Reduction of CO_2 Emissions for Automotive Systems

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OVERVIEW: The amount of CO_2 emission from the transport sector (including cars) accounts for about 20% of total CO_2 emissions. Accordingly, from the viewpoint of preventing global warming, reducing that proportion is a key issue. In regard to CO_2 emissions from cars, fuel economy standards are getting tougher all over the world, so improving fuel economy of cars is strongly desired. From now onwards, it is considered that fuel economy of engines will be further improved by boosting engine efficiency and by hybridization (electrification) of cars. What's more, improving fuel economy by improving "driving operation" (i.e. the operation in which a car is driven) and by smoothing traffic flows will come into the picture in the near future. Under these circumstances, with concern for the environment from the viewpoint of reducing CO_2 and other exhaust emissions, the Hitachi Group is comprehensively promoting a broad range of technical developments for reducing CO_2 emissions from cars.

INTRODUCTION

IN consideration of environmental problems, exhaust emission regulation and fuel economy standard of passenger cars and light trucks are being introduced on a global scale (for example, in Japan, Europe, and the United States). Although average fuel economy of passenger cars in Japan increased for a while during the "bubble economy" years around 1990, on the whole, fuel economy of cars has continued to fall since 1975. This trend was a result of the introduction of electronic control by microcomputers and weight-saving measures as well as introduction of technologies like gasoline direct injection and variable valve timing; consequently, CO_2 emission has been reduced considerably (see Fig. 1).

As the number of cars on the road has grown, however, CO_2 emissions have increased, and efforts to reduce the amount of CO_2 emissions in countries around the world have intensified. For example, in Japan, new fuel-economy standards must be met by 2015; in Europe, a target CO_2 emission amount of 120 g/km (corporate average) is set for 2012 and beyond; and in the United States, the new CAFE (Corporate Average Fuel Economy) standard of the new energy legislation for passenger cars are now in force.

Moreover, the first commitment period of the Kyoto Protocol (which commits countries to reducing greenhouse-effect gases like CO_2) starts from 2008, and further reductions in CO_2 emission will be stipulated from 2013. In particular, the CO_2 emission amount from the transport sector (including cars) takes up 20% of total CO_2 emissions; accordingly, car manufacturers are facing significant challenges in developing technologies for reducing this portion of total CO_2 emissions.

With thoughtful consideration to environmental issues, particularly from the standpoint of reducing CO_2 and exhaust emissions, the Hitachi Group is engaged in development for fuel-efficient passenger cars. As measures in the automotive field, reduction of passenger-car CO_2 emissions by improving engine efficiency, promoting hybridization or electrification of cars, and facilitating traffic flow by adopting ITS (intelligent transport systems) are commonly cited.

The rest of this report describes the efforts of Hitachi aimed at reducing CO_2 emissions for automotive systems and our corresponding technical solutions.

CO_2 REDUCTION TECHNOLOGY FOR ENGINES

Approach for CO_2 Reduction for Gasoline Engines

To reduce CO_2 emissions from cars, it is necessary to improve their fuel economy. This means extracting the kinetic energy from the combustion energy

