New Direct Fuel Injection Engine Control Systems for Meeting Future Fuel Economy Requirements and Emission Standards

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OVERVIEW: Recently, the need to reduce CO_2 levels has made increased fuel economy an urgent matter in Japan and Europe. Use of the highly efficient diesel engine is expected to increase and measures against emissions such as soot are a major problem. Gasoline engines, on the other hand, are more sustainable in terms of exhaust emissions, and are steadily approaching the diesel engine in terms of fuel economy as well. Since introducing a direct fuel injection engine control system in 1997, the Hitachi Group has continued to develop and manufacture system control and the main components for it, and now we are expanding into Europe as well. We are also proposing various advanced system solutions in response to needs for automobile fuel economy, emissions and power.

INTRODUCTION

SINCE coming on the market in earnest in 1997, the direct fuel injection engine has become widespread, mainly in Japan. Recently, though, the fuel economy and high performance characteristics of these engine systems also have created an opportunity for rapid penetration into the European market, where the CO_2 problem is getting worse.

The Hitachi Group has many years of experience in applying engine control system technology to direct fuel injection systems and also in offering products for those systems. Currently, we are proposing a new system to cope with the stricter environmental regulations concerning emissions and CO_2 that begin

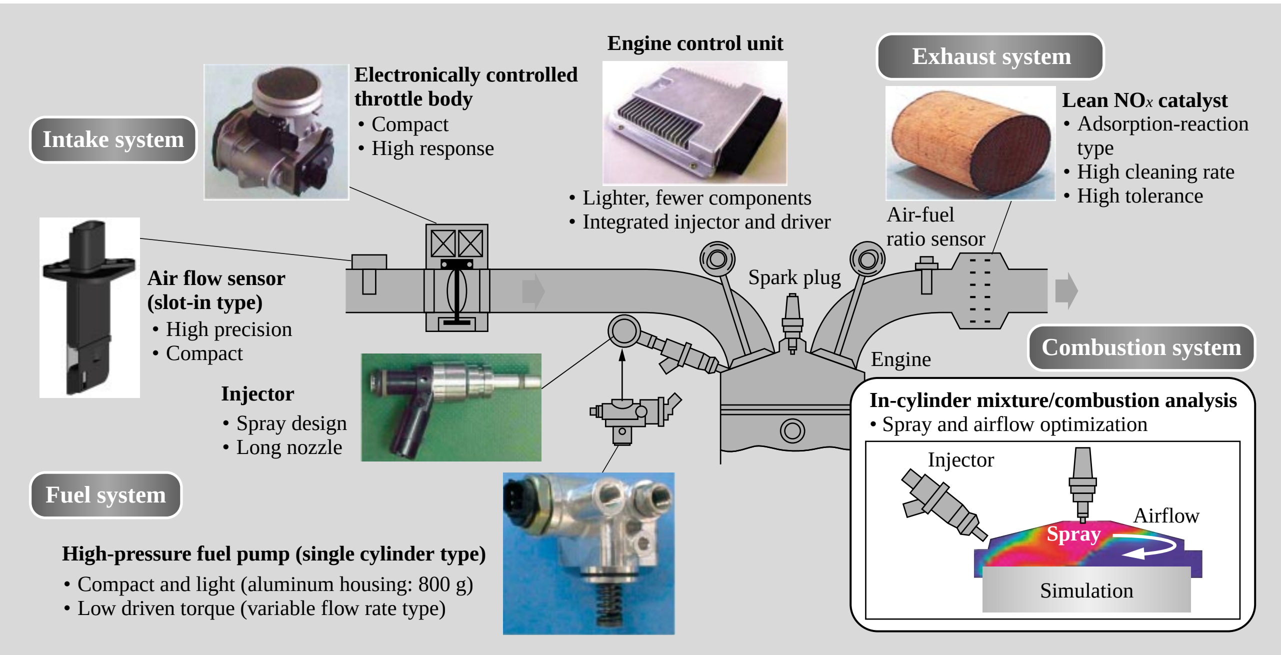


Fig. 1—Basic Structure and Main Components of Direct Fuel Injection Engine System.
In addition to manufacturing the major components of the direct fuel injection engine system, the Hitachi Group has developed various kinds of system control technology. Our components cover the entire system from air intake system to the fuel system and the exhaust system. With our proprietary simulation and analysis technology, we aim for optimization of the combustion system, including the fuel injection spray and airflow.

in 2005.

