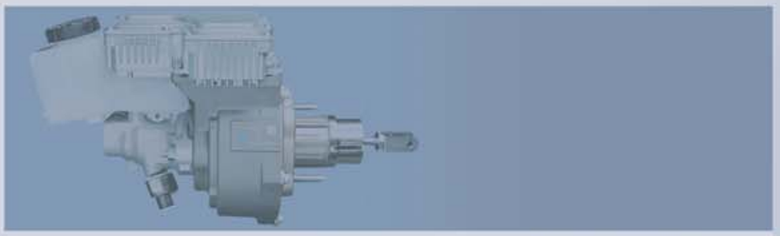
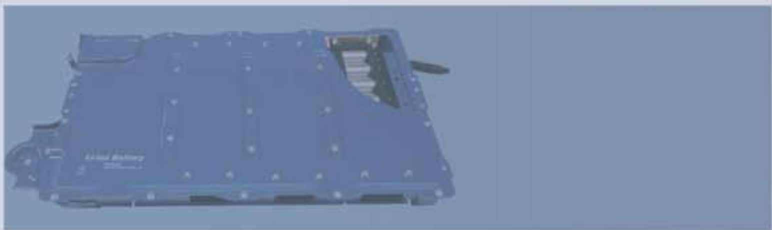
HITACHI
Inspire the Next

HITACHI REVIEW

Volume 63 Number 2 March 2014

Automotive System Technologies for Environment, Safety, and Information





HITACHI REVIEW Carried on the Web

www.hitachi.com/rev

Message from the Planner

HITACHI REVIEW
Volume 63 Number 2 March 2014

In terms of global environment and energy policy, automotive systems have a major role to play in the infrastructure of society, with nations around the world strengthening environmental standards. Meanwhile, the growing number of vehicles on the roads, especially in emerging economies, and the aging of the driving population are creating a need for the wider adoption of safe driving assistance systems. Rapid progress is also being made in the use of information technology to improve comfort and convenience and to add value to vehicles.

Given these circumstances, initiatives are being launched around the world aimed at utilizing advances in electronics and electric drive technologies to build highly efficient internal combustion engines and improve the mileage of electric vehicles, at implementing preventive safety through the use of environmental recognition sensors and chassis control systems technology, and at adopting smart practices for the use of electric vehicles that integrate with the electric power and telecommunications infrastructures.

This issue of Hitachi Review describes what Hitachi is doing to combine advanced technical capabilities in the fields of the environment, safety, and information to generate new value for people, vehicles, and society, and to help create a prosperous society.

The opening article was contributed by Dr. Georg Wachtmeister from the Technical University of Munich, a world leader in the field of internal combustion engines. Other articles look at global trends in automotive system technology; provide an overview of the products and technologies used in systems, components, and services supplied by Hitachi; and consider the outlook for the future.

These articles describe specific products and technologies used in these systems, components, and services. In the environmental field, these include engine management system technologies such as those used in gasoline direct injection systems for compliance with stricter standards, motor control system technologies for electric vehicles, highly efficient electric motors, compact inverters, lithium-ion batteries with high output and capacity, and precision sensors.

In the safety field, articles describe advanced vehicle safety control systems and chassis control systems that optimize vehicle driving, cornering, and stopping.

In the information field, articles describe a service that uses smartphones to provide drivers with information from the cloud that is easy to use, safe, and convenient; security technologies; and smart city initiatives.

Another article looks at techniques for the efficient development of software that is safe and highly reliable, including technologies for functional safety and advanced software verification techniques. I hope that this issue of Hitachi Review will provide readers with useful information on the activities of Hitachi.

Planner for this issue
"Automotive System Technologies for Environment, Safety, and Information"

Toshiharu Nogi
General Manager
Technology Development Division
Hitachi Automotive Systems, Ltd.

expert's commentary

Trends in R&D of Sustainable Vehicle Propulsion

Today's world is beset on one side by the challenges of global warming, on the other by the need to secure energy supplies in the face of diminishing resources. The ongoing increase in global energy demand only aggravates this situation. Vehicles burning fossil fuels in internal combustion engines emit carbon dioxide (CO_2) and consume valuable energy resources. Together with the existing trend toward megacities, this is a key factor that needs to be kept in mind when considering the future of individual mobility. However, there is also a clear trend toward the substitution of fossil energy with renewable energy, something that has the potential to provide a long-term solution.

The many sources of renewable energy include solar energy, wind energy, and biogas produced from biomass or even from microorganisms. Unfortunately, none of these technologies are yet a viable alternative to fossil energy. This needs to be taken into account when looking at trends in the research and development (R&D) of vehicle propulsion systems.

Assuming sufficient electric energy is available from renewable sources, electric mobility (e-mobility) is an attractive option for individual mobility in the future. Unfortunately, the amount of renewable electric power capacity remains small, and even if it were used for electric vehicles (EVs), there would still be a need to generate electricity from fossil sources for industrial and domestic use. Mobile storage of electric energy is another major challenge that has yet to be solved. This means that EVs do not have the potential to become a predominant or widely used propulsion system in the short term. Nevertheless, short-term countermeasures are still needed for the problems of global warming and increasing energy demand. Presently, the most effective short-term measure is to improve existing vehicle propulsion technology. Such opportunities for improving efficiency and emissions continue to exist.

One possibility is a propulsion system that combines an electric motor and internal combustion engine. Vehicles with these hybrid systems are becoming more and more common. The advantages include the capture of regenerative energy during braking and the potential use of the electric motor on its own to propel the vehicle. This results in a zero-emission propulsion system within the context of the vehicle itself, a factor of particular importance in locations where exhaust emissions are a concern. Nevertheless, scope for improvement remains. Further developments are needed in the characteristics of the internal combustion engine and electric motor, and energy storage remains a major challenge.

Another possibility with hybrids is the use of hydraulic energy storage and propulsion. While the durability and efficiency of these systems is good, they only make sense as a means of providing a power boost. The system required for a vehicle powered by hydraulic energy alone would be too big and heavy to be practical. Meanwhile, in addition to propulsion system enhancements, efficiency can also be improved through changes in the mode of operation. If the topology of the intended route is known, for example, the engine control unit (ECU) can predict energy demand and determine the optimal combination of regeneration and electrical or combustion propulsion, thereby achieving the full potential of the hybrid configuration.

More than a century on from the invention of the internal combustion engine, scope for improvement remains. Areas offering potential savings include the fuel, enhancements to the combustion process, and the reduction of parasitic losses. Waste heat recovery is another possibility being intensively studied. Alternative fuels include natural gas, which contains around 20% less carbon than gasoline and therefore emits an equivalently lower quantity of CO_2. A problem with natural gas, however, is that it consists primarily of methane, a much more potent greenhouse

Dr. Georg Wachtmeister

Professor, Chair of Internal Combustion Engines,
Technische Universität München

Professor Wachtmeister began his career at MAN B&W Diesel AG, starting out as technical manager for thermodynamics. He then became team leader for material strength (4-cycle engines) and manager of the Turbocharger Engineering Department. He was ultimately named senior vice president for 4-cycle engine technology. Professor Wachtmeister has been a full professor at TUM since 2004.

gas than CO_2. This means that either measures to prevent methane slip (incomplete combustion) or effective exhaust aftertreatment is required. A big advantage of gas propulsion, whether it be compressed natural gas (CNG), liquefied petroleum gas (LPG), or liquefied natural gas (LNG), is the wide availability of the gas. Reserves are geographically more widespread than oil, and it can also be produced from renewable biomass. Hydrogen is another potential fuel for internal combustion engines. While the combustion process of hydrogen in an engine is well-understood, production, distribution, and in-vehicle storage remain enormous challenges. Yet another approach is to improve the combustion process for conventional liquid fuels. Recent investigations have shown, for example, that optimizing the content of oxygen in the fuel itself can significantly reduce the generation of particles. This offers another way forward for combustion process development.

While the combustion process is already well developed, there are still details that can be improved. One example is the Otto direct injection (DI) engine with central injection. This leads to better mixture formation and thus to better combustion with higher efficiency and lower emissions. Modern calculation methods and highly sophisticated experimental techniques, such as the use of lasers for visualizing combustion progress, generate a lot of knowledge that can be used for improvements. The use of very flexible combustion process management is another key factor in successful development. A fully flexible gas exchange valve control system developed recently can be used to deliver the optimal amount of air into the cylinder at every operating point. Combined with multiple direct injection, this opens up the potential for new and innovative combustion processes, such as Otto homogeneous charge compression ignition (HCCI). While much research is still needed, these innovations demonstrate that considerable scope remains for reducing emissions.

When seeking to achieve 100% conversion of the chemical energy in the fuel into heat, and finally to torque, we also need to consider friction losses. This is a field that has experienced considerable activity in recent years. One well-known approach is to increase specific power output by downsizing. This takes advantage of the effect whereby a higher mean effective pressure increases the ratio between the mean effective pressure and friction losses. The limiting factor with this approach, however, is the increased load it places on engine materials. Thus it is also worthwhile to look at friction losses directly. Besides the ancillary components, the main sources of friction are the bearings, gas exchange valves, and the piston/liner system. Low-friction oils can help, as can optimizing geometries and choice of materials to minimize friction. There is particular scope of improvement in the tribological system formed by of the piston and liner. Continuous improvements are being made in the running surfaces of piston rings, contact pressures, and the shape of the piston skirt. Friction losses are not the only consideration in this work, however, with wear and blow-by also needing to be taken into consideration.

In conclusion, one can state that, in the long term, we need new approaches to ensure individual mobility. EVs are a possible solution but will take time, something that is not available. Therefore it is important to improve existing propulsion systems, namely the different types of internal combustion engine. In the interim, the intelligent combination of electric motors and internal combustion engines is a step in the right direction. The internal combustion engine itself also has further potential for increased efficiency, although it is unlikely that any one measure will bring a major improvement. Rather, what is needed is ongoing work on incremental improvements in various different areas that will sum up to a significant boost in efficiency.

Technotalk

Combining Technologies from Environment, Safety, and Information Sectors to Contribute to Global Society

Atsushi Kawabata Board Director, CTO and General Manager of Technology Development Division, Hitachi Automotive Systems, Ltd.
Yuzo Kadomukai General Manager of Strategic Business Management Division, Hitachi Automotive Systems, Ltd.
Seiji Suga General Manager of Engine Components & Control Brake Design Division, Hitachi Automotive Systems, Ltd.
John Nunneley Assistant to General Manager of Powertrain & Electronic Control Systems Division, Hitachi Automotive Systems, Ltd.
Noriyuki Maekawa Senior Engineer, Advanced Development Center, Technology Development Division, Hitachi Automotive Systems, Ltd.

AGAINST a background that includes global environmental and energy problems, automotive systems are undergoing a major transformation in their role as part of the infrastructure of society. In response to national regulations on vehicle carbon dioxide (CO_2) and exhaust gas emissions, along with other factors such as the growing demand for cars in emerging economies in particular and the wider adoption of safe driving assistance systems developed with a view to the aging of the driving population, Hitachi is picking up the pace of its collaboration with leading research institutions and activities at overseas research centers. Here we discuss these activities, the challenges they face, and the prospects for the future.

Business Climate and Global Operations

Maekawa: In its automotive systems business, Hitachi is striving to contribute to global society through the environment, safety, and information. To begin with, can you please tell us more about the business concepts and management strategies behind these automotive systems.

Kawabata: The business concept of Hitachi Automotive Systems, Ltd. is to combine advanced technical capabilities in the fields of environment, safety, and information to generate new value for people, vehicles, and society, and to help create a prosperous society. In this way, we are seeking to become the world's most trusted global corporation, supplying environmental products in the form of efficient vehicle energy control; safety products that provide safe driving control through the optimal control of vehicle driving, cornering, and stopping; and information products in the form of information and communication solutions that improve comfort and convenience for society.

Our management strategy is to strengthen the foundations of our global management. With recent developments including the tightening of national emission standards, such as those regulating emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulates, and revisions to national new car assessment programs (NCAPs) to strengthen safety requirements, there is a need to comply with these various regional standards in a timely manner. This makes it essential that business decision-making and business operations take place close to the market, and Hitachi is now beginning to operate not only its production facilities but also research and development (R&D) centers throughout the world.

In the case of new technologies such as advanced driver assistance systems (ADASs), meanwhile, Hitachi seeks to develop "tool packages," including platforms, in Japan and then move swiftly to deploy them in other countries. We are accelerating our R&D to deliver more innovative products.

Maekawa: Next, can you tell us about the business climate in which the automotive systems business operates.

Kadomukai: When you look at vehicle production volumes in different regions, it is clear that strong growth is taking place in emerging economies. Such nations accounted for 48% of total production in 2012, and it is anticipated that this will grow to 58% in 2020. In terms of vehicle segments, the proportion of small cars is increasing, being forecast to grow from 62% in 2012 to 65% in 2020, of which about 70% will be destined for emerging markets. A point to note in all of this is that about 80% of vehicle production in emerging economies will be by what are known as "global car manufacturers." This means that Hitachi needs to examine carefully the question of what products and technologies it should be supplying to which regions.

While production of electrically powered vehicles such as hybrid electric vehicles (HEVs) and electric vehicles (EVs) is growing at 13% annually, production of vehicles with internal combustion engines, such as gasoline- and diesel-powered vehicles, is also growing strongly, with these vehicles still expected to account for 94% by volume of total production in 2020. Along with this, it is anticipated that further environmental regulations such as those covering CO_2 and exhaust emissions will progressively be introduced, not only in developed economies but also in emerging ones. Vehicle safety assessments, too, are likely to become more stringent, with requirements extending beyond vehicle collision avoidance to include pedestrian safety.

Kawabata: Taking a broad view of technological trends in the global market, the environmental sector is seeing advances in sophisticated electronics and electric drive techniques, while there remains a need to improve the efficiency of internal combustion engines and electrically powered vehicles. In terms of safety, the objective is shifting from collision safety to preventive safety, with a need to focus on developing exterior recognition sensors and techniques for electronic chassis control in order to build cars that won't crash. In the case of information, I believe that advances are needed in digital technologies for linking vehicles to the outside world in order to improve comfort and convenience, and to add more value to vehicles. In other words, a fusion of information technology (IT), vehicles, and social infrastructure will be absolutely necessary.

Nunneley: Currently, the automotive market can be thought of as two separate growth markets in developed and emerging economies respectively, each of which demands different technologies. In developed markets like Japan, Europe, and North America, development is proceeding on advanced technologies, visual recognition systems, automatic parking, and automatic cruise control (ACC). In emerging markets on the other hand, there is growing demand for low-cost suspension, lightweight electronic stability control (ESC) units (anti-skidding systems), and products for small vehicles. These two markets appear set to continue their respective growth into the future.

Unification of Customer Strategies Regional Strategy of Local Production for Local Consumption

Maekawa: Given this environment, Hitachi has adopted a three-pronged global growth strategy consisting of a customer strategy, regional strategy, and product strategy. Can you first tell us about the customer strategy.

Nunneley: Our basic customer strategy is to pursue the three key pillars of environment, safety, and information. This closely matches the strategies of the major vehicle manufacturers. As part of this strategy, Hitachi appoints global account managers (GAM) to oversee its dealings with each of the major global vehicle manufacturers. This has allowed us to maintain an accurate and timely appreciation of our customers' business strategies. GAMs have the important role in more accurately ascertaining user needs.

Kawabata: Global vehicle manufacturers operate both production facilities and development centers throughout the world, and it is not uncommon for development work to take place outside its target market. Our customer strategy allows us to keep up with these developments around the world, and can be seen as the first step toward supplying better solutions to customers.

Maekawa: I understand that "local production for local consumption" is an important feature of Hitachi's regional strategy.

Nunneley: That's right. Because global vehicle manufacturers operate development centers around the world, we also need to build up our development centers at a global level. We are currently working on doing just this in the fields of vehicle tuning and the simulation and analysis of suspension and brakes. Similarly, to support global vehicle manufacturers, we intend to strengthen our design and development capabilities by increasing our global

Atsushi Kawabata

Board Director, CTO, and General Manager of Technology Development Division, Hitachi Automotive Systems, Ltd.

He has worked in Hitachi' s automotive systems group, Industrial Systems Transportation Systems Division, Mechanical Engineering Research Laboratory, and Rail Systems Company prior to taking up his current appointment in 2013.
Mr. Kawabata is Accounting Director of the Society of Automotive Engineers of Japan (JSAE) and a member of the Society of Instrument and Control Engineers (SICE), The Institute of Electronics, Information and Communication Engineers (IEICE), Information Processing Society of Japan (IPSJ), The Institute of Electrical Engineers of Japan (IEEJ), and The Japan Society of Mechanical Engineers (JSME).

development workforce by 240% by 2015.