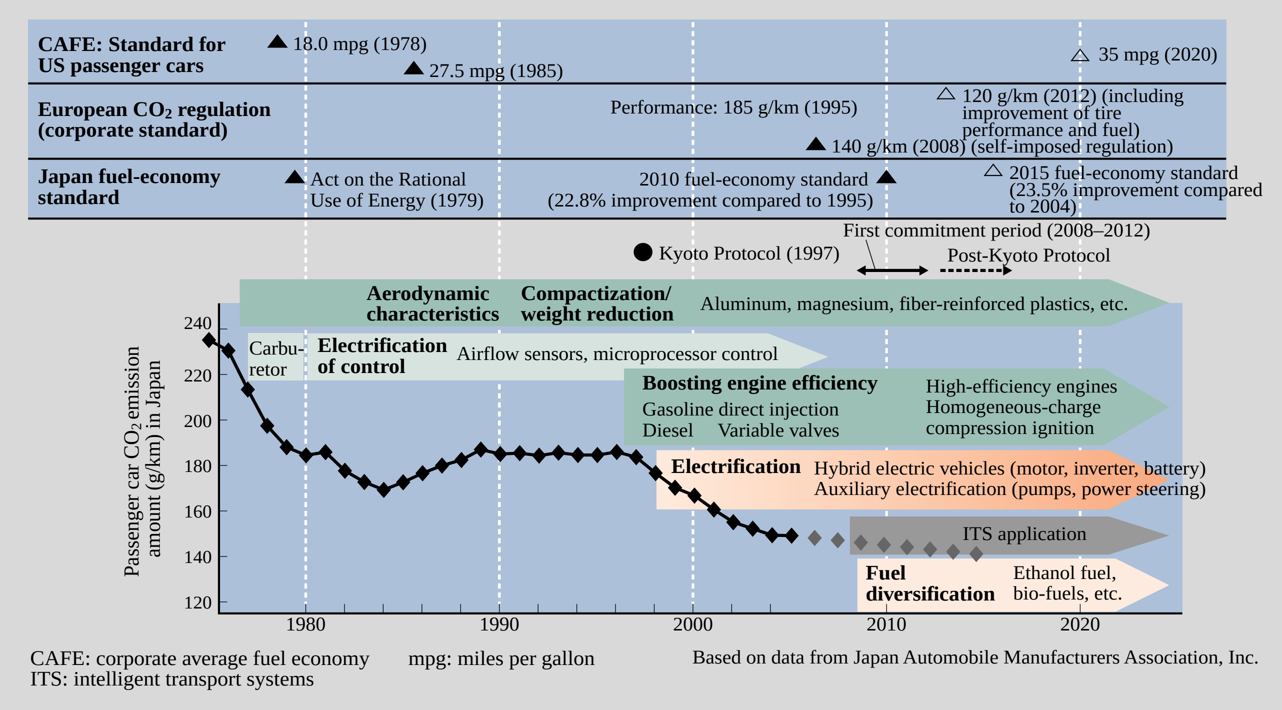

Fig. 1—Trends Regarding CO_2 Emission Reduction in Automotive Vehicles.
Since 1975, as a result of weight-saving technology as well as various electronic engine-control technologies and electrification technologies, fuel consumption per vehicle has decreased year on year. In consideration of global environmental issues, global fuel-economy standards have been regularly strengthened, the requirement to reduce CO_2 emission volume from vehicles has become tougher, and technologies for reducing CO_2 emission have become more and more important. In the future, in addition to fuel-consumption reduction by applying high-efficiency engines (such as ones with gasoline direct injection, variable valve, and diesel engines), reduction of CO_2 emission volume through electrification (such as hybrid electric vehicles), ITS application and diversification of fuels will continue.

supplied to the car without any waste. The energy flow in a car is shown schematically in Fig. 2. To utilize energy efficiently, it is important to reduce loss in the engine and various accessories and to reduce resistance when the car is running while recovering heat energy and kinetic energy[(1)].

As for reduction of engine loss, attaining high compression ratio and reducing pumping loss are cited. In regard to these approaches, at Hitachi, we are focusing our efforts on direct-injection engine systems (which inject fuel directly into the cylinders) and variable-valve systems (which lower pumping loss). Since direct-injection systems inject fuel directly into the cylinders, injection timing and fuel-air mixture distribution in the cylinders can be controlled freely, and improved fuel economy and high power output can be obtained by attaining high compression ratio. Moreover, since the degree of control freedom is high, improvements to properties such as engine-knock resistance, lean burn, and large-scale EGR (exhaust