For the intake system, we supply airflow sensors and electronic throttle body control for accurate control of engine air intake and torque. For the combustion system, we supply the world's lightest high-pressure fuel pump, which has an aluminum housing, and injectors that produce spray patterns for various combustion chamber shapes and combustion systems. For the exhaust system, we produce a lean NO_x (nitrogen oxides) catalyst that is highly efficient in removing NO_x during lean burn combustion. We have also made proposals concerning various factors that govern combustion, such as the injector spray characteristics and the shape of the piston and combustion chamber on the basis of proprietary simulations (see Fig. 1).

Here, we describe the most recent engine combustion technology and the control technology and components for implementing it.

DIRECT FUEL INJECTION ENGINE CONTROL SYSTEM

Characteristics and Application of Direct Fuel Injection Engine

The structures of the conventional port fuel injection engine and the direct fuel injection engine are compared in Fig. 2. In the direct fuel injection engine, fuel is injected directly into the engine cylinders, so the timing of the injection and the distribution of the mixture within the cylinder can be freely controlled. That makes it possible to raise the compression ratio and fuel economy as well as the power output. Furthermore, direct fuel injection engines have a high degree of freedom in control, so the basic engine characteristics such as knock tolerance and response, lean burn, and EGR (exhaust gas recirculation), can be greatly improved compared to port fuel injection systems. Using these superior basic characteristics, the Hitachi Group is developing a new system that includes variable valve control, and hybrid system and supercharger system downsizing to meet the stricter regulations (see Fig. 3).

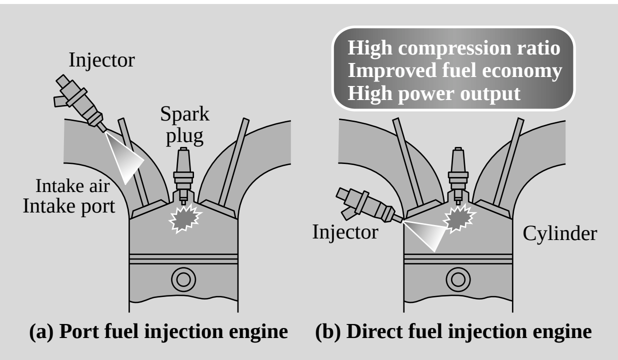


Fig. 2—Structures of Port Fuel Injection Engine and Direct Fuel Injection Engine.
In the direct fuel injection engine, the fuel is injected from the injector directly into the cylinder and burned, allowing a higher compression ratio and power output than does a port fuel injection engine.

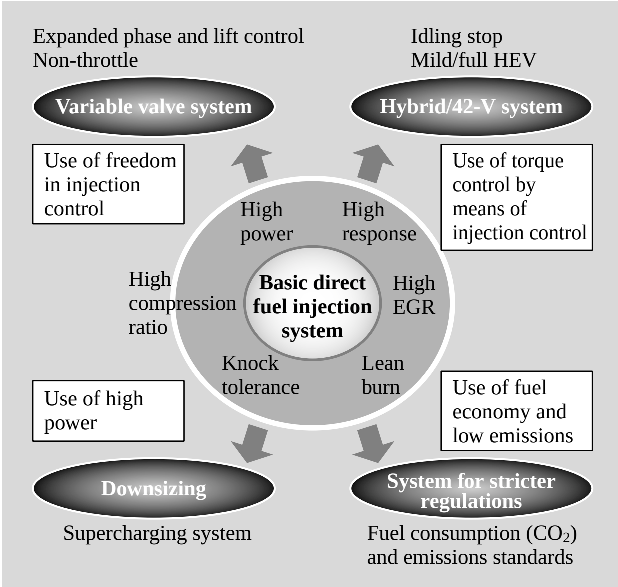


Fig. 3—Characteristics of Direct Fuel Injection Engine System.
The direct fuel injection engine has high power output, variable spray and low emissions characteristics, and is being applied to powertrains for meeting future requirements.

Configuration of Control System

Extracting the superior performance of the direct fuel injection engine requires an innovation of components and new advances in control system technology. Specifically, high-pressure fuel pumps and injectors are key components for attaining more precise control of the engine's basic process of combustion under high compression (5 to 12 MPa). With the objective of achieving highly responsive combustion control under high pressures, we are developing the key components for complete combustion under various driving conditions.