Product Strategy Involving Ongoing Global Standardization

Suga: Our product strategy includes work on building the next generation of environmental and safety systems, a key feature of which is standardization at the global level. An apprehension when technical development is conducted globally is that product designs and production processes will diverge, resulting in poor manufacturing practices. A key factor in avoiding this is modular design.

Nunneley: When modular design is used, designs can be put together on a global scale, allowing manufacturing to take place at any production site, no matter where in the world it is located. In the case of electrically controlled brakes (e-ACT), for example, sharing a standard core design means that the same design can be adapted for use in different models, ranging from small cars all the way up to comparatively large vehicles such as pickup trucks. This means that the system can be manufactured at brake production facilities around the world simply by changing the motor torques and ball screw mechanisms while keeping to the same core design.

Suga: Modular design is also used for valve timing control (VTC). By first studying the engines of customers around the world, we were able to narrow down to a small number of different types of VTC, and make it so that the provision of flexibility in the interface with customer engines was enough on its own to produce optimum results. Progress on standardization is being made not only in product design but also in the production machinery itself. To achieve this, we are producing more of our equipment in house, and have established production machinery facilities in China and the USA. To ensure quality, we are also working on the centralized collection of quality information from production sites around the world, and its collation in multi-lingual databases. This has given us the capability to share quality information globally.

Nunneley: Enhancing our system design capabilities is another major initiative that relates to product development. Suspension, brakes, and steering, once mechanical parts, have since become extremely complex systems. This is because they incorporate electronic control units (ECUs) and software, communicate between systems, collect data from the different actuator systems, and use these as the basis for control. Even brake and steering systems are no longer simple parts. Whereas brake systems of the past were limited to stopping the vehicle and operating the brake lights, they are now evolving into integrated vehicle systems with functions that include preventing skidding or operating in conjunction with external recognition sensors to brake automatically if a potential collision is detected. Enhancing our capacity for this type of system design so that we can keep ahead of other major suppliers is another important initiative that Hitachi is pursuing in the context of design. We need to be more than just a supplier of parts.

Kawabata: As you say, whereas the automotive systems business of Hitachi to date has focused on the supply of parts, in the future we need to supply new value in the form of packages that combine parts and involve a variety of different functions working together. Software modularization is an essential element in achieving this. By shifting to a development style that uses standard components for base technologies and then overlays these with only those additional features that vehicle manufacturers require for differentiation, our aim is to shorten development lead times, reduce costs, and supply products that are highly finished.

Yuzo Kadomukai

General Manager of Strategic Business Management Division, Hitachi Automotive Systems, Ltd.

He is currently engaged in business strategy for the automotive systems business. Dr. Kadomukai is a member of the JSAE.

Seiji Suga

General Manager of Engine Components & Control Brake Design Division, Hitachi Automotive Systems, Ltd.

He is currently engaged in the design and development of engine and controlled brake parts.

Growing Proportion of Products that Incorporate Electronics

Maekawa: What about products that incorporate electronics, another important sector?

Kadomukai: Electronics are essential for making cars with better fuel economy for the benefit of the environment and with safety features to prevent collisions. It seems likely that the proportion of products that incorporate electronics will continue to grow in the future. Hitachi, too, sees these products as a key axis in its growth strategy.

Nunneley: With its many years of experience in manufacturing products such as ECUs and electric motors, Hitachi is well placed for integrating electronics into vehicle systems such as brakes or suspension.

Kawabata: With Hitachi having divisions that develop advanced technologies such as navigation systems and car navigation units that use communications for realtime interoperation with the outside world, we can supply a full range of various different types of systems.

I believe that simulation will become increasingly important in the development of these electronics products. A variety of new approaches are being adopted, including full-vehicle analyses and simulating the operation of platforms that include microcontrollers. In response, Hitachi has installed supercomputers at its Japanese sites and is developing systems that provide secure and high-speed access to these from development centers around the world.

Maekawa: While integrated systems need to satisfy both safety and economic requirements, development would be very time-consuming if we needed to produce a new prototype each time we wanted to test these. This means that computer-based design will also play an increasingly important role in reducing the costs from prototyping through to product development.

Training the Workforce of the Future

Maekawa: What about the development of the personnel who underpin the automotive systems business?

Kawabata: People are the most important component of technical development. Our challenge for the future is to get the most out of our workforce in all parts of the world, not just by sending out people from Japan, but also by measures such as bringing staff to Japan for training. To achieve this, I want us to strive to augment and train locally recruited development and management staff. I also believe we should be strengthening our relationships with our R&D divisions, overseas research institutions, engineering companies, and universities with strong automotive programs.

Nunneley: In the future, each region will require capabilities such as application engineering, vehicle tuning, and simulation so that they can perform their work in ways that suit local circumstances in accordance with customer expectations. Achieving all of this from Japan would be difficult. This is why we have augmented our engineering capabilities in China. We also need to be able to customize vehicles, powertrains, and other products to meet the requirements of vehicle manufacturers in the USA, Europe, India, and elsewhere.

Kawabata: This is because requirements differ significantly between regions. Different markets have very different characteristics, such as demand for ultra-small cars in Japan and vehicles featuring advanced technology in Europe, and the large and diverse market in America. Regulations and other laws also differ. While Hitachi is a Japanese company with core technology developed in Japan, I believe that customizing this technology for applications that satisfy the requirements of different regions is something that can only be done in the regions concerned.

John Nunneley

Assistant to General Manager of Powertrain & Electronic Control Systems Division, Hitachi Automotive Systems, Ltd.

He is currently engaged in the design and development of electronically controlled brake systems and preventive safety systems.

Noriyuki Maekawa

Senior Engineer, Advanced Development Center, Technology Development Division, Hitachi Automotive Systems, Ltd.

He is currently engaged in the design and development of engine system and components.

Furthermore, it seems likely that the number of customized applications will continue to grow. Taking the example of stereo cameras sold in Japan and North America, the specifications in each market are different. Naturally, the amount of work required at each site will increase as the number of customized products grows. To ensure that this proceeds smoothly, I believe that Japan's role is to make sure that the underlying technology is fully worked out, and to establish practices that will allow simple customization.

Nunneley: Stereo cameras make a good example. People in each region need to decide for themselves how they are to be used, and then create the framework for doing so. This is because a stereo camera is no more than a sensor, and given that laws, road markings, and customs are different in each region, it can be used in a variety of ways. It also means that a way of passing this information back to the stereo camera design team in Japan is vital.

Kadomukai: In this sense, there is considerable significance in having Mr. John Nunneley with us given that his former responsibility was for development in the USA. We can increase the development and other business capabilities in each region by having their top developers lead core development in Japan, and then take this knowledge back to their own markets.

Nunneley: In pursuing this approach, we also need to develop engineers who can avoid parochialism and look at issues from a global perspective. This is because the products that Hitachi designs and markets are sold to people from all over the world.

I believe it will be of significant benefit to Hitachi if we can bring people from Europe, China, and North America into the groups that handle core development and design so that these groups can incorporate knowledge from all parts of the world into their products from the basic design stage.

Maekawa: Finally, can you give me your views on the outlook for automotive technology.

Kawabata: Above all else, I believe that, rather than considering products individually, we will need to adopt viewpoints that are closer to the customer, such as "comfortable driving" or "safe and secure driving." In the future, it is likely that systems will work by taking the intentions of the driver, as transmitted via the steering wheel, brakes, and other controls, and then have a computer assess the surrounding conditions and determine how best to control the vehicle. The ultimate objective is to have vehicles drive themselves without requiring a human driver. I look forward to Hitachi supplying the parts and systems that will make this possible, while also engaging in debate that looks to the future.

Suga: We also should not forget about more routine measures. Taking the ongoing challenge of improving fuel economy as an example, this is an area where Hitachi is working on a number of different fronts. These include the transmission efficiency of the powertrain, energy recovery and storage, and of course weight reduction, which remains an important consideration.

A lot of attention is being directed at measures for reducing the weight of different systems or parts.

Kawabata: In this sense, there is no escape from ongoing routine development aimed at wringing out yet more gains. I expect to see unpredicted breakthroughs emerge from the linking together of components. As a corporate group, Hitachi supplies not only car parts but also services such as data centers and communication systems. This is a major strength.

Nunneley: Another feature of Hitachi is that it is one of the few car parts suppliers, perhaps even the only one, able to handle all aspects of hybrid electric vehicle systems, including inverters, electric motors, and batteries. I want us to keep working on initiatives that will allow us to utilize these strengths to achieve significant growth and become the world's most trusted global corporation.

Global Business Development of Hitachi Automotive Systems

Yuzo Kadomukai, Dr. Eng.
Tomiya Itakura
Takayoshi Komai
Jumpei Komatsu

AUTOMOTIVE SYSTEM BUSINESS ENVIRONMENT

THE global vehicle market is expected to maintain strong annual growth of 3.2% by volume over the period between 2012 and 2020 (see Fig. 1).

By region, 0.8% annual growth in mature markets is predicted to be accompanied by annual growth of 5.5% in emerging regions, which are expected to account for 58% of global production by volume in 2020, up from 48% in 2012 and a forecast of 53% in 2015.

By vehicle segments, the proportion of small vehicles is expected to rise from 62% in 2012 to 65% in 2020. By power train, production of electric drive systems such as hybrid electric vehicles (HEVs) or electric vehicles (EVs) is expected to increase by 14.7% annually between 2012 and 2020. Despite this, growth in production of vehicles with conventional petrol or diesel internal combustion engines (ICEs) is also expected to grow strongly, and to still account for 94% of total volume by 2020.

Meanwhile, environmental regulations, safety testing standards, and other regulatory requirements are being strengthened around the world (see Fig. 2). Stronger combustion and exhaust gas regulations are also being adopted for things like carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulates, with standards in emerging regions expected to rise to levels similar to those in mature markets. At the same time, rules on vehicle safety testing are being tightened and extended to include pedestrian safety as well as vehicle collision avoidance.

Amid these developments, Hitachi operates globally to meet the needs of vehicle manufacturers who are grappling with environmental and safety technology while also seeking to expand their businesses in growing emerging regions.

OVERVIEW OF HITACHI AUTOMOTIVE SYSTEMS

In a push to become a major global player in the automotive system business, Hitachi Automotive

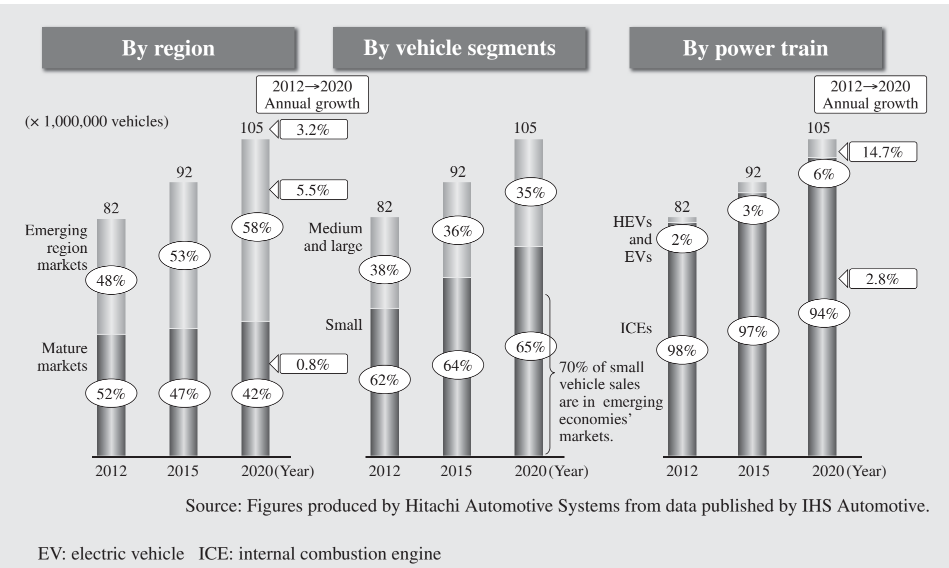
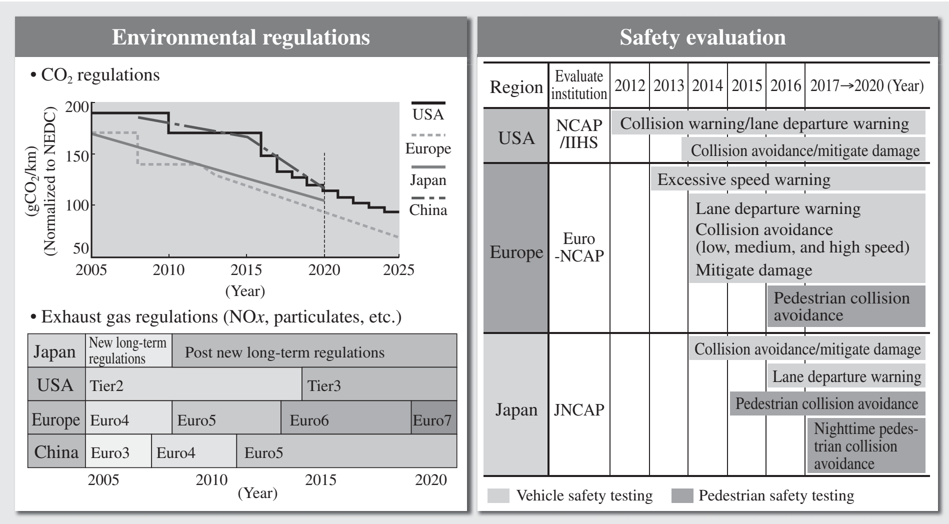


Fig. 1—Forecast Global Vehicle Production 2012–2020.
By market and vehicle type, strong growth in production volumes is anticipated in emerging regions (including Asia and South America) and small vehicles. By power train, while production of electric vehicles is expected to increase significantly, it is forecast that vehicles with ICEs will still account for 94% of production in 2020.



CO_2: carbon dioxide NEDC: New European Driving Cycle NOx: nitrogen oxides
NCAP: New Car Assessment Program IIHS: Insurance Institute for Highway Safety
JNCAP: Japan New Car Assessment Program

Fig. 2—Changes to Environmental Regulations and Safety Testing Standards.
Stronger environmental (combustion and exhaust gas) regulations are being adopted for things like CO_2, NOx, and particulates. Meanwhile, rules on vehicle safety testing are being tightened and extended to include pedestrian safety as well as vehicle collision avoidance.

Systems, Ltd. is transforming itself into an organization with a global market focus in which business decisions and operations take place closer to the market. Its business operations cover a wide range, including environmental products, such as engine management systems and hybrid systems; safety products, such as stereo cameras, suspensions, and brakes; information products, such as the car navigation systems from Clarion Co., Ltd.; and industrial machinery (see Fig. 3).

Since the global financial crisis that struck in the fall of 2008, Hitachi Automotive Systems, Ltd. has undergone a business restructuring that has included the rationalization of fixed costs as it sought to enhance its Monozukuri manufacturing capabilities and build an organization based on global earnings management. These efforts have been underpinned by the basic policies of a self-driven, earnings-focused management approach; faster decision making; a shift to a business structure suitable for global markets; and new integrated management of the company that transcends the boundaries within the organization. In addition to the adoption of a regional headquarters structure for overseas operations in FY2011, the company has also accelerated its shift to global operations through initiatives such as expanding its activities in emerging economies, establishing a global sales organization, strengthening research and development, standardizing manufacturing practices globally, implementing operational reforms, and developing staff.

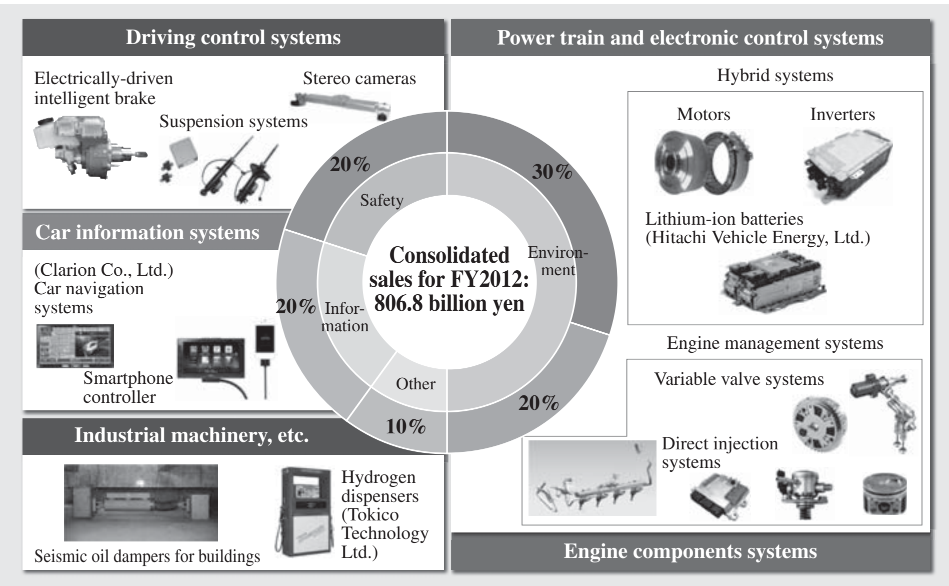


Fig. 3—Overview of Hitachi Automotive Systems, Ltd.
FY2012 sales were 806.8 billion yen, of which the environmental sector contributed approximately 50%, safety approximately 20%, information approximately 20%, and industrial machinery approximately 10%.