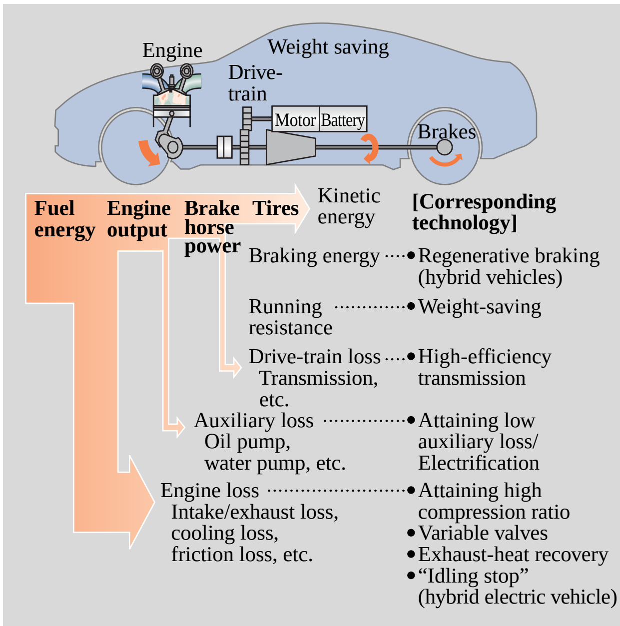

Fig. 2—Energy Flow Within an Automotive Vehicle.
To efficiently utilize energy, it is important to improve engine efficiency, reduce losses in various accessories, reduce drag while an automotive vehicle is running, and recover heat and kinetic energy.

gas recirculation) are expected. In the meantime, variable-valve systems reduce pumping loss by varying opening-closing timing, opening magnitude (lift amount), and opening period (operation angle) of valves and further improve engine efficiency through integration with direct-injection systems.

Engine Systems and Component Technologies

To extract superior performance from direct-injection engine systems and variable-valve systems, key components and their control technology for configuring the systems are required. In regard to these engine systems, subsystems of these key components and engine-control technologies under product development by Hitachi are described in the following.

To control combustion in an engine precisely, a direct-injection engine system must pay particular attention to the fuel-air mixture in the cylinders. Hitachi is providing fuel-injection subsystems composed of injectors (which produce a fuel-spray formulation corresponding to the shape of the combustion chamber and combustion process of the engine) and high-pressure fuel pumps, along with their drive circuits and control units for extracting maximum performance from them. Furthermore, by applying simulation and analysis technologies we have accumulated up till now, we are providing various solutions for injector-fuel spray, in-cylinder airflow, piston-crown specifications, and so on[2].

As for variable-valve systems, we are providing VTC (valve timing control), which can continuously vary valve timing, and VEL (variable valve event and lift control)[3], which can continuously vary valve lift amount and operation angle, as key components. With VEL, since drive friction is low and operation without a throttle valve of intake manifold is possible (giving significant reduction of pumping loss), fuel consumption is effectively lowered. Although VTC can only vary valve timing, we are continuing development of VTC with a unique mechanism [which can be electrically operated even at low RPM (revolutions per minute) and low oil temperature], as well as in the conventional hydraulic way. Furthermore, we are developing control technology for producing engine torque in response to individual drivers while lowering fuel consumption by controlling intake-air volume (by means of an airflow sensor that precisely detects the intake-air volume drawn into the engine, an electronically controlled throttle valve, and variable valves). In addition, we are developing components aimed at lowering loss in accessories such as variable-

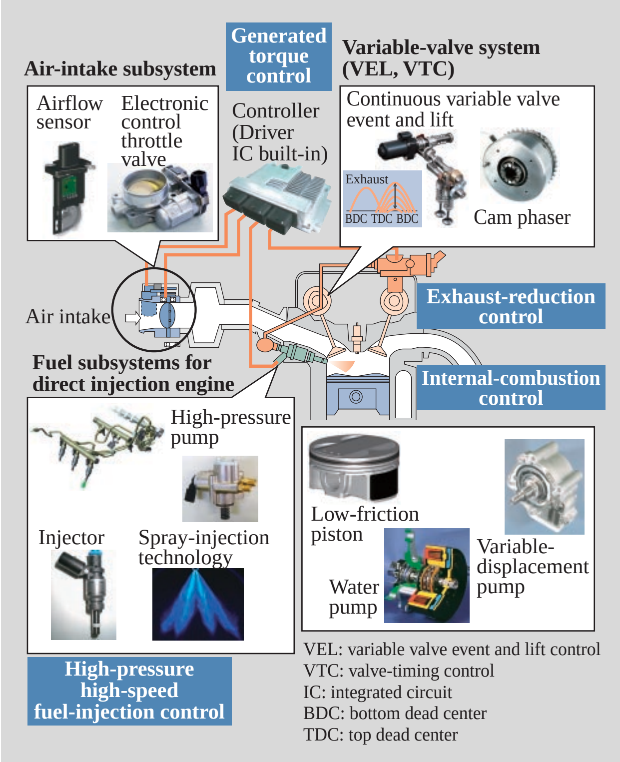

Fig. 3—The Engine System and its Main Components.
In addition to development of fuel for direct-injection engine, components and subsystems related to air intake, variable-valve subsystems, and low-loss products, development of various system-control technologies is ongoing.

displacement pumps and electric pumps for variably controlling discharge volume of engine (lubrication) oil (see Fig. 3).