Also, airflow sensors for accurate detection of the amount of air intake to the engine and highly responsive electronic throttle body control are being used to control the torque generated by the engine according to occasional changes in the requirements of the driver. Some direct fuel injection engines use a lean burn for highly efficient operation, so a lean NO_x catalyst for reducing NO_x under lean conditions

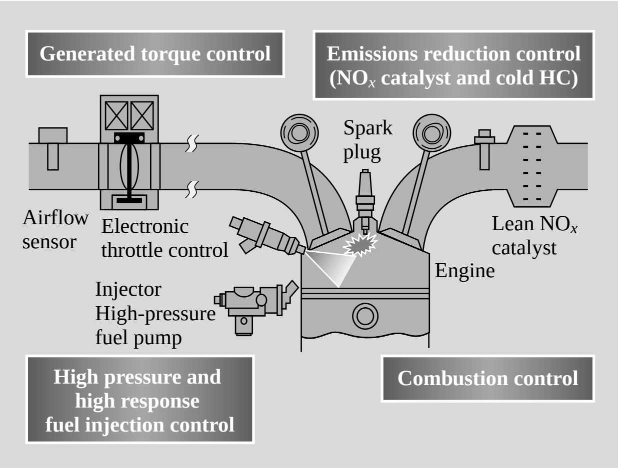


Fig. 4—Basic Structure and Main Functions of Direct Fuel Injection Engine Control System.
The functions include control of the torque that arises in various driving situations, optimal fuel injection, combustion control, emissions reduction control over the entire range from idling to high speed.

(excess oxygen) is required.

The Hitachi Group also supplies a high cleaning rate control for that purpose (see Fig. 4).

COMBUSTION TECHNOLOGY

Combustion Analysis Technology for Direct Fuel Injection Engines

For the opening of the injector, which is the key to in-cylinder combustion control, we are applying analysis technology that makes full use of simulation (see Fig. 5). The Hitachi Group engine combustion control technology is based on our irregular compressible fluid analysis program for analyzing pneumatic two-layer flow in nuclear power plants. Currently, we are making various improvements and increasing the practicality of the system. The main points of the improvements are to shorten the development turnaround time as much as possible and accurate reproduction of in-cylinder phenomena. For the former, we have developed the Voxel method, in which a 2 million-cell mesh can be created directly from a 3D-CAD (computer-aided design) diagram in about five minutes. That makes it possible to reduce the work involved in mesh creation, which previously took several weeks, and allow surveys concerning piston shape and other parameters of the combustion chamber to be performed in a short time. Concerning the second of the two points, the objective was to improve accuracy in reproducing the air movement within the cylinder. The development of technology for directly simulating turbulence will allow the spray shape and air movement in the cylinder, which strongly affect combustion, to be reproduced with high accuracy.

An example of applying this simulation to the direct fuel injection engine is shown in Fig. 5. In the calculation of the air mixture injected directly into the cylinder and the resulting combustion flame, it is