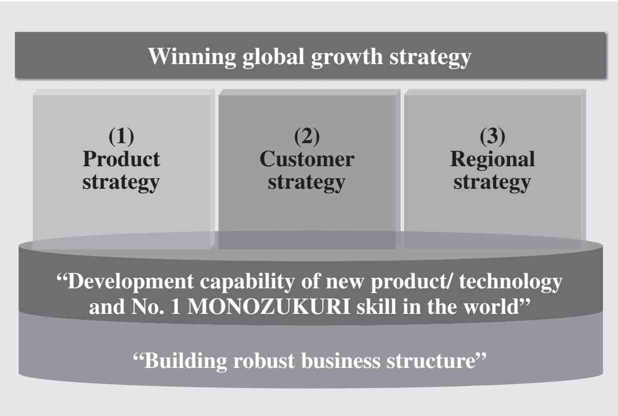


Fig. 4—Global Growth Strategy.
On the basis of three growth strategies focusing on products, customers, and regions, Hitachi is working on building a robust business structure, and on strengthening its manufacturing capabilities and the new product and new technology development capabilities that support these strategies.

Fig. 5—Winter Performance Testing at Tokachi, Hokkaido, in Japan.
Ongoing vehicle testing is conducted under a variety of environmental conditions at test tracks in Japan and elsewhere under different weather conditions and terrains.

IMPLEMENTATION OF GLOBAL GROWTH STRATEGY

The three pillars of Hitachi's global growth strategy are products, customers, and regions. The product strategy is based on offering next-generation environmental and safety systems that contribute to society. The customer strategy involves strengthening Hitachi's ability to support automotive manufacturers as they move toward globally standardized vehicle platforms and power trains. The regional strategy, meanwhile, uses a "local production for local consumption" business model as the basis for growth.

To provide the business infrastructure to support this strategy, Hitachi is seeking to implement policies of "building a robust business structure" and "development capability of new product/technology and No. 1 MONOZUKURI skill in the world" (see Fig. 4).

The development of new products and technologies is the basis of growth. To this end, Hitachi's plans include acceleration of the implementation of projects managed directly from global headquarters; these projects will form the core of future business activities, while also utilizing key Hitachi technologies and involving joint research with universities outside Japan. To boost its ability to develop vehicle systems, Hitachi also intends to improve actual vehicle/machine testing environments by setting up and using resources such as engine test beds and test tracks (see Fig. 5).

The following sections describe the specific actions planned for various aspects of the global growth strategy.

PRODUCT STRATEGY BASED ON NEXT-GENERATION ENVIRONMENTAL AND SAFETY SYSTEMS THAT CONTRIBUTE TO SOCIETY

As advances in environmental and safety technology lead to larger and more complex systems, the importance of "electronic and motorized" technology (meaning the use of electronic control systems and electric motors) is growing. As part of this trend, automotive products suppliers with expertise in this "electronic and motorized" technology are taking on broader development responsibilities.

Hitachi is placing particular emphasis on the development of next-generation systems that contribute to society in the environmental and safety areas. Hitachi is also continuing to increase the proportion of products that incorporate electronics, and is globally standardizing products that have a core role in the system.

In this way, things like safety improvements and the regional optimization of energy management are facilitated through use of information technology for integration with social infrastructure (see Fig. 6).

CUSTOMER STRATEGY BASED ON MEETING NEEDS GLOBALLY

As they expand their operations in emerging regions, automotive manufacturers seek to achieve competitiveness by standardizing global platforms and pursuing economies of scale. In response to this trend, Hitachi Automotive Systems, Ltd. established new regional headquarters in 2011 to provide customers in each region with a single point of contact and establish

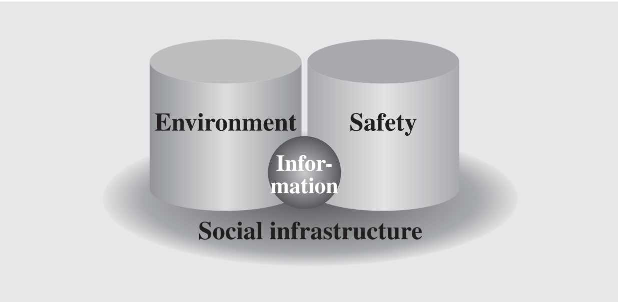


Fig. 6—Hitachi Automotive Systems, Ltd. Businesses.
In addition to focusing on development in the environmental and safety sectors, Hitachi is also seeking to use information technology for integration with social infrastructure.

a structure that allows the business to be optimized in terms of customers and regions.

In response to the accelerating globalization of automotive manufacturers, Hitachi moved to full-scale deployment of global account manager (GAM) and global account team (GAT) activities in 2012 to meet customer needs in ways that span regional and national borders. Specifically, GAMs act as leaders for business inquiries that relate to production facilities in different regions or countries. In this case, the GAM sets up a cross-regional GAT to deliver the best technologies, products, and solutions while maintaining a shared awareness of the sales growth strategies and other information relating to the customer, the automotive manufacturer.

A new sales engineering department was also set up in 2011 to boost the company's capacity for collecting and analyzing the increasingly complex and diverse needs of customers, and to strengthen its ability to propose solutions based on consideration of both the needs of the customer and the resources of the company.

REGIONAL STRATEGY BASED ON MAKING GREATER USE OF "LOCAL PRODUCTION FOR LOCAL CONSUMPTION"

In response to the globalization of the automotive industry, Hitachi is accelerating its expansion into emerging regions. In addition to operating facilities around the world, it is also expanding the scale of its business operations outside Japan.

As part of this approach, the regional headquarters manage their respective regions with the aims of achieving speedier management through faster and local decision-making, and operating their businesses in ways that are deeply integrated with the local region and well-adapted to its characteristics and other needs.

Specifically, Hitachi has established a global business structure based on a "five key regions operation," the five regions being Japan, which has a global corporate role, the regional headquarter of US, and the respective headquarters for China, Asia, and Europe (see Fig. 7). This regionally based management structure means that businesses are operated locally, including among other things the increasing assignment of local managers to senior management roles at the regional headquarters.

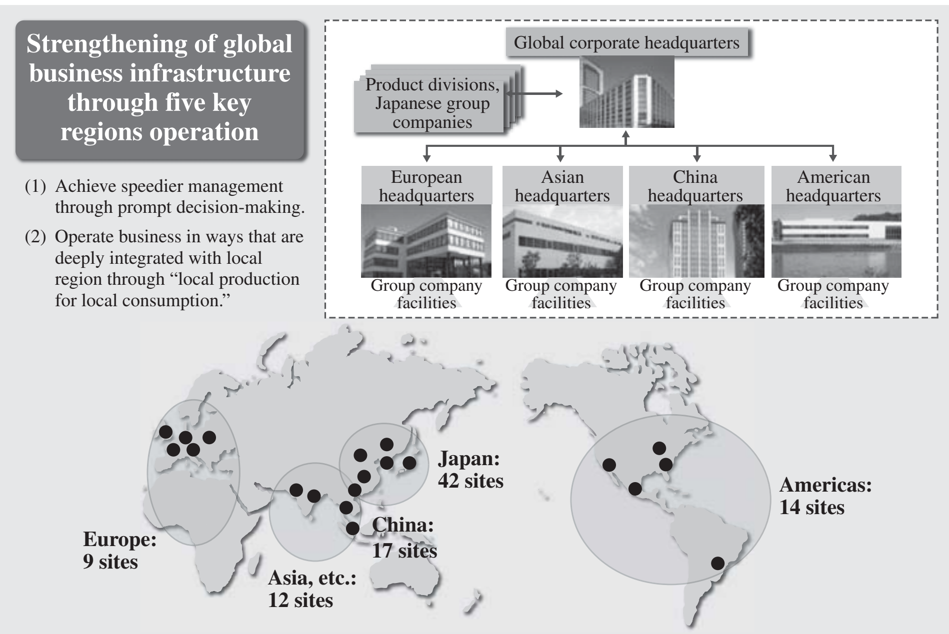


Fig. 7—Five Key Regions Operation and 94 Sites Located throughout the World.
Hitachi is working toward "local production for local consumption," with an organizational structure based on five key regions. These consist of the regional headquarters in the Americas, China, Asia, and Europe, and the global corporate headquarters in Japan.

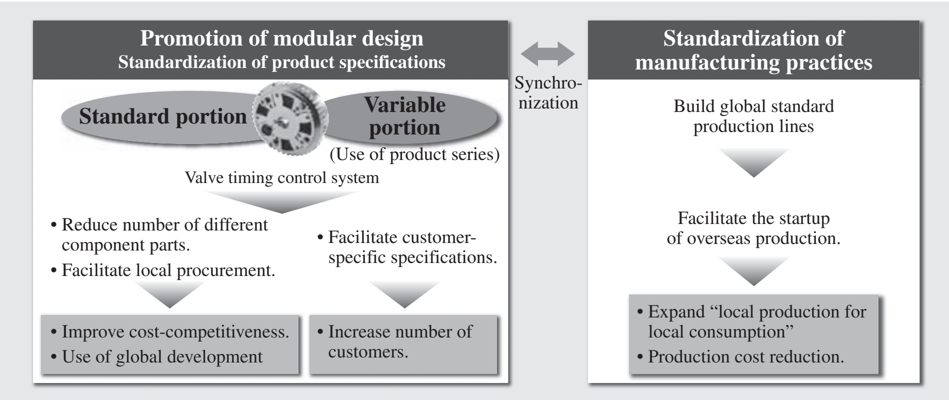


Fig. 8—Global Standardization of Products and Manufacturing Practices.
By combining use of modular design with the standardization of manufacturing practices, Hitachi is seeking to speed up the shift to "local production for local consumption" and cut production costs.

Hitachi Automotive Systems, Ltd. operates 94 sites around the world, with the number of production facilities located in emerging regions increasing from 19 in FY2008 to 23 in FY2011 (with new facilities having been opened in China, the Czech Republic, and India) and 27 in FY2012 (including the establishment of new subsidiaries in China, India, and the United Mexican States). Meanwhile, Hitachi is also considering setting up new operations in countries where it currently has sales staff stationed, including the Federative Republic of Brazil, the Russian Federation, and the Republic of Indonesia.

STRENGTHENING BUSINESS INFRASTRUCTURE FOR GLOBAL GROWTH

Adoption of Global Organizational Structures for Functional Departments

To speed up decision-making and to optimize and manage its global operations, Hitachi Automotive Systems, Ltd. has reorganized its functional departments, which include manufacturing, information systems, material procurement, and quality assurance.

In the case of quality assurance departments, the global corporate division is responsible for governance and formulating overall policy while the departments based at factories in Japan and elsewhere have responsibility for achieving the Key Performance Indicators (KPIs), such as those that deal with daily production activities. As part of this, Hitachi has set up a global quality assurance committee made up of members representing each region. The committee works with the quality assurance departments at the regional operating companies to strengthen global governance.

Hitachi has also introduced a Global Quality and Incident information Control system (G-QUICs) for quality innovation; the system centralizes quality, customer, and other information so that it can be shared at a global level and actions implemented quickly.

Global Standardization of Products

In its manufacturing activities, Hitachi is utilizing modular design and working toward the standardization of production technology to help deliver products in a timely manner that meets customer needs at a competitive price and quality (see Fig. 8).

By increasing the extent to which products follow standardized specifications, modular design helps minimize the number of different component parts and facilitates the use of local procurement and production. In order to standardize production technology, meanwhile, scalable low-cost production lines are being developed that can keep pace with the growth in emerging region markets. Mechanisms are also being put in place to facilitate the establishment of overseas production systems. The objectives of these two measures are to make significant cuts in production costs and to expand the use of "local production for local consumption" at production facilities located in the markets they serve.

Hitachi has also established new production equipment divisions in Japan, the USA, and China so that it can increase the in-house and local production of equipment based on the "Global One Design" approach.

Operational Reforms

Restructuring operations to suit global business practices is essential to achieving optimal production at international facilities that take orders from corporate customers located around the world.

To accomplish this, Hitachi is working on reforms that extend beyond just its global production management and encompass all business processes, including development, design, production engineering, procurement, and sales. One example is how the use of high-speed simulation systems has significantly reduced the time needed to prepare production plans.

To strengthen production management at the global level, Hitachi has also set up the new Global Production Control Center (GPCC). This organization has the job of establishing rules and other mechanisms for optimal global production and getting them adopted at all facilities within the group.

Global Human Resource Development

Along with the expansion of its production facilities around the world, Hitachi also set up the Global MONOZUKURI Center in 2012 to strengthen its capabilities, including global production engineering and equipment maintenance. It has also adopted human resource development initiatives, including expanding its program for bringing key personnel from its overseas operations to Japan for training. This offers long-term postings at Japanese facilities, not only to senior personnel such as local factory managers and executives, but also to mid-level staff from departments such as design, production engineering, procurement, sales, and planning.

Other initiatives currently in progress include global grading and the use of a global personnel database set up by Hitachi for the flexible recruitment of senior staff from across the group.

CREATING NEW VALUE FOR PEOPLE, VEHICLES, AND SOCIETY

This article has described the main measures being adopted in the global operations of Hitachi Automotive Systems, Ltd. Through these measures, Hitachi is meeting customer needs by responding appropriately to the progressive globalization of the automotive industry. Hitachi is also putting effort into enhancing its brand, including promoting its leading edge technologies though activities such as its sponsorship in the IndyCar Series and exhibits at motor shows around the world.

The Hitachi Automotive Systems group intends to work together and exhibit teamwork, and to continue contributing to the realization of a prosperous society through the creation of new value for people, vehicles, and society, with customer satisfaction at the forefront.

ABOUT THE AUTHORS

Yuzo Kadomukai, Dr. Eng.

Strategic Business Management Division, Hitachi Automotive Systems, Ltd. He is currently engaged in strategy planning for the automotive systems business. Dr. Kadomukai is a member of the Society of Automotive Engineers of Japan (JSAE).

Tomiya Itakura

Strategic Business Management Division, Hitachi Automotive Systems, Ltd. He is currently engaged in management strategy for the automotive systems business. Mr. Itakura is a member of the JSAE.

Takayoshi Komai

Business Planning Department, Strategic Business Management Division, Hitachi Automotive Systems, Ltd. He is currently engaged in management planning for the automotive systems business.

Jumpei Komatsu

Business Planning Department, Strategic Business Management Division, Hitachi Automotive Systems, Ltd. He is currently engaged in management planning for the automotive systems business.

Role of Overseas R&D in Expanding Global Automotive Business

George Saikalis
Harsha Badarinarayan
Yoichi Sugita

OVERVIEW: In the recent past, there has been a strong initiative within Hitachi to expand our business to a much broader, more diverse, and emerging global market. The Hitachi Automotive Division is one such business group that sees the potential to diversify our customer portfolio globally so that we are competitive in markets that we have not explored in the past. In this regard, strong collaboration with overseas R&D will be the key for fast product development, quicker time-to-market, and the building of stronger relationships with local customers. There is an effort to form a 'Global One Team' within Hitachi comprising R&D facilities around the world, including in Japan, Europe and the USA, that will enable business units in those geographical locations to accelerate their product development and be at the cutting edge of technology by providing solutions for site-specific issues through organic growth and collaborations with leading universities. This article gives an overview of our current global R&D activities in some of these overseas labs, highlighting our key technologies and long-term commitment to our customers.

INTRODUCTION

THE aim of realizing a truly global Hitachi operation would require the different entities, including both business groups and research and development (R&D) facilities, that are spread across the globe to be aligned towards a common goal. In order to transform the 'strong business in Japan' into a 'winning business in the global market,' to achieve the targets set out in the 2015 Mid-term Management Plan, and to drive the strategic growth of the Hitachi Group, it is essential that concrete measures be taken to enhance collaboration between overseas and domestic business and R&D.