Activities Concerning Gasoline Homogeneous Charge Compression Ignition Engines

For further improving fuel economy of gasoline engines, technical development of an engine system called HCCI (homogeneous charge compression ignition)[4] is continuing. Fuel-air mixture of HCCI engine is pre-mixed as homogeneous mixture. Effective compression ratio and internal EGR of HCCI engine are controlled by variable valves. The internal EGR controls in-cylinder temperature. These operations realize auto ignition of HCCI engine. Combustion of HCCI engine has higher heat efficiency and lower temperature (low NO_x) than a conventional combustion. So, low fuel consumption and low emission are consistent in HCCI engine.

Regarding commercial application of an HCCI engine, achieving stable combustion is a key issue. In response to that issue, an engine using fuel subsystems

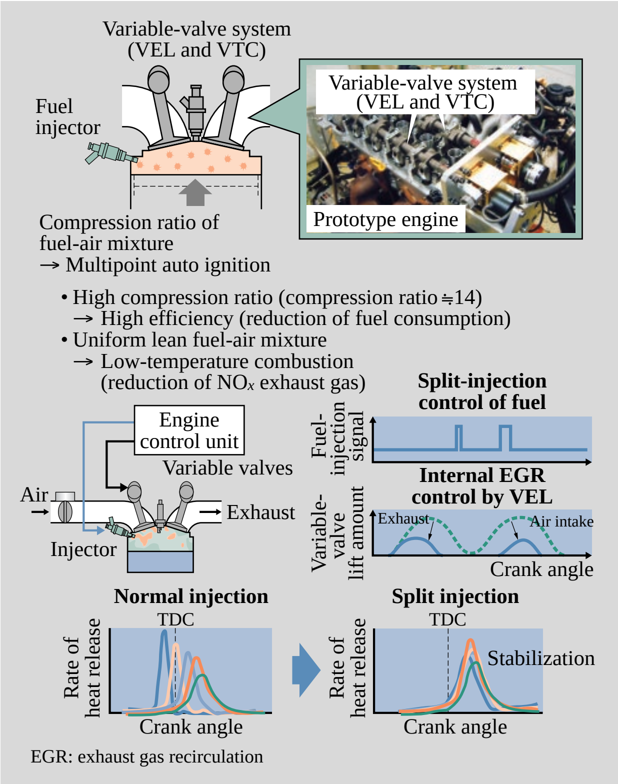

Fig. 4—Concept Called Homogeneous Charge Compression Ignition and a Prototype Engine Based on that Concept.
By means of high compression ratio and multipoint-auto-ignition combustion with even and lean fuel-mixture distribution, it is possible to attain both low fuel consumption and low emission. The prototype engine is composed of an in-line four-cylinder direct injection system and a variable-valve system, and stable operation is achieved by variable-valve and injection control.