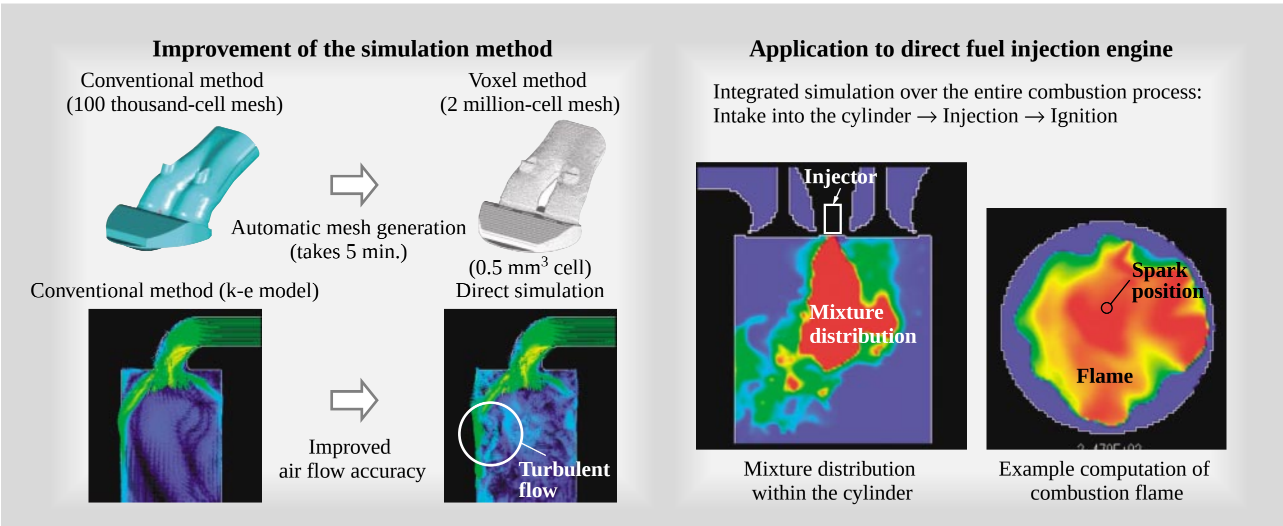


Fig. 5—Simulation of Air Movement in Engine and Combustion Analysis with Example of Application to Direct Fuel Injection Engine.
Aiming for fast and accurate mesh generation, we are performing integrated simulations that cover the entire combustion process, beginning with air intake into the cylinder and including injection of the fuel, ignition, and combustion. The results are used to determine injector spray characteristics and propose shapes for the combustion chamber, and other aspects of developing combustion technology for the direct fuel injection engine.

important to optimize the distribution of the air mixture with respect to maintaining ignitability. The key to that optimization is the spray characteristic of the injector. Using this analysis technology to determine the spray characteristics of the injector, we have proposed shapes of the combustion chamber and the intake system to vehicle manufacturers.

Development of New Injection Method

The performance of a direct fuel injection engine is developing according to requirements concerning fuel consumption and emissions. Currently, most commercial engines employ injection systems that use conical spray patterns (see Fig. 6). With that conventional method, the spray from the injector is ignited by the spark plug after the spray hits the surface of the piston. In the lead spray injection system developed for the next-generation engine, the injected spray does not hit the piston, but is distributed in the cylinder at the time of combustion. The quantity of unburned fuel is therefore reduced because no fuel adheres to the piston. In addition, the effect of the lead spray is to increase the freedom in spark timing and injection timing, allowing control of the start of combustion and the combustion period according to the vehicle operating circumstances. As a result, this method achieves higher fuel economy and lower amounts of unburned fuel (HC: hydrocarbon) and NO_x emissions.

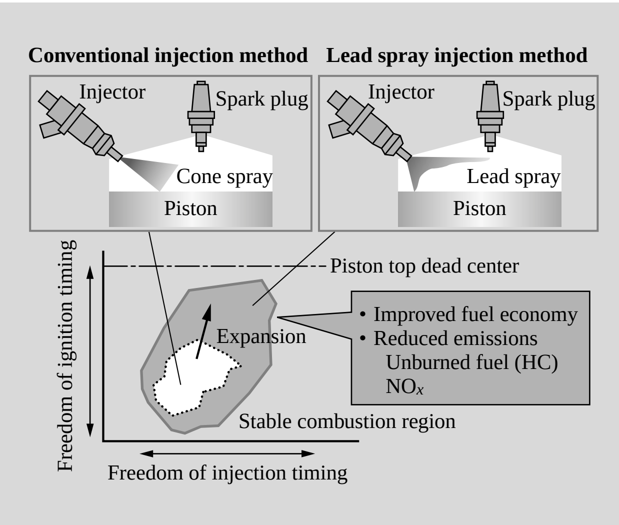


Fig. 6—Comparison of Next-generation Direct Fuel Injection with Conventional Method.
We will supply lead spray injection as the next-generation injection system. In this way, the Hitachi Group aims to improve fuel economy and reduce emissions.

COMPONENT TECHNOLOGY

Injector

The appearance and structure of the injector, a key component of the direct fuel injection engine, and examples of the spray shapes are shown in Fig. 7. In a direct fuel injection engine, the fuel must be injected in a short period of time and at pressures at least 40 times higher than in port fuel injection. Therefore, the Hitachi Group has applied analysis technology such as dynamic magnetic field analysis to increase solenoid driving power to achieve faster valve action. We have also made the injector 50% smaller and lighter than our previous products.