This article describes R&D activities in the area of automotive technology that are being carried out in Europe and the USA. The final goal of 'global' collaboration is that technology should be made available to all Hitachi group companies, regardless of where it is developed, to ensure efficient use of resources and to enhance the capabilities of each R&D facility through collaboration.

RESEARCH ACTIVITY IN EUROPE (TEEL/AUTOMOTIVE)

The Transportation, Energy and Environment Research Laboratory (TEEL) was established in October 2005 and has offices in Germany and the UK. TEEL's mission is to support automotive, train, and energy businesses in Europe and world-wide by utilizing state-of-the-art technologies through joint research projects with universities and consortia, as well as contributing European advanced technology to Hitachi's R&D network.

Germany is known as the birthplace of the automotive and as an automotive technology leader in Europe and, possibly, worldwide. The acquisition of cutting-edge technology from Europe will help Hitachi to be competitive in the global market. In this context, TEEL has established long-term collaborations with the Technical University of Munich (TUM) in the field of engine combustion technology and with Forschungsgesellschaft Kraftfahrwesen mbH Aachen (fka) in the development of chassis control technology and driver assistance systems.

Engine Combustion Technology

In order to mitigate global warming and reduce harmful emissions, regulations affecting the automotive industry will become stricter worldwide. European regulations are among the strictest. To cope with this and to provide the necessary solutions, European universities and research institutes have become leaders in the understanding of internal combustion engine technology.

Hitachi started collaborative research with TUM in 2009. TUM is one of the leading European universities in the field of engine combustion. The main objectives are the development of advanced combustion simulation technology and combustion control systems by using sophisticated measurement systems and by applying advanced design capabilities to new experimental devices.

TUM has built a single-cylinder research engine using Hitachi components, such as different types of fuel injectors, a high pressure fuel pump, and a variable valve system. The engine can run in spark ignition (SI) and homogeneous charge compression ignition (HCCI) modes, and is used to analyze the combustion process and measure emissions (see Fig. 1).

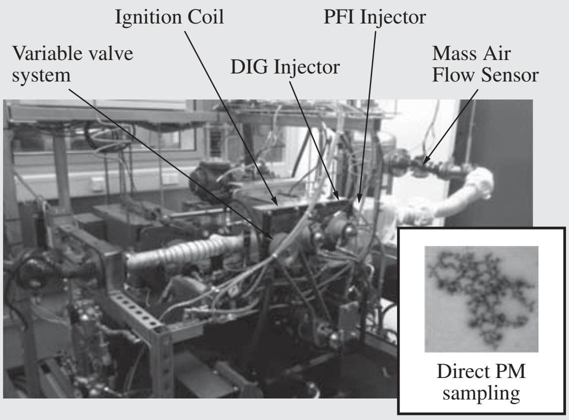
Using TUM's particulate matter (PM) sampling probe, which is capable of extracting PM directly from the combustion chamber, various PM measurements were taken and subsequently analyzed with a scanning electron microscope (SEM). The results of this work were then used in the further development of combustion simulation technology.

Combustion simulation technology can be used to design fuel supply components and in system control. For these purposes, Hitachi and TUM have developed three-dimensional combustion simulation technology for estimating the amount of particulate matter generation in direct-injetion gasoline (DIG) engines. Analyzing the mechanism for PM generation in DIG engines requires more detailed modeling than conventional PM estimation models, which are mainly used in the simulation of diesel engine combustion. This is because the amount of PM produced by a DIG engine is considerably less than that from a diesel engine. Therefore TEEL and TUM jointly developed a detailed chemical PM reaction model (see Fig. 2). Finally, to reduce simulation costs, a framework was developed that links the detailed chemical PM reaction model to the three-dimensional combustion simulation technology. This uses a PM generation rate database derived from a detailed chemistry model.

The next steps are to develop combustion concepts with next-generation technologies led by Europe. These include a central mount injection system, high-pressure fuel supply system, and variable valve system, and are intended for achieving compliance with future CO_2 regulations around 2020.

Chassis-motion Control Technology

To improve vehicle performance in terms of the environment, safety, and driver experience, it is important not only to improve each component, but also to develop a new chassis-motion control system that can assist the driver during routine driving. In this context, TEEL is focusing on the development of a



PFI: port fuel injection PM: particulate matter
DIG: direct injection gasoline

Fig. 1—Single-cylinder Research Engine at TUM.
The engine includes Hitachi components and is used to conduct combustion analysis and emission measurements for simulation model development.

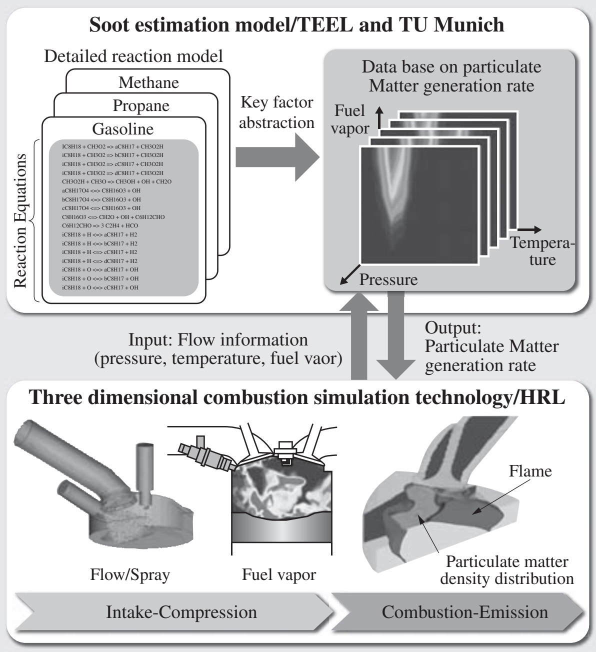


Fig. 2—Three-dimensional Combustion Technology for Analyzing Mechanisms of Particulate Matter Generation.
TEEL and TUM have developed a detailed reaction model and a framework that links the detailed chemical model and three-dimensional combustion simulation technology.

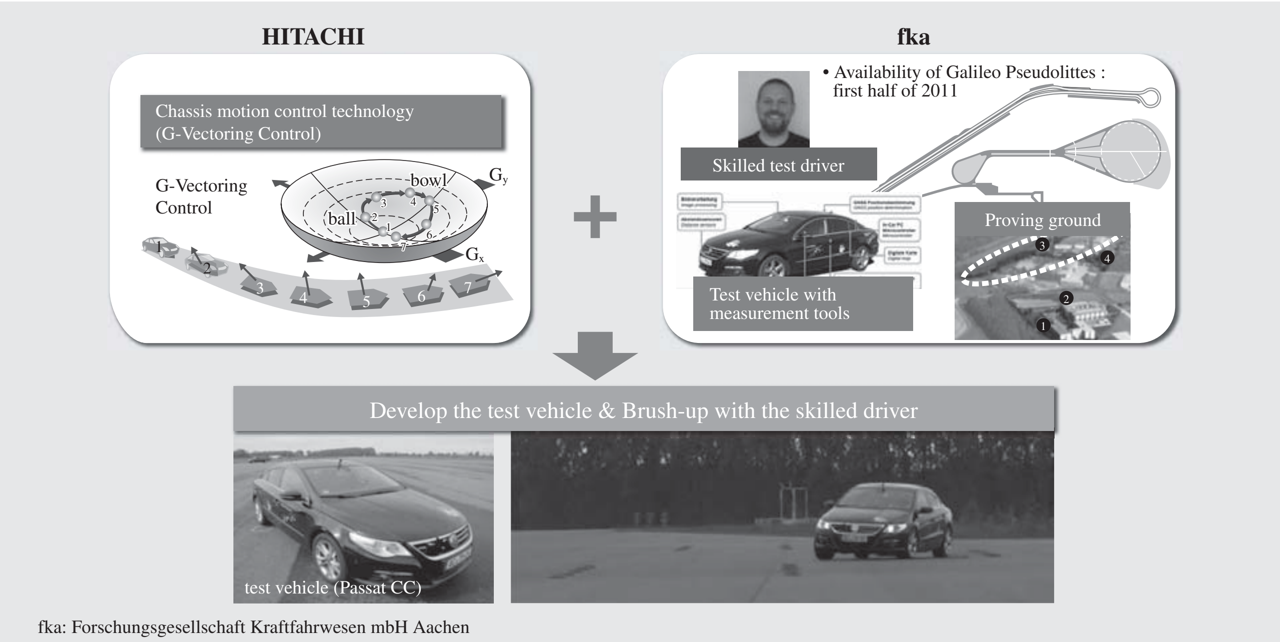


Fig. 3—Overview of First Project (Evaluation of G-Vectoring Control in Germany).
A Volkswagen Passat CC test vehicle with G-Vectoring Control was evaluated by a skilled driver in Germany.

human-inspired driver assistance system that is based on a control algorithm derived from a skilled driver. This is intended to improve driving quality, not only during routine driving, but also over a wide range of speed and weather conditions (highway speeds and conditions such as heavy rain, snow, or fog).

The first step was an evaluation of Hitachi's G-Vectoring Control (GVC)[1] chassis motion control system by fka in Germany (see Fig. 3). Founded in 1981 as a spin-off from the Institut für Kraftfahrzeuge of RWTH Aachen University (ika), fka is a leading engineering company in the field of automotive technology. In this project, Hitachi provided the GVC algorithm, which controls longitudinal acceleration in coordination with lateral motion and seamlessly changes the direction of the resulting acceleration on a "g-g" diagram, and fka provided the test vehicle (a Volkswagen Passat CC), a skilled test driver, and their proving ground.

The test driver tested the performance of GVC in cornering and obstacle avoidance (elk test) on dry-asphalt[2]. The test results indicated that use of GVC for deceleration control improved vehicle agility and helped prevent understeer during cornering and obstacle avoidance (see Fig. 4). The test driver also commented that deceleration under GVC provided more time for avoiding the markers and made vehicle control easier. These results indicate that use of GVC for deceleration control helps avoid obstacles without reducing driver comfort under German conditions.

RESEARCH ACTIVITY IN NORTH AMERICA (APL)

Automotive Products Research Laboratory (APL), Hitachi America R&D's first laboratory, was opened back in 1989 in Michigan. APL is a corporate research lab and is involved in research on a wide range of products in collaboration with Hitachi Automotive Systems Americas (HIAMS) AM. APL is strategically located close to the main US automotive customers fostering a close interaction for engineering, research and direct interfacing with local customers. Its

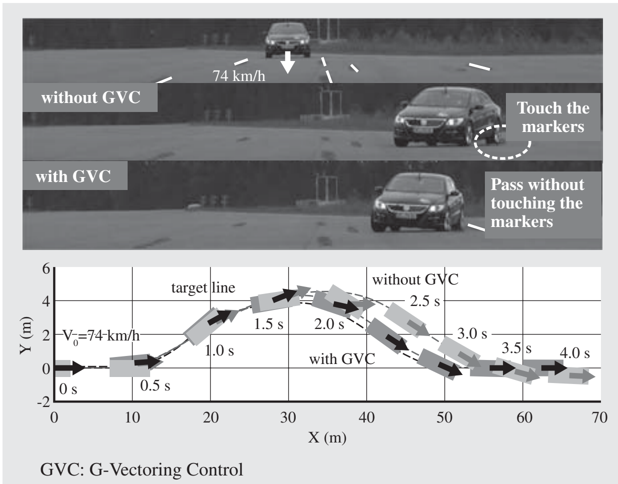


Fig. 4—Result of evaluation test in Germany.
Double lane change test called "elk test" was performed as the evaluation test of GVC. GVC could improve the obstacle avoidance performance without discomfort.

technical work covers the introduction of new concepts for electronic and mechatronic vehicle systems and the provision of 'solution-oriented' R&D. Activities include projects on embedded system development for automotive controllers; system modeling; engine research; chassis and suspension activity; materials research; noise, vibration, and harshness (NVH); and electromagnetic compatibility (EMC). The following sections consider two important research areas at APL in detail: (a) The development of virtual hardware-in-the-loop systems for greater product robustness, and (b) A computational approach to materials engineering for automotive component design.

Virtual Hardware-in-the-loop Simulation (vHILS) for Robust Automotive Product Design

The biggest challenge faced by the next generation of automotive electronic control units (ECUs) is the increasing complexity that results from the large number of interconnected ECUs and the increasing amount of software executing on them. It is not unusual for a luxury vehicle to have several dozen ECUs with several million lines of embedded software code. Ensuring the robust design of such complex systems, especially from a tier 1 supplier's perspective, requires advanced hardware and software validation methods. Products must also comply with the automotive functional safety standard (ISO26262) introduced in 2011. This is becoming a standard requirement from our automotive original equipment manufacturer (OEM) customers.

Advances in simulation technology and multi-domain simulation tools have driven the adoption of model-based development (MBD) as a mainstream development process, especially during the design phase of product development. Following the traditional 'V-cycle' development process, software development and validation proceed through a series of MBD processes, starting from a model-in-the-loop simulation (MILS), and proceeding to software-in-the-loop simulation (SILS), processor-in-the-loop simulation (PILS), and finally hardware-in-the-loop simulation (HILS).

HILS systems are usually very expensive and involve significant hardware and labor costs to operate. They are also characterized by the separation of observation and operation, which can make it difficult to correlate a problematic software behavior with its impact on the physical system. It is also difficult to reproduce error states when dealing with fault injection and failure mode and effects analysis (FMEA) for testing product reliability. In order to deal with these HILS issues, APL has been developing a virtual HILS system. As the name suggests, this involves implementing the complete HILS system virtually on a high-performance personal computer (PC) (see Fig. 5).

In comparison with HILS, which combines a real hardware ECU with a simulated physical system (plant model), vHILS uses a simulation model of the ECU itself with a low level of abstraction, including a high-fidelity model of the microcontroller that can

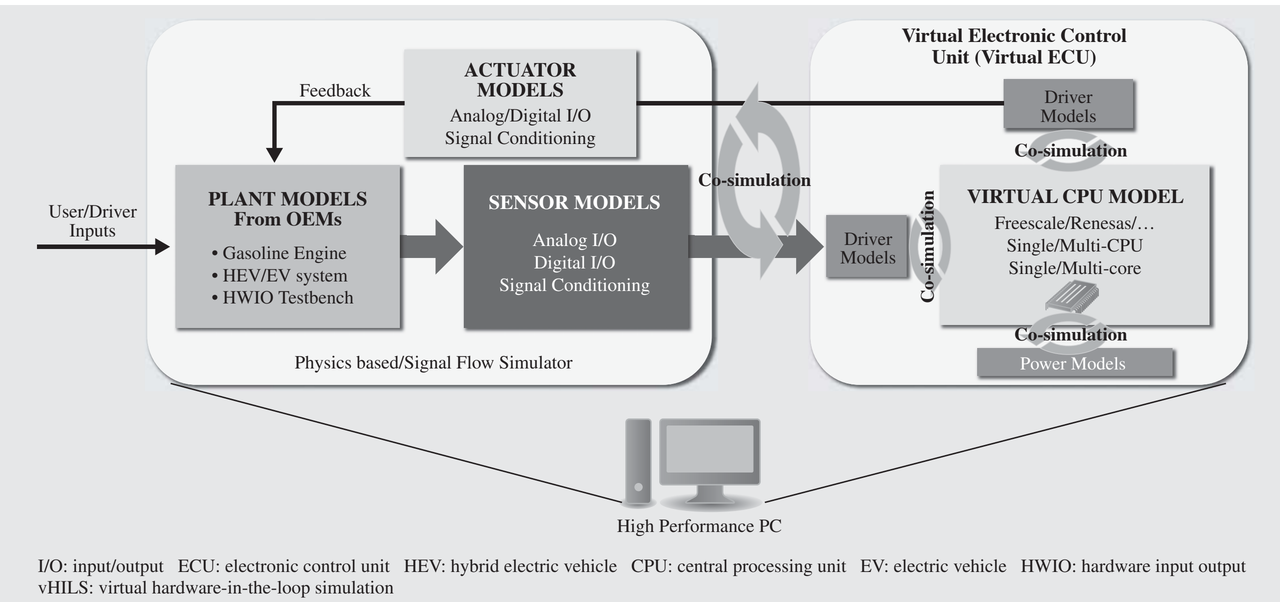


Fig. 5—vHILS.
Workflow for vHILS implementation.

execute the same production-grade software as the real ECU. The plant models used in the HILS system are reusable, and use co-simulation technology to interface with the ECU model. APL has proven expertise in co-simulation technology, with successful projects involving international co-simulation in which models are run across multiple research labs.

vHILS technology offers several benefits, including fully virtualized HILS, easy duplication of simulation environments, detailed target visibility (visualization of hardware and software execution), and automation. It also provides an environment for virtually testing functional safety compliance and a tool for fault injection and virtual FMEA (vFMEA). From a tier 1 supplier's standpoint, the vHILS approach can be placed within the existing controller development cycle as shown in Fig. 6.