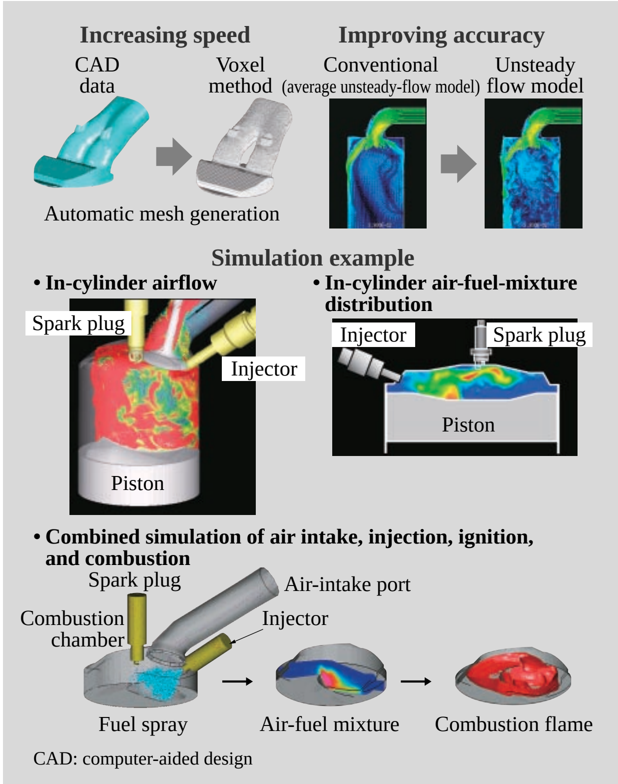

Fig. 5—Simulation and Analysis Technology.
The engine-combustion simulation technique achieves high-speed mesh generation by the voxel method and accuracy improvement by modeling of unsteady flow. Based on this analysis technique, specifications of product components and combustion concepts are being proposed.

for the direct-injection and variable valves (VEL and VTC) has been prototyped, and technical development for comprehensively controlling combustion of the HCCI engine is continuing(5). As for this prototype engine, stable combustion under internal EGR control using variable valves and precise split-injection control of fuel is being experimentally demonstrated. Moreover, according to test data and simulation results concerning the prototype engine, compared to a conventional engine, the engine is forecast to reduce fuel consumption by 20%(6) (see Fig. 4).

Simulation and Analysis Technology

Presently, as for continuing development of injectors for direct injection engines, variable valves, and homogeneous charge compression ignition, analysis technology making use of simulation is being applied. The engine-combustion simulation technology is based on an unsteady and compressible-flow analysis program used for analyzing gas-liquid two-phase flow in pipe work of nuclear plants. This technology is being developed with focus on shortening TAT (turnaround time) and accurately reproducing phenomena occurring in the cylinders. As regards TAT, a voxel method that can create meshes directly from a CAD (computer-aided design) drawing was developed, and the man-hours needed for mesh creation was reduced. In regard to recreating in-cylinder phenomena, through development of a method that directly simulates turbulent flow, accuracy of recreation of the airflow (which strongly affects spray formation and combustion) was improved(3).

An example of applying this simulation technology to development of a direct-injection engine is shown in Fig. 5. The conditions regarding the fuel-air mixture formed and its combustion flame can be calculated in accordance with the flow of air and fuel in a cylinder. In the case of a direct-injection engine, from the viewpoint of assuring ignitability, the fuel-air-mixture

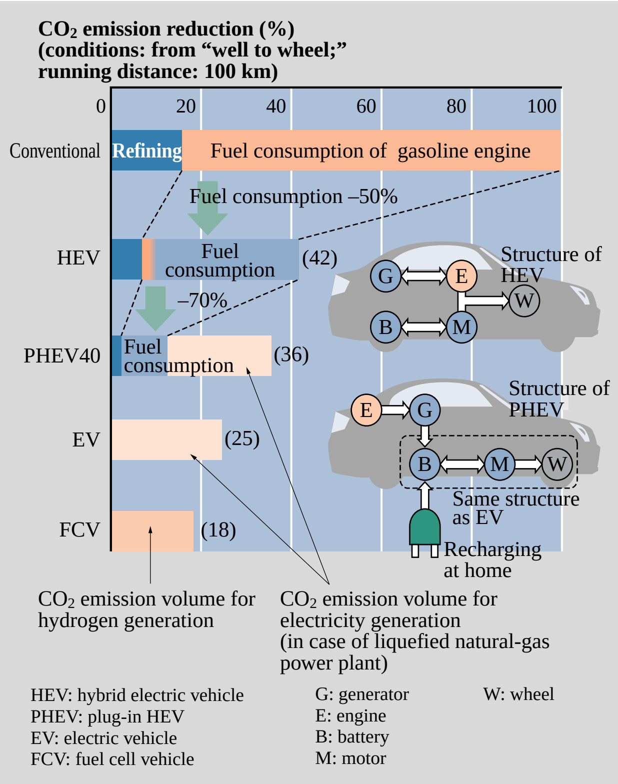

Fig. 6—Trends Regarding HEVs Aimed at Reducing CO_2 Emissions.
Large-scale reduction of CO_2 emissions is possible through vehicle electrification such as PHEV and EV.

distribution is a key factor. By utilizing the simulation and analysis in the manner described above, we are offering configurations for the combustion chamber and intake manifolds, in addition to combustion concepts, from among an injector specification for producing the optimum fuel-air mixture.

