model's open structure made this very easy. Now the various investigations can be performed and appropriate function optimizations made. If necessary, the tests can even be automated.

A comparison with the conventional approach showed that using a HIL simulator is eight times more efficient. In addition, the HIL simulator helped to recognize controller artifacts, which let the engineers eliminate potential problems. By using HIL simulation early and consistently, it was possible to reliably determine the cylinder charge for the various operating modes and optimize the overall controller strategy. Even though long-term tests were run for interference factors such as tolerances and wear, the proactive use of HIL simulation for function validation in engine control would bring savings of 2,500 hours.

Process Optimization with Real-Time MIL

A further test method demonstrates the flexibility and testing capabilities that simulation brings. The method is based on MIL simulation and was extended to include real-time MIL simulation. The plant model and the controller model both run on the

Figure 6: Stations where real-time MIL simulation is performed.

> "SKYACTIV-G posed enormous challenges regarding development time. Products and services from dSPACE supported the model-based development, which enabled us to overcome the hurdles."
>
> *Keisuke Yayoi, Mazda*

simulator, where they form a closed loop (figure 6). The real-time capability naturally depends on the processing power. In this case, the processor was a DS1006 Quad-Core Processor Board. The advantage of using common dSPACE products is that test cases can be reused between HIL and MIL. The method was used to promptly solve problems that occurred in the actual vehicle. The HIL environment, which is closer to the actual vehicle, is used to analyze the mechanism of problems and find countermeasures. Then the countermeasures are introduced to the control models, where the positive/negative effects are verified in the MIL environment. The engineers were able to carry out a series of verification processes efficiently by reusing the HIL test cases. In order to reduce problems in actual vehicles, we are currently investigating ways to utilize MIL more effectively in early stages on the left side of the development V-cycle. ■

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Team at Mazda
Mazda HIL MIL team members who worked on the SKYACTIV control systems. From left to right: Yoichi Teraoka, Yasuhiro Doi, Keisuke Yayoi, Satoshi Komori, Takuro Miyoshi.