When the traditional approach is used, hardware or board-level problems can go undetected during the design stage, not appearing until HILS testing in the validation phase. The OEMs may also request that changes be incorporated late in the design stage. Both of these can result in large time and development costs for hardware redesign, as indicated by the red feedback arrows in Fig. 6. On the other hand, the vHILS approach allows software validation to take place early in the design stage itself and potentially eliminates the time taken for hardware redesign and the associated development costs. It also provides an opportunity to provide feedback to the OEM about their specification early in the design phase. This may be necessary, for example, if an error in the specification looks like it may cause the product to function inappropriately in the system.

It is important to note, however, that this does not eliminate the need for HILS testing in the validation phase, which is typically performed by the OEM at their facility in collaboration with the tier 1 supplier. This process involves a real test of the actual product. Rather, the value of vHILS lies in its allowing early software validation and helping reduce the overall time to market by detecting hardware-related faults early. Fig. 7 shows an example of how use of vHILS reduced the development time for an adaptive cruise control system to be supplied to a Japanese OEM.

Computational Approach to Materials in Automotive Component Development

Automotive components usually experience a complex deformation history during service. The nature of the load and how the material responds are key factors in improving the design of a component for specific applications such as service life. Most materials research for new component development adopts an empirical or trial and error approach. Computational tools such as finite element methods have been widely adopted and have proved beneficial in many areas such as mechanical engineering.

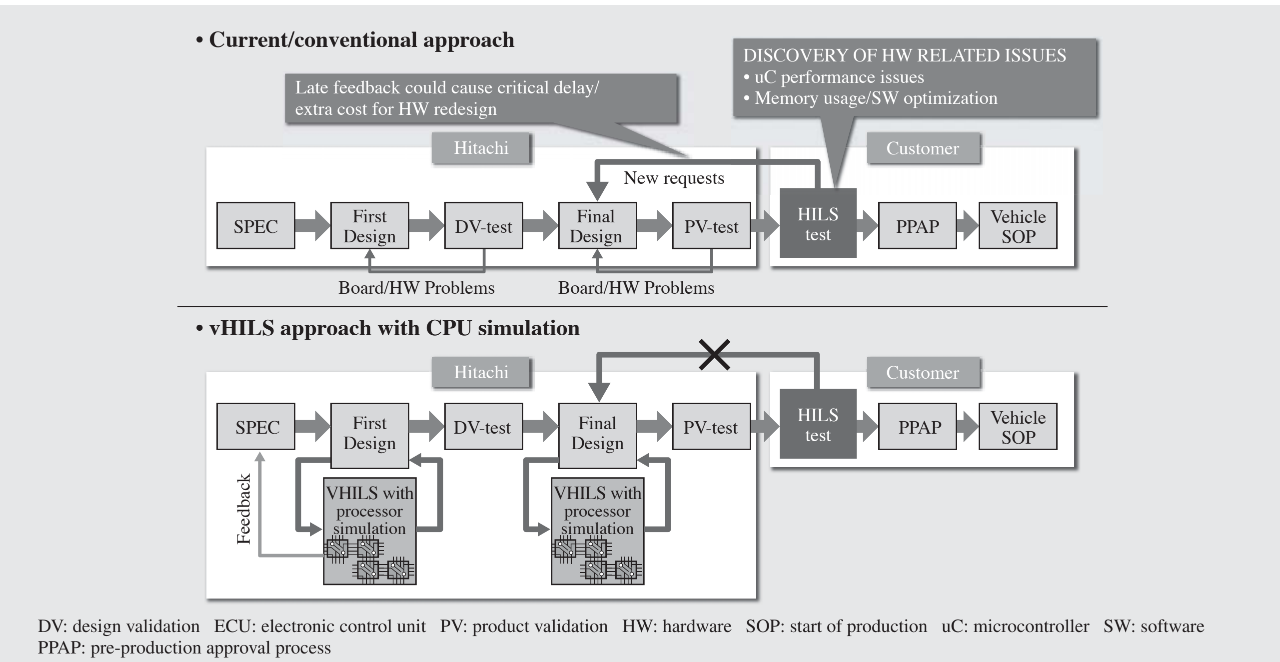


Fig. 6—Benefits of vHILS and its Role in Controller Development Cycle.
vHILS approach ensures no delay in hardware implementation at the customer's end.

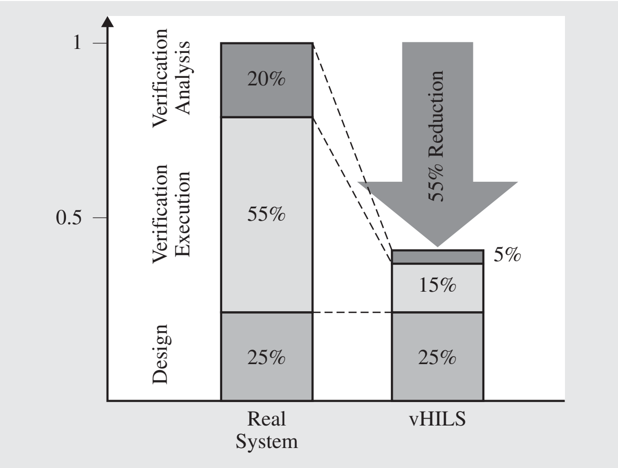


Fig. 7—Reduction in Development Cycle Time.
Reduction in development time can translate to improved profitability.

However, computational tools have yet to be widely used in materials engineering, not only because of the complexities of materials over different scales, from nanometer to meters, but also because there has been a lack of effort aimed at using computational tools in materials development.

APL has embarked on research into the simulation of deformation in materials or components using a combination of advanced computational tools and theoretical materials science, specifically a technique called the crystal plasticity finite element method (CPFEM). With the objective of predicting the non-uniform deformation behavior of automotive components, APL is developing a mesoscale simulation methodology that uses CPFEM to analyze component deformation under uniaxial and multi-axial loads. The two different modes of material deformation are elastic and plastic deformation, each of which has different characteristics. In CPFEM, the stress-strain gradient is assumed to arise solely from crystalline slip during plastic deformation, and from lattice stretching, rotation, and rigid body motion during elastic deformation. The plastic strain rate is thus calculated from a summation of slip rates over all slip systems, appropriately weighed by the tensor products of their respective slip directions and the normal to the slip plane. For a given slip system, the slip rate is related to the resolved shear stress by a postulated flow rule, such as the power law form in the classic Peirce-Asaro-Needleman model. The slip strength, meanwhile, is governed by a hardening equation which may depend on the slip strains in all slip systems (see Fig. 8).

Consider, as an example, predicting the surface shear strain distribution during uniaxial tensile loading of polycrystalline austenitic stainless steel 316 with a random crystal orientation. Fig. 9 shows how a miniature dog bone model is constructed and further meshed. Only the gage section is modeled using CPFEM, with the Mises-Plasticity law being used for the remaining material. The gage section consists of 375 cubic grains, each of which is assigned a set of crystal plasticity parameters (the values are the same as in Ref.[3]) and a random crystal orientation. One end of the specimen is completely fixed, while a uniform tensile stress is applied on the other end. Fig. 9 shows the cumulative shear strain due to crystalline slip

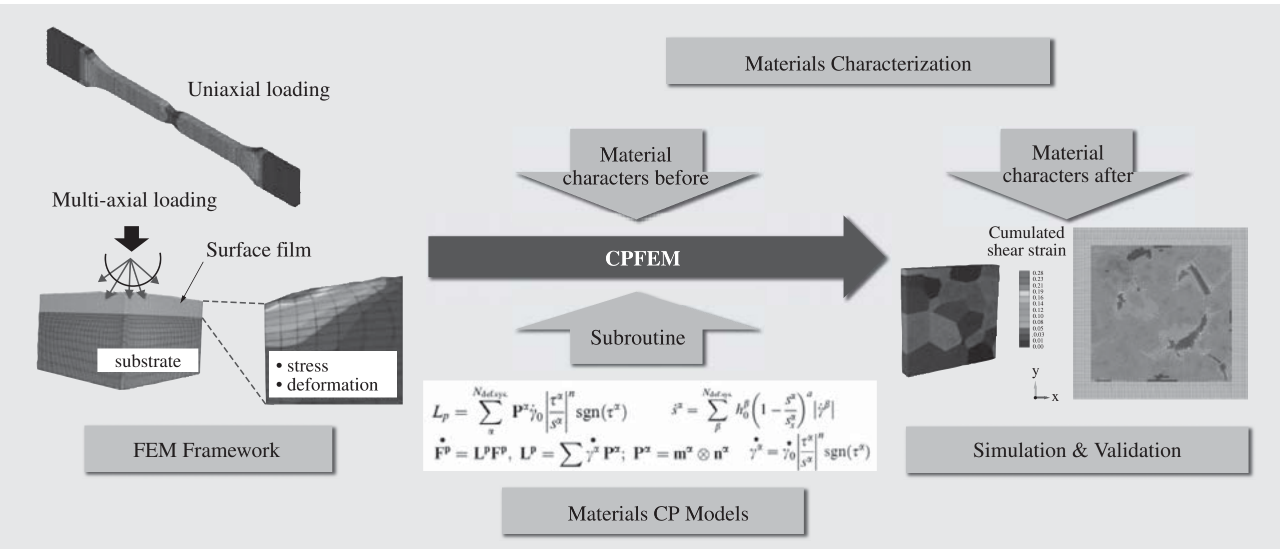


Fig. 8—Overview of Research into Deformation Simulation Using CPFEM.
APL will implement this methodology to support future product designs.

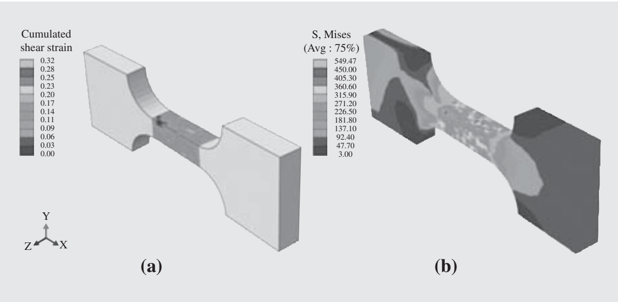


Fig. 9—CPFEM Model for Simulating Uniaxial Tensile Testing.
The SUS316 material is assumed to have a random crystalline orientation. The results show: (a) cumulative shear strain over all slip systems in the gage section, and (b) Mises stress over the whole specimen.

and the Mises stress contour for a certain level of deformation.

CPFEM is seen as a powerful tool for predicting and interpreting material deformation behavior. While the above simulation assumes a random orientation and uses assumed grain shapes and sizes, it demonstrates the ability of CPFEM to be used for mesoscale simulation.

CONCLUSION

This article has described some of the advanced automotive R&D activities that are underway in Europe and the United States.

A wide range of research activities have been explained in detail, including spray pattern analysis and combustion research, chassis dynamics and control, vHILS implementation for product development, and the use of computational analysis for materials engineering. Hitachi will also have the opportunity to participate in 'global Tokken' projects which help achieve synergies between the goals and research topics at different R&D facilities within Hitachi.

One of the major benefits of having operations around the globe is that different regions can strive to become a 'center of excellence' in specific technical areas. This can benefit the company as a whole if this expertise can then be shared among different research and business groups worldwide to create a truly 'global' collaboration. In any large conglomerate, such as Hitachi, it is often the case that the same or similar type of work (in terms of research) may be carried out by different groups who may not be in communication with each other. This is an inefficient allocation of resource, time, and money, and does not add value. Instead, the ideal is to have a global collaborative effort that maximizes our available resources and minimizes redundancies, while also contributing to social innovation. This would enable Hitachi to provide cutting-edge technology to our customers while keeping a step ahead of our competitors.

REFERENCES

(1) M. Yamakado et al., "G-Vectoring, New Vehicle Dynamics Control Technology for Safe Driving," Hitachi Review **58**, pp. 346–350 (Dec. 2009).

(2) J. Takahashi et al., "Superior Driver Handling Performance Using a "G-Vectoring" Braking Assistance System," 21st Aachener Kolloquium Fahrzeug- und Motorentechnik 1, pp. 727–748 (2012).

(3) LL Zheng et al., Scripta Mater 2013; 68:265

ABOUT THE AUTHORS

George Saikalis, Ph.D.
Research and Development Division, Hitachi America, Ltd. He is currently Vice President engaged in many aspects of automotive R&D. Dr. Saikalis is a member of IEEE and SAE.

Harsha Badarinarayan, Ph.D.
Research and Development Division, Hitachi America, Ltd. He is currently Sr. Researcher & Group Leader engaged in automotive R&D. Dr. Badarinarayan is a member of ASME and SAE.

Yoichi Sugita, Dr. Eng.
Research and Development Division, Hitachi, Ltd. He is currently engaged in management of the Transportation, Energy and Environment Research Laboratory.

Engine Management System for Compliance with Different Environmental Standards

Minoru Osuga
Yoshinori Ichinosawa
Takuya Mayuzumi

OVERVIEW: The remainder of this decade will see a tightening of automotive environmental standards around the world. The situation is becoming more diverse, including the international standardization of driving test modes, tighter rules on particulates for gasoline-powered vehicles, and CO_2 incentives. Hitachi Automotive Systems, Ltd. is developing engine management systems to suit different needs. Systems for reducing CO_2 emissions include engine downsizing systems, engine control systems that allow higher compression ratios, and stop & start systems that extend the length of time the engine is stopped. Remarkable advances are also being made in the fuel injectors, variable valve mechanisms, starters, controllers, and other components used in these systems.

INTRODUCTION

ENVIRONMENTAL standards covering carbon dioxide (CO_2) and exhaust emissions are set to be tightened over the remainder of this decade. In addition to the convergence of regulatory levels, there is also a trend toward the standardization of things like driving test modes and CO_2 incentives. To comply with these new standards, engine management systems need to be developed based on conditions and perspectives different from those in the past.

This article describes advances in engine management systems that comply with environmental standards from around the world.

GLOBAL ENVIRONMENTAL STANDARDS AND SYSTEMS FOR COMPLYING WITH THEM

Fig. 1 shows an overview of the changes in global automotive environmental standards and the development of engine management systems. While Europe has been taking the lead in CO_2 standards, it is anticipated that North America, too, will adopt equally stringent rules. Also under consideration is the standardization of the different driving mode stipulations that have applied in Japan, the USA, and Europe [Worldwide Harmonized Light Duty Driving Test Cycle (WLTC)], and of the modes that are based on actual driving conditions [Real Driving Emission (RDE)]. Another possibility is greater use of compressed natural gas (CNG) in different parts of the world after 2020, prompted by the production of shale gas, particularly in North America.

Particulate number/particulate matter (PN/PM) standards for exhaust emissions are also becoming tighter. Europe is leading the world in this area, with the Euro 6c standard for PN being particularly stringent. As the standards will also cover direct injection of gasoline (DIG) engines, complying with these rules is an urgent task.

The figure also shows work on engine management system development. Hitachi sees the development of highly efficient engine systems and engine management systems as central to this work.

In the area of emissions reduction, there is an urgent need for ways of improving PN/PM performance in highly efficient DIG engines, as described above. Hitachi has succeeded in adopting higher compression ratios to improve efficiency through better anti-knock performance using pistons and DIG, and is working on the development of engine downsizing systems based on DIG and the associated high boosting technology. The key features include a wide dynamic range of DIG that supports high boosting and a cooled exhaust gas recirculation (EGR) control technique for anti-knock. Developments aimed at the future implementation of lean-burn combustion and homogeneous charge compression ignition (HCCI) are also in progress.