Utilizing this simulation and analysis technology, we are proposing solutions for reducing CO_2 emission — such as system control for optimally driving various devices, reducing loss in accessories, and improving efficiency (especially for variable-valve systems and fuel subsystems for direct injection) and homogeneous charge compression-ignition systems aimed at the vehicles of the future — one after another.

CO_2 REDUCTION BY HYBRID AND ELECTRIC VEHICLES

Trends Concerning Hybrid and Electric Vehicles

In regard to reducing CO_2 emission from individual vehicles as well as lowering fuel consumption, much hope is pinned on HEVs (hybrid electric vehicles). Furthermore, aiming at commercialization of PHEVs ("plug-in" HEVs), namely, HEVs that can be recharged at home, development is pushing ahead. CO_2 emissions from conventional gasoline-engine cars, HEVs, PHEVs, EVs (electric vehicles), and FCVs (fuel cell vehicles) are compared in Fig. 6. The calculation of CO_2 emissions uses total "well-to-wheel" efficiencies (i.e. from refining at the oil well to combustion in the vehicle) published by various organizations[(7)–(9)]. Under the assumption of a running distance of 100 km, the HEV data is based on the Japanese 10–15-mode test-drive cycle for fuel consumption, the PHEV [i.e. "PHEV40," which can run for 40 miles (64 km) on one battery charge] data are drawn from US governmental figures, and the EV and FCV data are from reference[(9)]. Moreover, the electrical power generation for the PHEV and EV used LNG (liquefied natural gas). In the figure, two examples of system configurations are shown: the series-parallel hybrid system for the HEV, and the series hybrid system (using the engine to generate electrical power) for the PHEV. The arrows indicate the flow of power in each configuration.

According to the figure, CO_2 emission is reduced by about 50% by switching from a conventional-engine vehicle to an HEV, and by subsequently switching the HEV to a PHEV, it can be reduced by another 70% through improvement in single-battery-charge running distance. In total, the CO_2 emission ratios for the HEV and the PHEV differ by only 6%, because it was assumed that the electric-power generation for the PHEV was done by burning fossil fuel (i.e. LNG); however; if nuclear or wind power were assumed, this difference would be even bigger. In this way, it can be considered that CO_2 emission volume can be significantly reduced by electrification from HEVs to PHEVs and EVs. In accordance with the results described above, as key technologies for handling the switch from HEVs to PHEVs and EVs that will allow longer electric-running distance, R&D (research and development) on boosting battery capacity, increasing motor and inverter power, and improving heat resistance is pushing forward.

Battery Technology for HEVs

As a battery for HEVs, the Li-ion (lithium-ion) rechargeable battery — which offers the advantages of high energy density, high power density (i.e. input/output performance), and long life — are drawing most attention as the main battery of the future[(11)]. Hitachi has been a driving force behind R&D on large-scale Li-ion rechargeable batteries since the beginning of the 1990s. Accordingly, at the same time, a cell

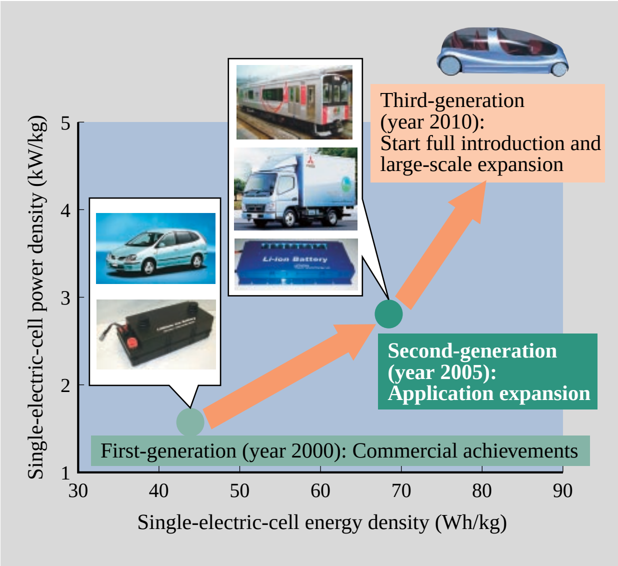

Fig. 7—Roadmap for Lithium-ion Rechargeable Batteries for HEVs.
To directly improve energy regeneration and power-assist performance while a car is running, improving battery power density is effective in reducing CO_2 emission.