Furthermore, in addition to employing our original "swirl type" pattern for the shaping and atomization of the fuel spray, we have made it possible to shape the injection spray to match the engine and the combustion system with technology for designing the shape of the nozzle tip. The spray shapes (see Fig. 7) include the symmetrical cone, the bent cone for conforming to the engine layout, and the latest horseshoe shape spray for the lead spray injection method described above. The lead spray method allows good ignitability to be maintained under various driving conditions by optimizing the specifications of

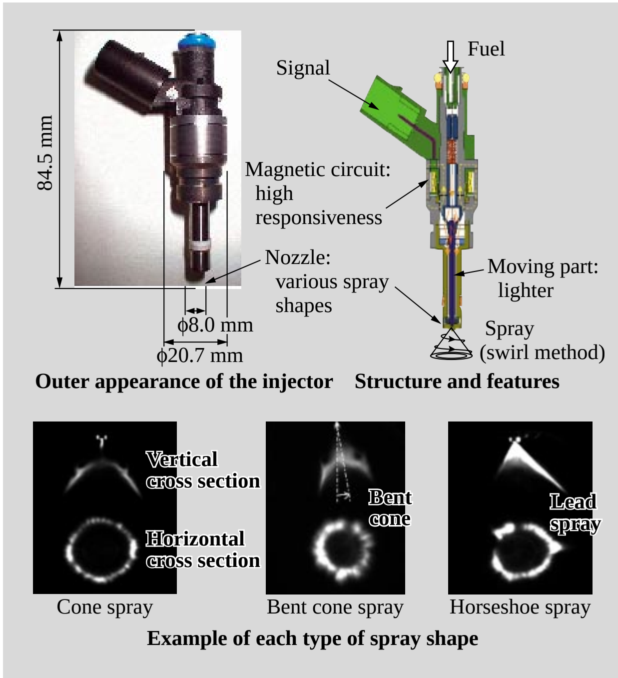


Fig. 7—Appearance and Structure of Injector, with Spray Shape Examples.
Increased responsiveness of the magnetic circuit and lighter moving parts aim at high-speed valve response, while the shape of the nozzle provides a spray that is suited to the engine and the combustion method.

the lead spray part of the horseshoe spray for the shape of the combustion chamber.

High-pressure Fuel Pump and Fuel Line System

A high-pressure fuel pump that produces high fuel pressures (5 to 12 MPa) and an example of fuel line optimization are shown in Fig. 8. The high-pressure fuel pump employs a single-cylinder plunger pump and a housing made of aluminum with a plated surface and can handle alcohol fuels E10 as well. At 800 g, this is the world's lightest pump.

The pump is driven by the engine cam shaft. The fuel is drawn into the pump and expelled by the reciprocating motion of the plunger. The driving loss can be minimized by using a flow control valve to vary the timing of the opening of the pump intake valve so as to supply just the amount of fuel output that is needed. This reduction in driving loss also contributes to reduction in fuel consumption.

In the development of a pump that includes flow control specifications and the configuration of the high-pressure fuel lines, we used our hydraulic system behavior analysis software. As a result, the behavior of the cams and valves and each of the other parts is known and the information can be used as feedback into the design process to achieve a highly efficient pump. An example in which the arrangement of the fuel line system decreases the pressure pulses is shown in Fig. 8. We are proposing a high-pressure line arrangement that was optimized by estimating the pressure pulses in the high-pressure lines.