In the area of energy management, meanwhile, progress is being made on the adoption of electric drive systems and the variable control of pumps that reduce friction in auxiliary systems. Hitachi is also developing technology for the regeneration of energy to charge the battery during deceleration that works

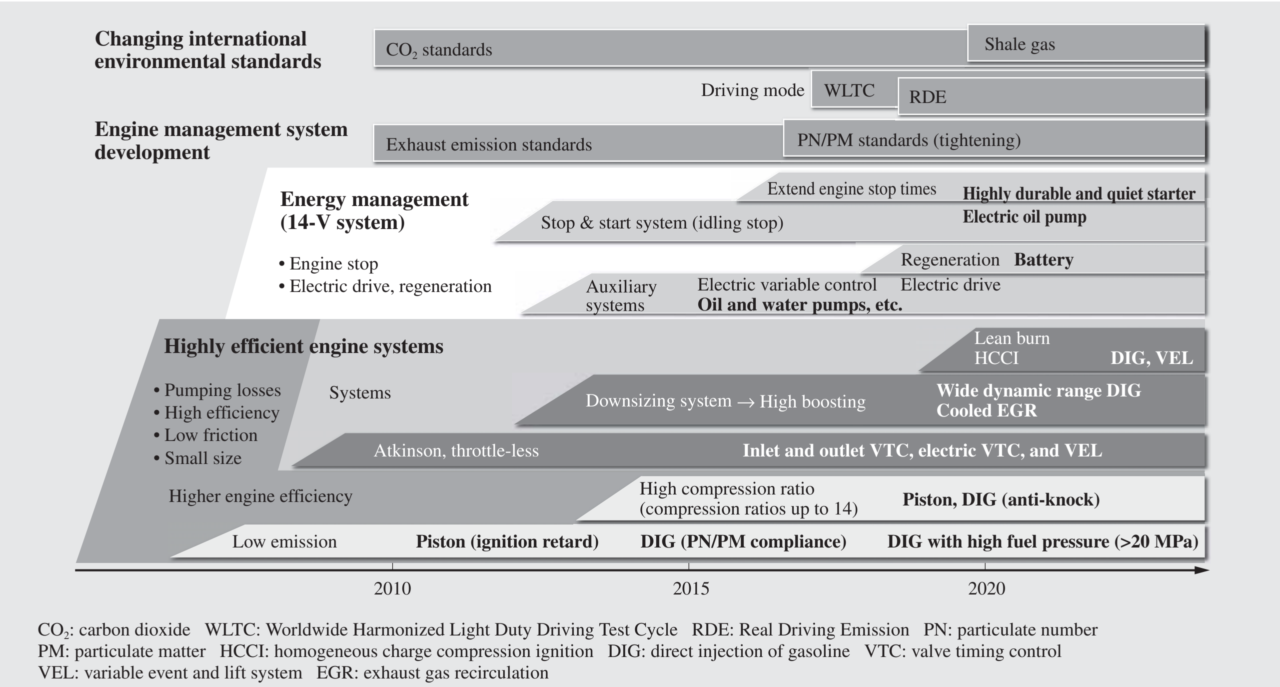


Fig. 1—Development of Engine Management Systems to Reduce CO_2 Emissions.
In addition to regulatory requirements, there is a trend toward the globalization of driving test modes and CO_2 incentives. The strengthening of PN/PM standards has added urgency to the development of systems that can comply with these rules. Hitachi is developing systems for reducing CO_2 emissions that are based on engine efficiency improvements and energy management.

with electric drive systems. Greater use is being made of idling stop, and future systems will extend the length of time the engine is able to stop.

DEVELOPMENT OF ENGINE SYSTEMS FOR REDUCING CO_2 EMISSIONS

This section describes the development of systems for highly efficient engines and energy management. Hitachi develops DIG systems that work with high boosting and high compression ratios and feature reduced PN/PM levels and improved anti-knock performance (see Fig. 2). The former uses a quick-response multiple injection technique that injects fuel up to five different times during each intake stroke to achieve a homogenous air-fuel mixture in the combustion chamber. The key technologies for this are injectors with a wide dynamic range and the drive circuits and electronic control units (ECUs). These technologies are combined with a short penetration spray and higher fuel pressures (20 MPa, currently 15 MPa) to comply with the tighter standards.

Cooled EGR and a piston cooling system are used to improve anti-knock performance. To measure the large pulse flow that results from EGR, a bi-directional type of silicon (Si) mass air flow sensor (MAFS) is used together with an inlet pipe pressure sensor to perform precise measurement of the EGR ratio. Also, precise control of the amount of EGR is achieved by using quick-response electric valve timing control (VTC) and an electrically controlled throttle body.

Hitachi also supplies a small ignition coil with high energy output that improves combustion strength when using EGR. Piston cooling for better anti-knock performance is achieved by incorporating cooling channels into the pistons and using a variable-capacity oil pump to control cooling based on operating conditions.

Fig. 3 shows a stop & start system for energy management and technologies for use with electric drive systems. To reduce CO_2 emissions by stopping the engine for a longer time, the idling stop system has been enhanced to create a system that can also stop the engine during deceleration and normal driving. To avoid discontinuity when restarting the stopped engine, Hitachi has developed a starter with high durability, quiet operation, and improved meshing performance. Because battery management is required if stopping the engine for a longer time, Hitachi has responded by developing a regenerative battery system that supports electric drive of equipment together with state-of-charge (SOC) control.

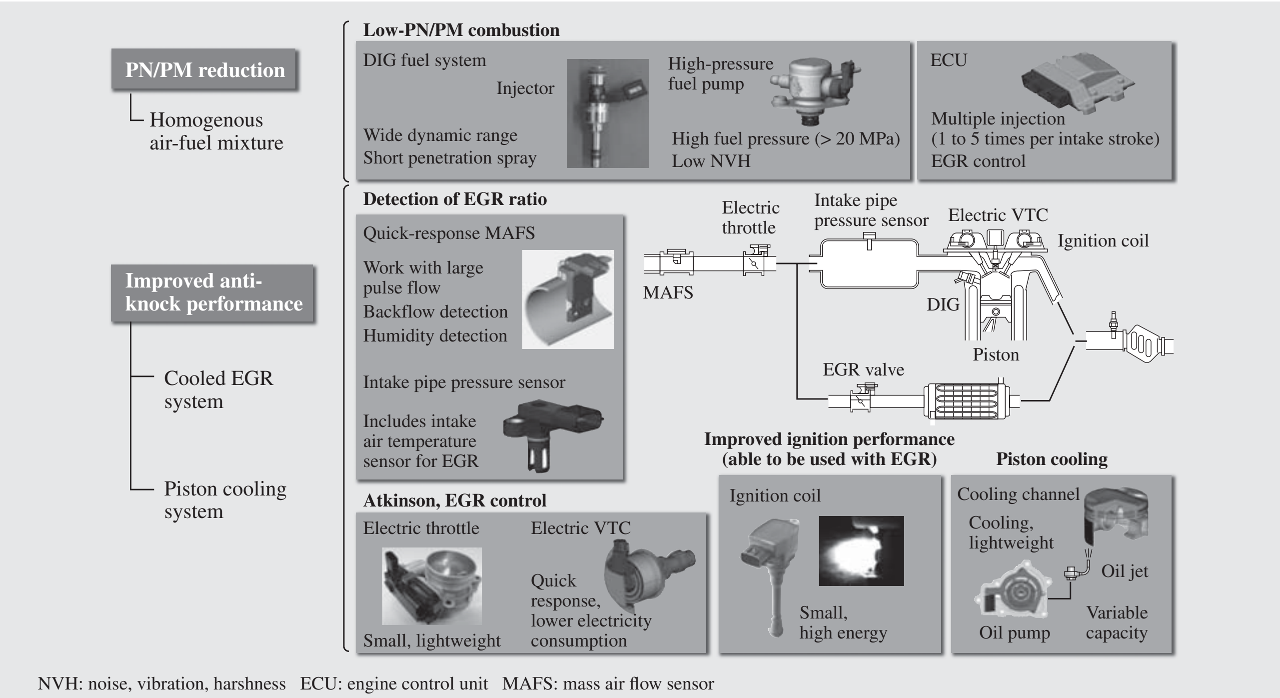


Fig. 2—DIG System for Compliance with Different Environment Standards.
The DIG system features use of high boosting for engine downsizing and to reduce PN/PM, and anti-knock technologies that work with high compression ratios.

NEXT GENERATION OF COMPONENTS

DIG Injector and Drive Control

This section describes DIG fuel systems, electric VTC, and starters for stop & start operation. These are key next-generation components.

Fig. 4 shows a DIG injector that complies with PN/PM standards, and its associated benefits. Achieving a homogenous air-fuel mixture and preventing the adhesion of fuel to the combustion chamber walls are key factors in reducing PN/PM levels. Accordingly, Hitachi has improved the multi-hole nozzles and shortened the spray penetration depth. The low-PN spray has a significantly shorter penetration depth for producing a highly homogeneous spray.

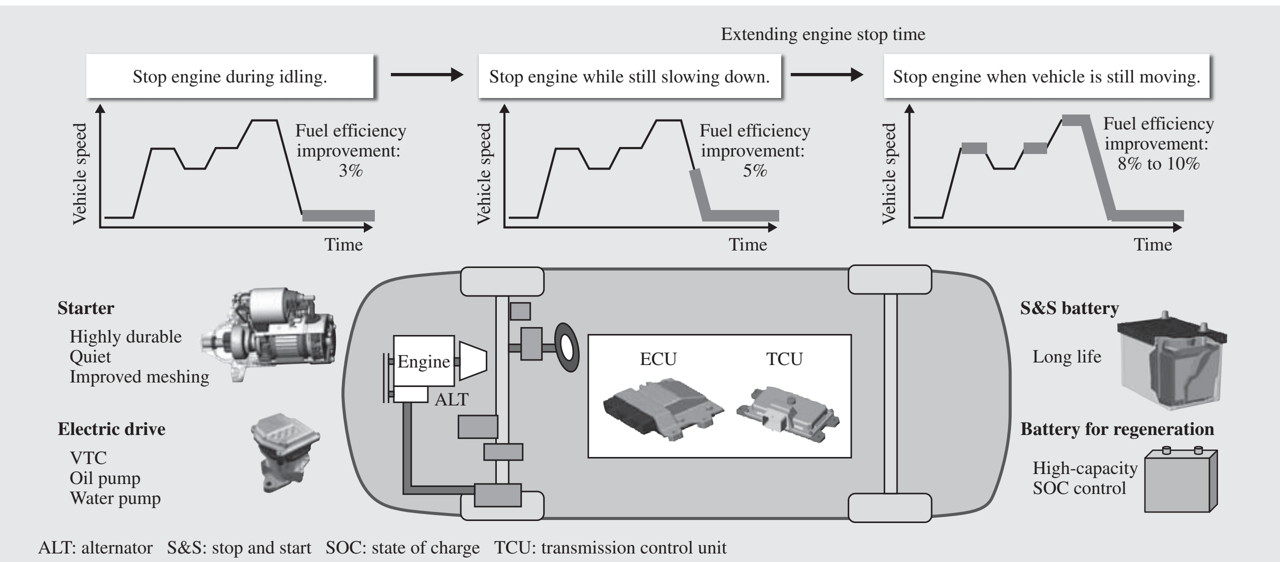


Fig. 3—Stop & Start System and Electric Drive System.
The stop & start system extends the engine stop time to include times when the vehicle is still moving. Used together with electric drive for control equipment and a battery management system, CO_2 emissions are reduced under real-world driving conditions.

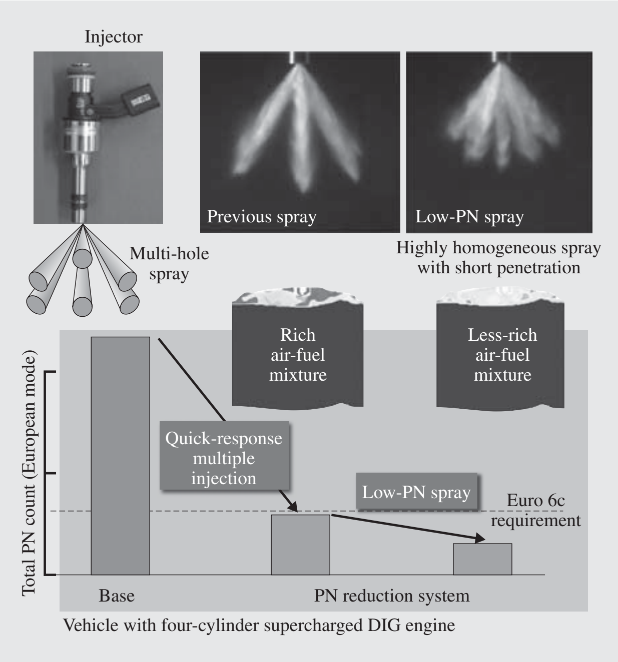


Fig. 4—DIG Injector for Complying with PN/PM Standards and its Benefits.
The figure shows an overview of a DIG system that achieves Euro 6c compliance through the use of quick-response multiple injection and a low-PN spray.

Fig. 4 also shows the reduction in PN level for a four-cylinder supercharged DIG engine measured using the European mode. Compliance with the Euro 6c PN standards can be achieved by using quick-response multiple injection that homogenizes the air-fuel mixture in combination with a low-PN spray. The simulation results for two air-fuel mixtures shown in Fig. 4 demonstrate the effect of the low-PN spray, with the reduction in spray penetration depth and greater homogeneity for a rich air-fuel mixture resulting in significantly lower PN levels.

Design and Operating Characteristics of Electric VTC

In electric VTC, a drive unit optimally controls an electric motor in accordance with phase control commands from the ECU (see Fig. 5). The direct current (DC) motor and reducer are integrated into a single unit that is attached to the camshaft. Because the motor rotates along with the camshaft, there is no need to synchronize rotation with the camshaft. Because motor drive is only used for VTC phase angle conversion, the system has lower electricity consumption and a quick response. The reduction of drive load permits the use of an inexpensive brushed motor. The components the reducer are arranged in the radial direction to reduce the total length. The unit also delivers high torque with low friction by transmitting torque via a roller.

Fig. 6 compares the operating characteristics of electric VTC with an alternative method. As other forms of VTC require attachment to the chain case mount, the motor needs to synchronize its rotation with the engine revolutions in addition to driving phase conversion. With the Hitachi system, in contrast, the drive operates during only phase conversion because the motor is attached to the camshaft, resulting in lower electricity consumption.

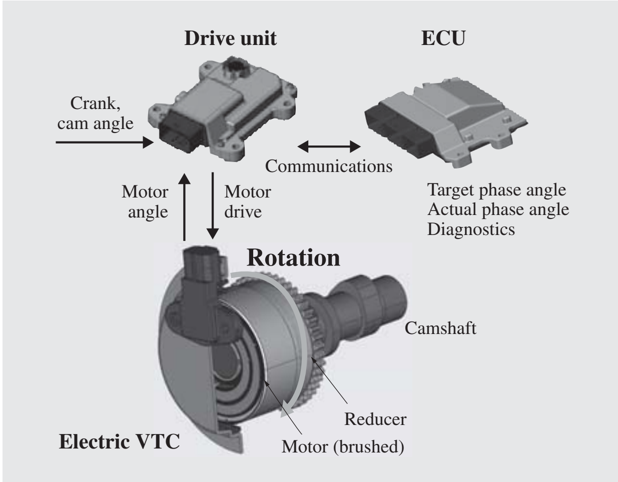


Fig. 5—Structure of Electric VTC System.
This compact electric VTC system combines a motor and reducer in a single package.

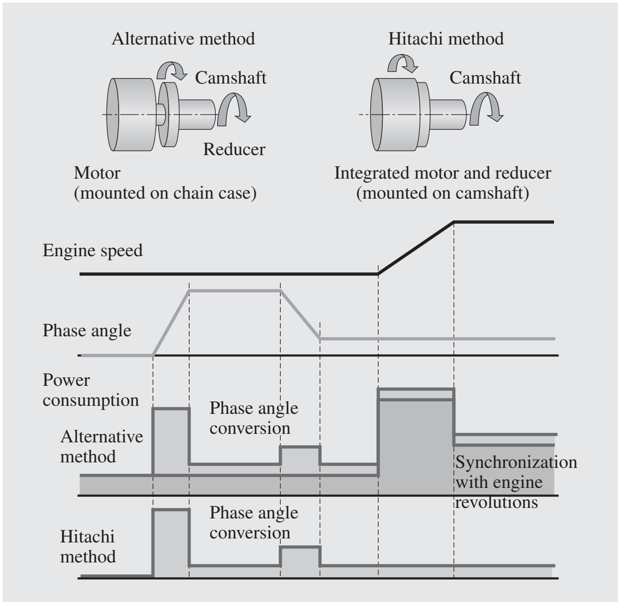


Fig. 6—VTC Power Consumption.
The new system reduces the power consumed during VTC control compared with the alternative method.

Restart Control and Starter for Stop & Start System

Fig. 7 shows the stop & start system and its improvement. The previous system (a) stops the engine after the vehicle stops. The new system (b) stops the engine while the vehicle is still moving.

However, because the vehicle is still moving, it is possible that the driver may have a change of mind and accelerate again after the engine stops, at which point the engine revolutions will have slowed. To ensure that the engine restarts promptly in such cases, the system predicts the slowed engine speed and uses this to ensure that the meshing of the starter and engine can occur quickly. Also, by controlling the engine's fuel injection and ignition to ensure combustion occurs correctly on the first power stroke after meshing the starter, the engine revolutions can be increased quickly, with the characteristics shown in the Fig. 7 graph as (b)-1, and the vehicle can accelerate smoothly.