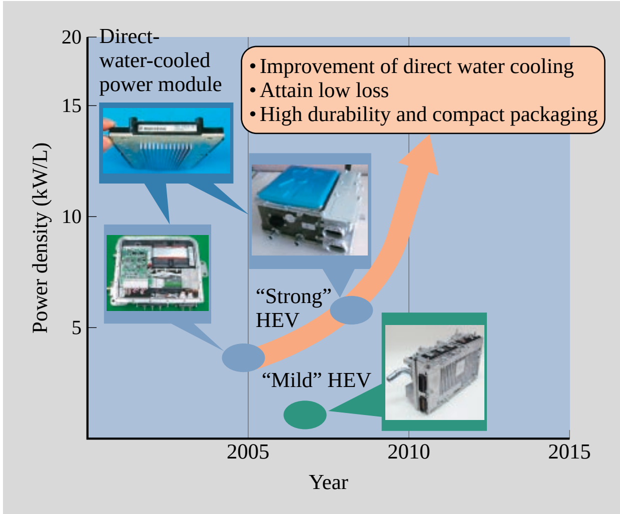

Fig. 8—Roadmap for Inverters for HEVs.
"Strong" HEV (300-V class) motors are used, and acceleration assistance is possible; "mild" HEV (42-V class) motors are mainly used for start-up and regenerative braking.

controller for drawing maximum performance from the battery and operating it safely has been developed. As the first battery in the world to be introduced in market vehicles in applications to EVs (both passenger cars and motorcycles) and HEVs, it is establishing a good track record.

Hitachi's roadmap for HEV-use Li-ion rechargeable batteries is shown in Fig. 7. The first-generation Li-ion rechargeable battery (with a power output of 1.8 kW/kg) hit the market in the year 2000 and has found many commercial applications since then. After that, the second-generation Li-ion rechargeable battery (with 1.5 times improved performance, i.e. power output of 3.0 kW/kg) was developed, and it has been increasingly used since then. At present, it is being introduced into delivery-use hybrid truck and hybrid railroad vehicles.

Improvement of power density is directly connected to performance gains by energy regenerative braking during car running and by power-assist schemes, so it is considered to be effective for improving fuel-economy and reducing CO_2 emission. Given that, technical development for further improving power density by significantly reducing resistance loss in a battery is being engaged upon. Targeting full-scale introduction of HEVs from 2010 onwards, wide-ranging technical development — from development of materials for the third generation of Li-ion rechargeable batteries to control technologies for those batteries — is pushing ahead, and Li-ion-battery systems for HEVs will be introduced from now onwards.

Inverter Technology for HEVs

As for inverters for HEVs, in contrast to ones for industrial uses, they are almost never in steady operation under rated load, and their output power changes as needed in response to driving conditions concerning the car. As a result, the power devices of the inverter dictate its current rating under thermal conditions. In the case of high-voltage HEVs (referred to as "strong HEVs"), although a water-cooling system is used to cool the power devices, Hitachi has developed a unique system called "direct water cooling[11]."

Hitachi's roadmap for HEV-use inverters is shown in Fig. 8. As for the term "power density" used here, the total maximum power outputs are values split according to volume of inverter equipment. The direct-water-cooling systems shown in the figure are characterized by the shape of the cooling fins formed on the underside (i.e. a copper base) of the power module. Since heat-release grease is not used, thermal resistance is reduced by 25% in comparison with indirect cooling using a separate module and cooling fins. The circulating-water temperature has an upper limit of 75°C. As for the low-voltage (42-V) HEVs (i.e. "mild HEVs")[12], indirect water cooling using the engine coolant is a special feature.