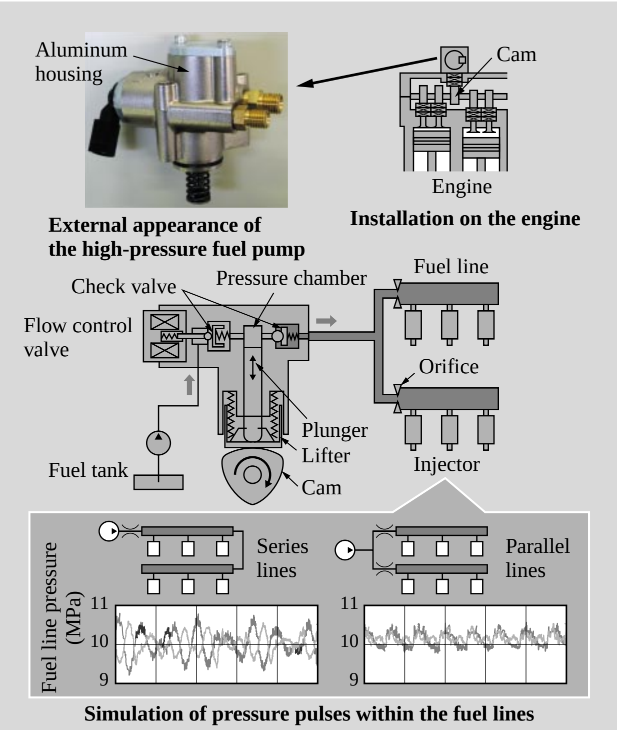
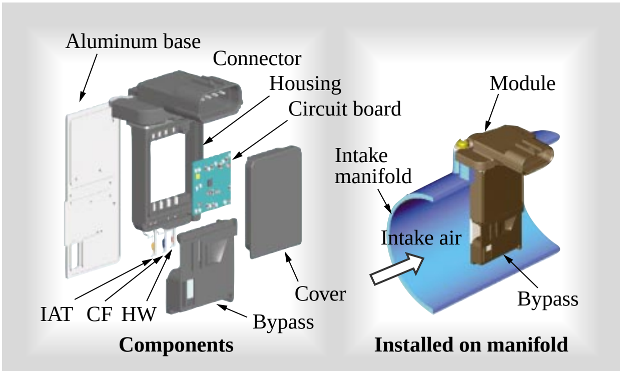


Fig. 8—Structure of High-pressure Fuel Pump and Example of Optimization of High-pressure Lines.
In addition to achieving the world's lightest pump (800 gm) by using an aluminum body, we used proprietary simulations to develop a high-pressure fuel line system with reduced pulsation.

Highly Accurate Airflow Sensor

In a direct fuel injection system, accurate measurement of the amount of airflow is needed, even when pulsing in the air intake is increased by lean burn and high EGR. We are dealing with that problem by improving an already successful airflow sensor. The structure of the slot-in airflow sensor is shown in Fig. 9. The slot-in sensor reduces the circuit board area by half by using a layered structure and other such means, and integrates the circuit case with the sensor mounting unit. Furthermore, using a modular structure in which the detour bypass is mounted on an aluminum base allows reduction in size and increase in performance. We were thus able to reduce the price by decreasing the component cost and raising productivity. Mounting this module in the intake of the air cleaner or other such place makes it possible to measure the airflow.

We also reduced measurement error caused by pulsing and temperature changes. Concerning air intake pulsing, we reduced the measurement error due



IAT: intake air temperature sensor
CF: cold film; heat-sensing resistor for temperature control
HW: hot wire; heat-generating resistor for flow sensor

Fig. 9—Structure of Slot-in Airflow Sensor.
Productivity in manufacturing is improved by layering the component modules on the aluminum base, allowing a unidirectional stacking assembly method. Other than the connectors, the components can be formed into two parts, an upper part and a lower part, thus allowing cost reduction by multi-part installation.

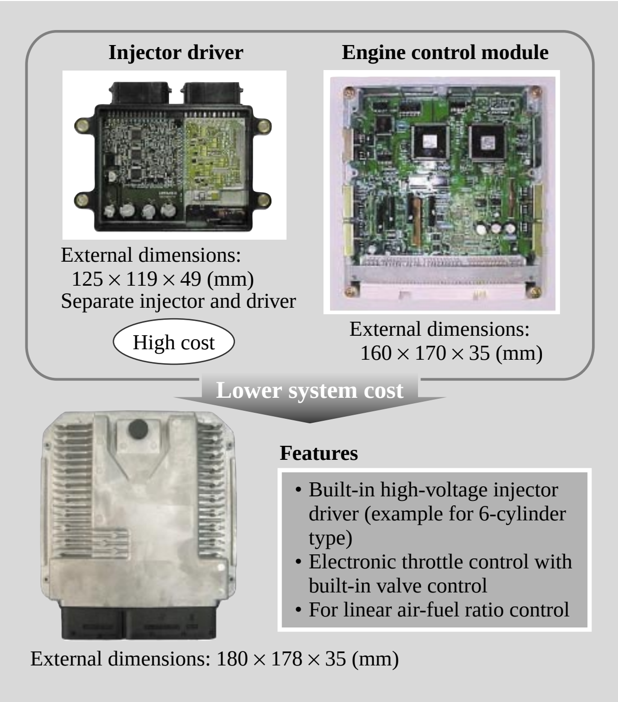


Fig. 10—Engine Control Module with Integrated Injector Driver.
Reduction of size, weight and cost are the objective of integrating the injector and driver with the engine control module, which had previously been separate units.

to pulsing by half by placing a sensor inside the bypass used to reduce the pulsing itself and optimizing across the bypass to improve performance factors such as initial accuracy and output noise. We also reduced the error due to temperature change by trying to achieve a balance between insulation by molded plastic and heat radiation from the aluminum base.