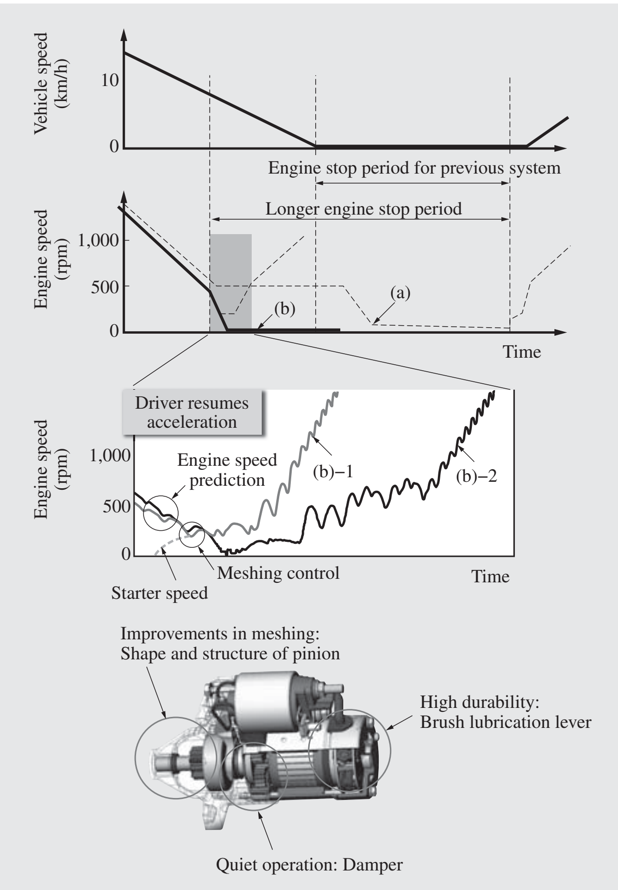


Fig. 7—Starter System Able to Deal with Change of Mind by Driver, and its Control.
By predicting engine speed, controlling starter meshing, and improving the starter, Hitachi has implemented a system that can respond smoothly when the driver changes their mind.

Enhancements of the starter included improving the shape and structure of the pinion for better meshing performance and greater durability, and improving the brushes and adopting a lubrication lever to allow a faster drive speed. The starter was also made significantly quieter during starting (less cranking noise) by fitting a damper to internal parts subject to vibration.

IMPROVEMENTS TO CONTROLLER

Fig. 8 shows advanced ECU technology for next-generation engine management systems (DIG) and a DIG multiple injection function for compliance with Euro 6c standards. Because multiple injection requires that the injector be driven by short high-speed pulses, precise control of the drive waveform was achieved by using a newly developed application-specific integrated circuit (ASIC) for this purpose. To achieve multiple injection with short pulses, the lift behavior of the injector valves is controlled based on the number of injections and fuel pressure [drive with low minimum injection amount (Qmin)]. This results in both faster injector response and quick-response multiple injection.

While the DIG injector uses a boosted drive voltage (60 V), multiple injection requires a shorter boost

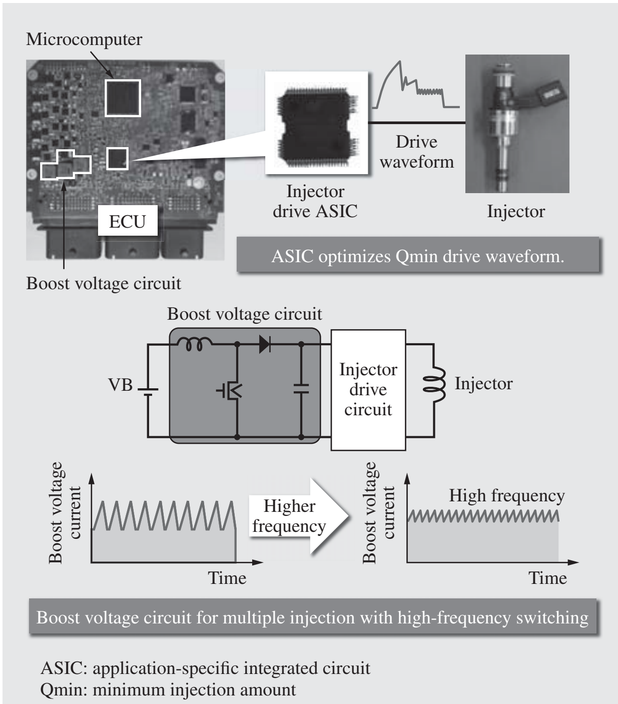


Fig. 8—Injector Drive and Multiple Injection Support.
Quick-response multiple injection is achieved using a highly efficient boost voltage circuit, with a new ASIC that provides a smaller Qmin.

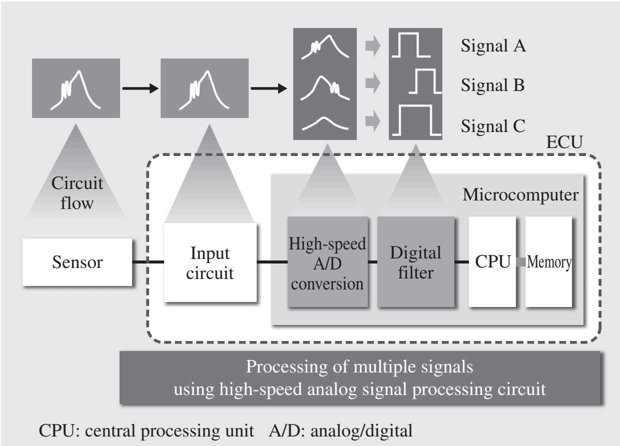


Fig. 9—Processing of Multiple Signals to Support Multi-function Sensing.
Processing of multiple signals is supported to allow more sophisticated sensing in the next generation of engine management systems.

voltage duration. To achieve this, the next generation of ECUs uses high-frequency switching to implement compact boost voltage circuits with quick response and high efficiency. This ECU technology can perform up to five quick-response multiple injections during each intake stroke.

More advanced engine systems require signal processing techniques that can work with multi-function sensing. Because of the need for sophisticated processing of ion current, knock sensor data (noise-tolerant), and other sensor signals (including from internal cylinder pressure sensors in the future), Hitachi has developed techniques for processing multiple signals using high-speed analog signal processing circuits (see Fig. 9). To ensure that they can process a number of signals without overloading the central processing unit (CPU), high-speed analog/digital (A/D) conversion and digital filter functions have been added to new microcomputers to increase A/D conversion speed. The digital filters provide greater flexibility for window and timing settings, and allow the desired signal processing to be implemented.

These advances in ECUs allow the performance of engine systems to be improved by supporting high-speed actuator drive and more sophisticated sensing.

CONCLUSIONS

This article has described the development of the next generation of engine management systems that comply with environmental standards from around the world.

Hitachi supplies advanced environmental systems by improving both components and control techniques.

REFERENCES

(1) M. Osuga et al., "Environmentally Friendly Engine Control Systems," Hitachi Review **58**, pp. 313–318 (Dec. 2009).
(2) M. Osuga et al., "New Direct Fuel Injection Engine Control Systems for Meeting Future Fuel Economy Requirements and Emission Standards," Hitachi Review **53**, pp. 193–199 (Nov. 2004).

ABOUT THE AUTHORS

Minoru Osuga
Control System Design Department, Electronic Device Design Division, Powertrain & Electronic Control System Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of a direct injection system. Mr. Osuga is a member of The Japan Society of Mechanical Engineers (JSME) and the Society of Automotive Engineers of Japan (JSAE).

Yoshinori Ichinosawa
Engine Components Design Department, Engine Components Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of variable valve actuation. Mr. Ichinosawa is a member of the JSAE.

Takuya Mayuzumi
ECU Design Department, Electronic Device Design Division, Powertrain & Electronic Control System Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of an engine controller for direct injection engine. Mr. Mayuzumi is a member of the JSAE.

Dynamic Motor Control System for Enhancing Energy Efficiency and Safety of EVs

Hideki Miyazaki
Tatsuyuki Yamamoto
Hitoshi Kobayashi
Atsushi Yokoyama

OVERVIEW: Hitachi researches and develops control technologies and systems for electric vehicle motors that provide better energy efficiency and safety. This has included using an EV test vehicle to demonstrate the use of the electric motor in traction control and antilock braking, utilizing the rapid changes in torque made possible by the superior torque response of electric motors to maintain vehicle traction even on slippery road surfaces. G-vectoring control and electric yaw-moment control are techniques that will be used with electric drive control in the future. Hitachi has proposed these together with methods for analyzing heat and energy consumption in the motor and other components under near-real-world conditions.

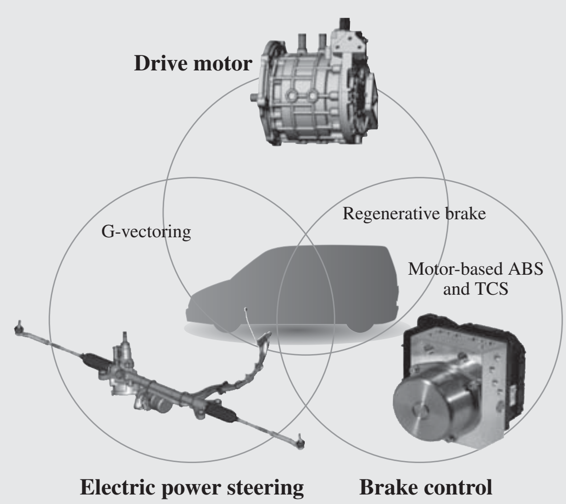
INTRODUCTION

HYBRID electric vehicles (HEVs) and other types of electric vehicles (EVs) have some features that are beneficial to environmentally conscious energy efficiency. Also, it has become possible for such vehicles to be used for energy storage as part of social infrastructure(1) and their superior acceleration and deceleration performance can enhance driving performance. Mobility will take on many different forms in the future, with experiments and demonstrations being conducted around the world. Hitachi takes a user's perspective to designing future vehicles and conducts research into the components and systems that they will require.

In anticipation of future work on control systems capable of delivering both energy efficiency and improvements in driving performance in dangerous driving situations, this article describes the results of simulation and trials using a test vehicle.

CONCEPT BEHIND NEXT-GENERATION EVs

The use of devices such as stereo cameras to improve visibility and techniques that compensate for errors of judgment is an effective way to prevent accidents. The improvement of driving performance in dangerous situations can also be used to prevent accidents that are about to happen. The drive motors used in EVs have a fast response to requested changes in torque (approximately 1 ms), meaning they are suitable for instantaneous control of the vehicle in ways that take account of factors such as road friction and wheel slip. Meanwhile, increasing use is being made of electric drive in the steering and brakes that respectively steer and slow down the vehicle, with electric power steering already in widespread use. If electric motors are to be used to improve driving performance in dangerous situations, then it is necessary that the steering, brakes, and other systems be controlled in tandem. Examples include regenerative braking, in which the electric motor and brakes interoperate during deceleration and braking, and G-vectoring control, which uses the electric motor and brakes to compensate for lateral acceleration that results from steering operation(2), (3). It is anticipated that future use of motor-based traction control systems (TCSs) and antilock brake systems (ABSs) will feature interoperation between the electric motor and brakes (see Fig. 1).



EV: electric vehicle ABS: antilock brake system
TCS: traction control system

Fig. 1—EV Control.
The motor not only powers the vehicle, but also interoperates with the steering and brakes to assist with cornering and stopping.

The main function of the drive motor during deceleration is energy regeneration. This means using the motor to generate electric power from the kinetic energy of the vehicle. An issue for these vehicles will be the extent to which energy efficiency achieved through the use of regeneration can be combined with the improvement of driving performance. Regarding this issue, Hitachi has conducted trials using an EV test vehicle.

Fig. 2 shows Hitachi's roadmap for EV control. Hitachi envisions moving toward autonomous driving in the future through a fusion of environmental technologies (electric motors and electric drive control) with both safety technology and information technology.

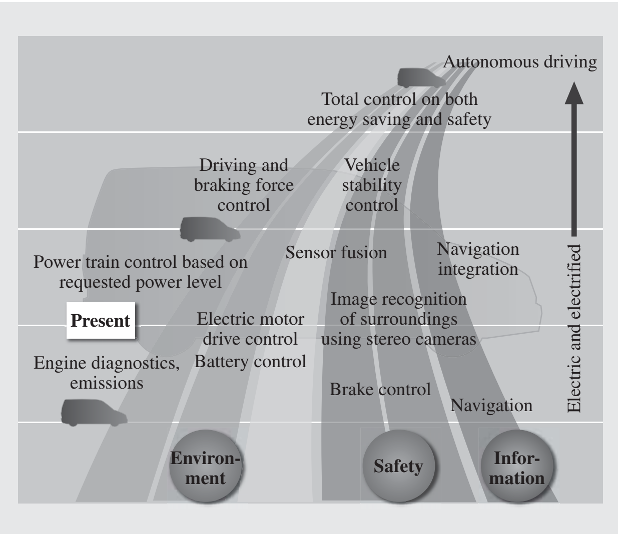


Fig. 2—Roadmap for EV Control.
Hitachi is working toward autonomous driving by fusing environmental technologies (electric motors and electric drive control) with safety and information technologies.

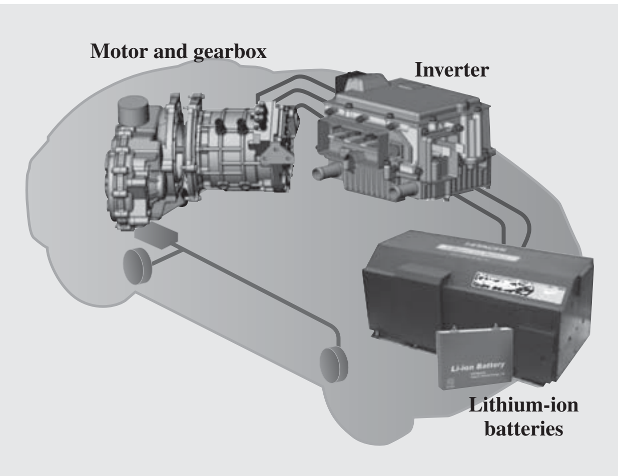


Fig. 3—Structure of EV Test Vehicle.
Hitachi built an EV test vehicle by fitting an electric motor, inverter, and lithium-ion batteries that it had developed in a commercially available vehicle.

EV TEST VEHICLE DEMONSTRATIONS

Hitachi built an EV test vehicle by fitting an electric motor, inverter, and lithium-ion batteries that it had developed in a commercially available vehicle, and used this vehicle to trial electric drive control (see Fig. 3). Table 1 lists the main specifications of the EV test vehicle and its components.

The functions tested for use in EV control were a motor-based TCS and ABS in which rapid changes in torque were used to maintain traction on a slippery road surface. Conventional TCSs and ABSs use dedicated components and are implemented as controllers of the brakes and engine. The demonstration was conducted under conditions of low road friction, and a control system was studied that detected changes in speed when the wheels were on the verge of spinning out and controlled the drive motor torque to minimize slip (see Fig. 4).

TABLE 1. Specifications of EV Test Vehicle
The motor and gearbox and the battery were both specially designed for the EV test vehicle.

Motor	Maximum torque: 180 Nm Maximum speed: 12,000 min^{-1} Output: 90 kW, permanent magnet, water cooled
Inverter	600 V, 400 A (max.) IGBT module with double-surface direct water cooling
Lithium-ion batteries	Voltage: 350 V (@50% SOC) Capacity: 8.34 kWh, Range per charge: 80 km*
Vehicle weight	1,151 kg
Maximum speed	140 km/h

* Calculated from actual results on test track
IGBT: insulated gate bipolar transistor SOC: state of charge

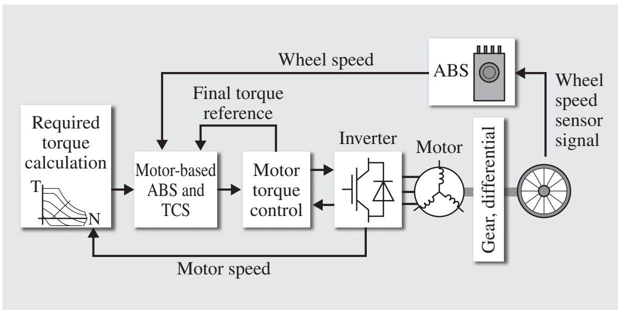


Fig. 4—Motor-based TCS and ABS Control.
In circumstances where ABS or TCS are activated, the control system detects the change in speed when the wheels are about to spin out and controls the electric motor torque to minimize slip.