From now onwards, as well as further improving our direct-water-cooling systems, we will continue to develop high-heat-resistance and compact packaging for the whole inverter body while creating low-loss power devices and to offer solutions for hybrid vehicles in the form of technology for handling future power increases and better heat resistance. In particular, the reduction of power loss is promoting development of technology for lowering dynamic power loss during high-current switching (by lowering the inductance of bus-bar wiring and improving the characteristics of devices).

CO_2 REDUCTION TECHNOLOGY APPLYING ITS

In addition to improving the performance of the main body of a car, reducing CO_2 emissions by utilizing ITS (intelligent transport systems) has been gaining much attention in recent times. An overview of the factors that affect fuel economy and their relevant improvement technologies are shown schematically in Fig. 9. As for the factors that can be handled by ITS, driving operation and traffic conditions are the main ones, and their corresponding technologies are described below.

CO_2 Reduction Through Improvement of Driving Operation

Fuel-consumption performance of a car changes in accordance with the driving operation of its driver. It has been reported that a driving operation in which the accelerator pedal is slowly depressed — without sudden bursts of speed — can improve fuel economy by as much as 20%[13]. In light of that fact, in-vehicle terminal devices that provide tactical driving advice and urge driving that subdues fuel consumption, after analyzing a driver's driving trends, are being developed[14].

CO_2 Reduction by Appropriate Selection of Driving Routes

Giving appropriate directions in response to traffic conditions is one approach being tried to constrain fuel consumption. Hitachi is developing technologies that apply statistical methods and "probe cars" and that precisely forecast trip times. With these technologies, it is possible to present routes to drivers that avoid traffic jams and thereby get them to their destination quickly. Supplied to Nissan Motor Co., Ltd., this technology is being used to provide actual services[15].

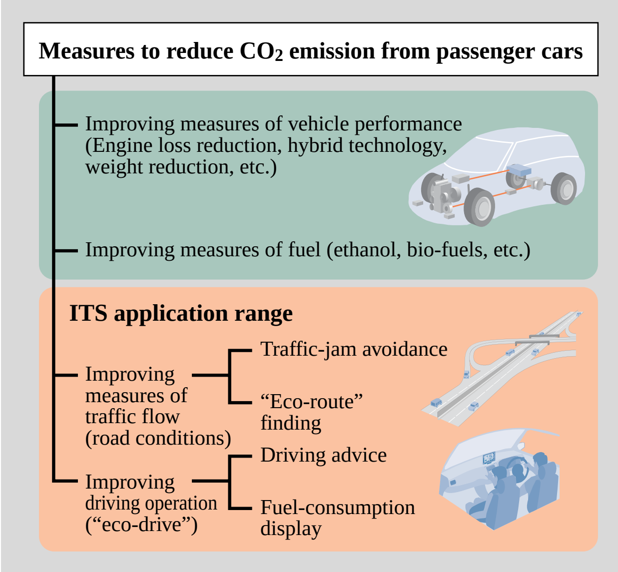

Fig. 9—Contributing Factors Affecting Fuel Economy and Corresponding Improvement Techniques.
In addition to improvements of vehicle performance to reduce CO_2 emission, applying ITS (such as driving advice, fuel-consumption display, and searching for economical routes) also reduces CO_2 emission.

In the future, by means of CO_2-emission forecasting technology that takes into account the geological formation (i.e. altitude difference, etc.), it is thought possible that this technology will evolve toward route guidance that incurs even lower fuel consumption. In the USA, efforts by car manufacturers and local governments aimed at further promoting these technologies are underway[16]. Likewise, Hitachi is propelling continuous technical developments that will further expand traffic-information technology and contribute to reduction of CO_2 emission.

CONCLUSIONS

This report described the three main approaches that Hitachi is focusing on for reducing CO_2 emissions from passenger cars: development of high-efficiency engines, "hybridization" and electrification of drive trains, and application of ITS. As for the car industry, in addition to these three approaches, other approaches — such as improving efficiency of the drive systems that transmit motive energy (including the transmission system), lightening the weight of the car body, and improving fuel economy due to chassis parts — are being worked on comprehensively[17], and it is expected that implementation of various new technologies will continue from now onwards. Hitachi will continue to comprehensively promote a broad range of technical developments for reducing CO_2 emissions from passenger cars.

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