Although the interior of the engine compartment is heated by exhaust heat, etc., the temperature inside the air intake is low because the air is brought in from outside the compartment. With the slot-in airflow sensor, in addition to reducing the temperature change in the circuitry and sensor module by the heat radiated from the aluminum base, reliability is increased by extension of lifetime by reduced thermal stress in the mounts. What is more, a proven bobbin-wound hot wire is used on the flow sensor to increase the air-tightness of the circuit board case, thus improving reliability.

Engine Control Module with Integrated Injector Driver

In direct fuel injection, there is a new need for an injector driver for driving the injector at high speed for injection under high combustion pressure. We integrated the injector driver, which has previously been a separate unit, with the engine control module to reduce size, weight and cost (see Fig. 10). Moreover, the use of a waterproof construction allows mounting inside the engine compartment, thus improving ease of installation in the vehicle and reducing the wiring needed.

The main features of the integrated unit are a 50% reduction in number of parts, 50% reduction in weight and lower cost, all achieved by integration of the injector driver and use of custom ICs (integrated circuits). Furthermore, we developed a new custom ICs that centralize peripheral functions for the power supply and output and for the injector driver. Using these custom ICs allowed a large reduction in the number of parts and made it possible to integrate the injector driver with the engine control module.

SYSTEM PERFORMANCE AND FUTURE DEVELOPMENT

In addition to developing the combustion control technology and components based on spray shaping described above, the Hitachi Group has been proposing system solutions that combine control technology with direct fuel injection.

Future development of system performance is projected in Fig. 11. The lead spray injection system described here is for low-emission gas vehicles

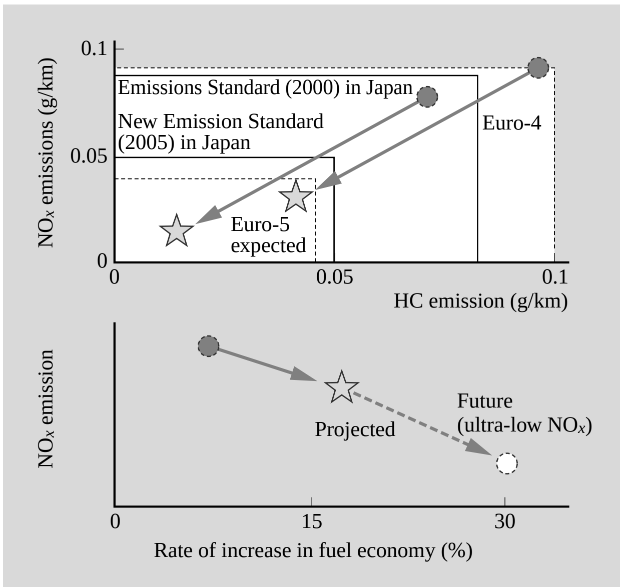


Fig. 11—Comparison of Performance of Injection Methods and Their Future Development.
The lead spray injection method can cope with the new, stronger emissions regulations that begin in 2005. For future systems beyond 2010, we aim for yet higher performance.

designed to meet the New Emissions Standard (2005) in Japan by reducing NO_x and HC emissions and which will also meet the requirements for the Euro-5 regulations (a half amount of Euro-4) in Europe. Together with reducing NO_x emissions, a 16% improvement in fuel economy compared to port fuel injection can also be achieved. Furthermore, we are taking on the development of a system for improving mileage by 30% while attaining ultra-low NO_x emission, targeting 2010.

CONCLUSIONS

We have described direct fuel injection engine control system solutions that have been developed by the Hitachi Group.

We have continuously applied our proven technology to control system products for the direct fuel injection engine since it was first developed in 1997.

Furthermore, to meet the requirements of environmental regulations, etc., we are also developing various kinds of technology for injection spray shaping and components based on consumption analysis technology.

The engine system is expected to continue to evolve even after 2010. The Hitachi Group will continue to propose new solutions for the engines of the future.

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