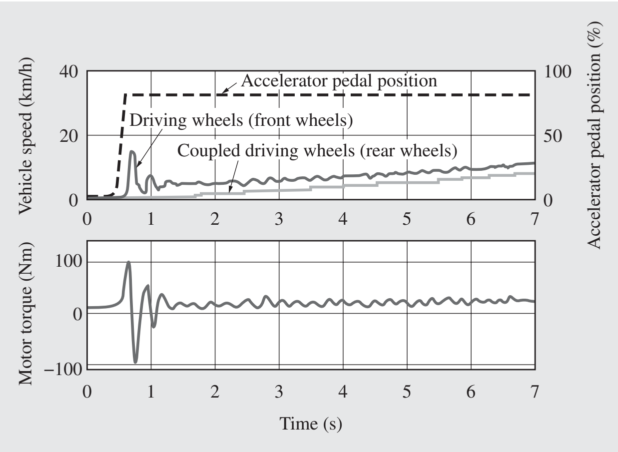


Fig. 5—Demonstration Results for Motor-based TCS.
The vehicle was able to accelerate from a halt on a frozen road without slip by applying rapid changes in the torque to the driving wheels (front wheels).

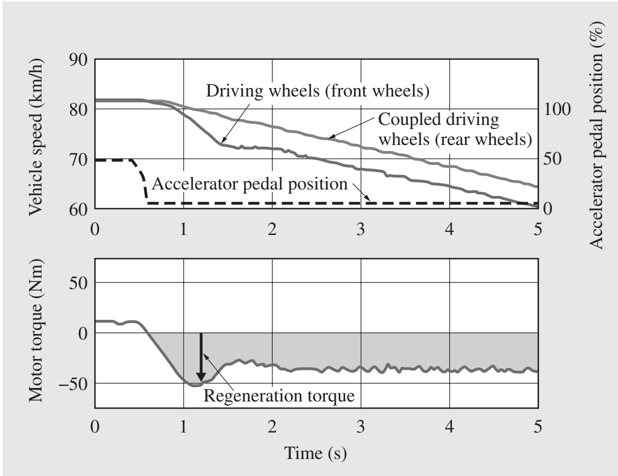


Fig. 6—Demonstration Results for Motor-based ABS.
Slip was prevented and regeneration maintained by detecting the speed difference between the driving wheels and coupled driving wheels and varying the motor torque accordingly.

Fig. 5 shows the effect of using motor-based TCS when the EV test vehicle accelerated from a halt on a frozen road. Rapid changes in the torque applied to the driving wheels allowed the vehicle to accelerate without wheel slip.

Similarly, Fig. 6 shows the test results for motor-based ABS on a frozen road. Torque control of the driving wheels (front wheels) based on the difference in speed between the driving wheels and coupled driving wheels provided the vehicle with good grip and prevented slip. The electric motor could thus, be used for regeneration during this situation; the demonstration showed that energy efficiency can be combined with the improvement of driving performance.

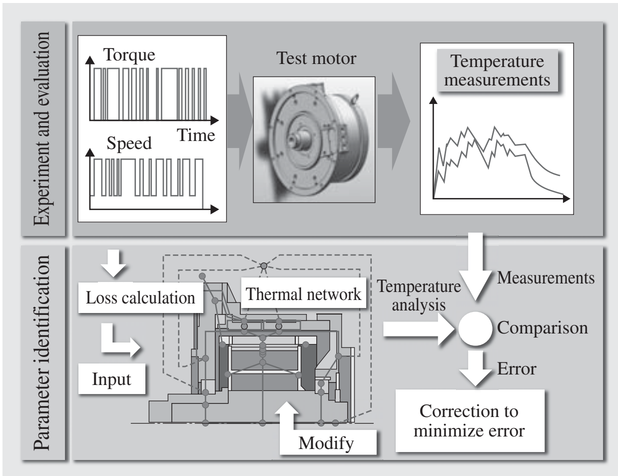


Fig. 7—Method of Identification for Motor Thermal Design Parameters.
A feature of the method is that it uses recursive correction to converge on the thermal network model parameters (thermal resistances and heat capacities), with reference to experimental results.

ANALYSIS TECHNIQUES FOR HEAT AND ENERGY

Because EV drive motors typically operate continuously with variable output, keeping their internal temperature within the permitted range is a concern. While many studies have been published on the thermal analysis of electric motors, the challenge is to devise a method for estimating the internal thermal resistance and heat capacity parameters. Accordingly, Hitachi has investigated a method that applies recursive correction to an analytical model based on experimental results (a model of the motor as a thermal network of thermal resistances and heat capacities) (see Fig. 7). A similar method for estimating the temperature of the magnets embedded in the motor rotor has also been studied(4).

Thermal analysis uses the estimated losses in the motor and inverter, with losses being calculated by considering both the fundamental waveform and harmonic components based on an initial analysis of the motor current. The analysis can also include battery energy consumption based on the vehicle's driving pattern and estimated losses in each component. Fig. 8 shows a comparison of the measured values (the coil temperature in the motor and the battery state of charge) with the calculated values based on the driving pattern of the EV test vehicle. It is believed that the error in the motor temperature is largely due to errors in boundary conditions such as case temperature. Further work aimed at improving accuracy is planned.

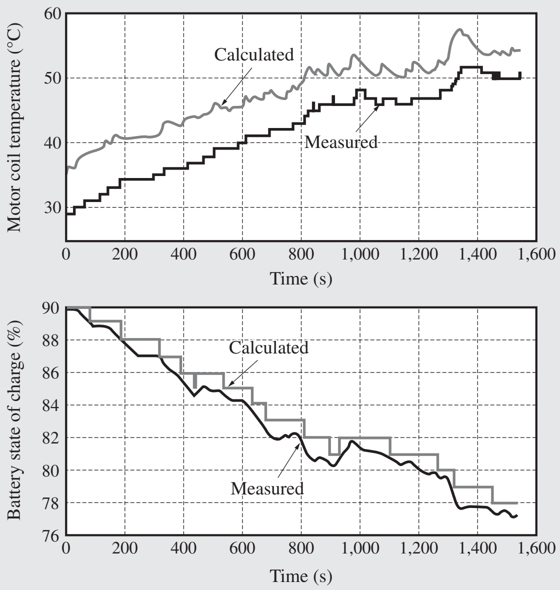


Fig. 8—Simulation of Motor Coil Temperature and Battery State of Charge.
The simulation performs an analysis to obtain the temperature of the coil in the motor and the state of charge of the battery for an input driving pattern of the test EV.

FUTURE TECHNOLOGIES FOR ELECTRIC DRIVE CONTROL

Hitachi has devised G-vectoring control as a means of improving stability and ride comfort during cornering by applying driving and braking force to the vehicle in proportion to the rate of change of lateral acceleration(2). Although the technology was first developed on the assumption that this accelerating or braking would be provided by the electronically controlled friction brake and engine, an electric motor can also be used to provide the required acceleration or braking control. Use of energy regeneration means that employing an electric motor for G-vectoring control is more energy efficient than employing the friction brake.

The fuel savings due to electric G-vectoring can be obtained analytically for a given road that includes corners. Assuming a 10-km stretch of road contains three pairs of curves that have radii of curvature of 30 m, 50 m, and 100 m, for example, a saving in electric power consumption of approximately 5% can be achieved compared to using the friction brake for G-vectoring control(3).

In-wheel electric motors are widely recognized as being capable of improving vehicle driving performance. Because in-wheel motors can provide drive or braking independently to the left and right wheels, they can be used for active control of vehicle cornering trajectory by generating a yaw moment in the vehicle. However, a characteristic of this approach is that the available difference between left and right motor torque diminishes for the faster motor speeds that accompany high-speed driving. In response, Hitachi has developed a new actuator called a "motorized yaw-moment mechanism"(5) (see Fig. 9). The mechanism consists of two rows of planetary gears that link the left and right wheels. By applying motor torque to one of the planetary gears, a single motor can generate opposite torque at the left and right wheels. The motor rotates at a speed proportional to the speed difference between the left and right wheels during cornering, but remains idle when the vehicle is driving in a straight line. As there is no loss of torque due to the vehicle accelerating, a relatively small motor (rated output in the 1 to 3 kW range) can generate adequate torque across the entire vehicle speed range. Because this mechanism can control small amounts of yaw moment with high precision, it is also suitable for use in preventive safety systems such as lane-keeping support systems.

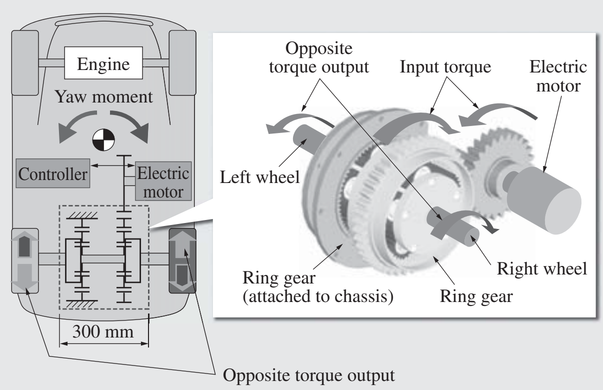


Fig. 9—Motorized Yaw Moment Control.
The control system controls yaw moment by using a single motor to apply opposite torque to the left and right wheels.

CONCLUSIONS

With EVs steadily gaining acceptance in the marketplace, Hitachi is conducting research into EV control techniques that utilize the electric motor, anticipating that this will become an important aspect of vehicle appeal in the future. Whereas the indicators of electric motor performance in the past have been high output, small size, and high efficiency, future demand will be for highly responsive characteristics combined with quiet operation, including control. The use of electric drive throughout the vehicle cannot be assessed simply by the conventional practice of evaluating motors on test beds. Instead, Hitachi believes that it is becoming increasingly important to perform experimental testing under near-real-world conditions, including practices such as the use of test vehicles and simulations of different driving scenarios.

REFERENCES

(1) T. Hirota, "Present and Future of Electric Vehicles, Latest Technologies for Automotive Power Electronics," Society of Automotive Engineers of Japan Symposium, No. 09-12, 20124803, pp. 1–6 (Feb. 2012) in Japanese.
(2) M. Yamakado et al., "Proposal of the Longitudinal Driver Model in Coordination with Vehicle Lateral Motion Based upon Jerk Information," Transactions of the Society of Automotive Engineers of Japan, **39**, No. 3, pp. 53–58 May 2008) in Japanese.
(3) A. Yokoyama et al., "Energy Regeneration Effects of G-Vectoring Control Using Electric Motor," Transactions of the Society of Automotive Engineers of Japan, **44**, No. 4, pp. 1027–1032 (Jul. 2013) in Japanese.
(4) Y. Imanishi et al., "Development of Rotor Temperature Estimation Technique for Electric Vehicle Motor," Fall Conference of The Society of Automotive Engineers of Japan, 63-20135861 (2013) in Japanese.
(5) A. Yokoyama et al., "Development of the Motorized Direct Yaw-moment Control System," Transactions of the Society of Automotive Engineers of Japan, **40**, No. 3, pp. 641–646 (Jun. 2009) in Japanese.

ABOUT THE AUTHORS

Hideki Miyazaki
Advanced Development Center, Technology Development Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the research and development of motor drive systems for next-generation electric vehicles. Mr. Miyazaki is a member of The Institute of Electrical Engineers of Japan (IEEJ) and the Society of Automotive Engineers of Japan (JSAE).

Tatsuyuki Yamamoto
Advanced Development Center, Technology Development Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the research and development of system technology for next-generation electric vehicles. Mr. Yamamoto is a member of the JSAE.

Hitoshi Kobayashi
Advanced Development Center, Technology Development Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the research and development of system and control technology for next-generation electric vehicles.

Atsushi Yokoyama
Information and Control Systems Research Center, Department of Green Mobility Research, Hitachi Research Laboratory, Hitachi, Ltd. He is currently engaged in the research and development of cruise control systems. Mr. Yokoyama is a member of the JSAE.

Development of Standard Motor for Green Vehicles

Hiroshi Hamano
Yasuyuki Saito
Satoshi Kikuchi

OVERVIEW: Against a background of environmental problems, there is growing demand in the automotive industry for the electrification of vehicle powertrains. However, there are a number of different configurations that can be used for electrification, including HEVs, EVs, and PHEVs, each of which has different requirements for the electric motor specifications, such as output, torque, or physical dimensions. Seeking to satisfy these different requirements separately for each new motor would end up significantly increasing the costs, effort, and time involved in motor development. Hitachi Automotive Systems, Ltd. is devising its own proprietary technologies in response to this challenge, such as the RR-rotor, while also developing a standard electric motor for powering green vehicles that will be suitable for a range of different uses.

INTRODUCTION

THE tightening of standards for fuel economy and exhaust emissions in response to global environmental problems has directed attention toward the electrification of vehicle powertrains. For this purpose, Hitachi has in the past adopted interior permanent magnet (IPM) synchronous motors that feature small size, light weight, high output, and high efficiency, and has developed electric motors that deliver high torque relative to their bulk. It has also succeeded in delivering high performance and shorter development times by drawing on know-how built up over many years in fields such as insulation technology, and by adopting digital engineering techniques such as using the Large-scale Universal Vector Electromagnetic Fields Numerical Simulator (LUVENS) for tasks such as designing motor core shapes and optimizing magnet positions. LUVENS was developed in-house and features advanced functions and high speed. However, customer requirements for electric powertrain motors cover a range of different configurations, such as hybrid electric vehicles (HEVs), electric vehicles (EVs), and plug-in hybrid electric vehicles (PHEVs), each of which has different requirements for specifications such as output, torque, and physical dimensions. Because developing each of these motor types individually would involve huge cost and effort, while also slowing down the development process, Hitachi is developing a standard motor for green vehicles (vehicles that use electric drive) that will be able to satisfy all of these different specifications.

This article gives an overview of the standard motor for green vehicles currently being developed.

OVERVIEW OF STANDARD MOTOR FOR GREEN VEHICLES

The concept behind the standard motor is to reduce the development workload and to standardize components, production equipment, and manufacturing practices by designing standard motor specifications that will suit a variety of different types of electrically powered vehicles, such as HEVs, EVs, and PHEVs, as well as different size classes of vehicles, while still providing features such as small size, light weight, high output, high efficiency, quiet operation, and low vibrations. The aim is to develop a low-cost motor while also improving development efficiency. The requirements for realizing this concept include physical dimensions that will allow vehicle layouts to be designed in a standardized way over different classes of vehicles, output characteristics that satisfy a wide range of output requirements, time ratings that suit the characteristics of different types of electrically powered vehicles, and a range of model variations to suit different end uses. The following sections describe the thinking behind the methods adopted to achieve these objectives.

Stator Winding Design for Standard Motor

To achieve small size and high torque density, wave winding using square-profile wire was chosen for the stator windings on the standard motor. Compared with the distributed windings with circular-profile wire used in the past, those with square-profile wire provide an approximately 20% improvement in packing factor (conductor cross-section/slot cross-section) and an approximately 15% improvement in motor output

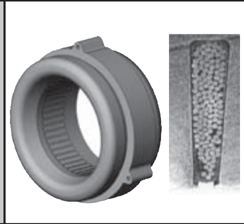
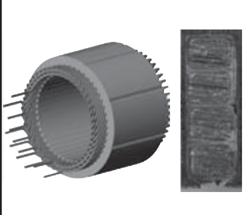
	Distributed winding with circular-profile wire (previous motors)	Wave winding with square-profile wire
Slot cross-section		
Torque density	60–70 (Nm/L)	70–80 (Nm/L)
Packing factor	40–45 (%)	60–65 (%)

Fig. 1—Stator Windings for Standard Motor.
Use of wave winding with square-profile wire provides high packing factor, small size, high torque, and high efficiency.

torque density (output torque/ stator core $D^2 \times L$) (see Fig. 1).

Selection of Motor Diameter

The term “electrically powered vehicle” covers a range of configurations, with different motor layouts in each case. For the standard motor, Hitachi focused on the following two typical motor layouts.
(1) Long cylindrical type intended for use in conjunction with a reduction gear. Used primarily in EVs.
(2) Flat cylindrical type intended to be built into the transmission or located between the engine and transmission. Used primarily in HEVs.

Looking first at the thinking behind the selection of motor diameter for the long cylindrical type used in EVs, this type of motor is typically used in conjunction with a reduction gear and is located under the bonnet in place of the engine and transmission in a conventional vehicle. This type of motor also typically uses water cooling, with a water jacket forming part of the motor case through which water can be circulated. Accordingly, an external diameter of 200 mm was selected for the stator core to satisfy these conditions together with the minimum ground clearance.

In the case of the flat cylindrical type for HEVs, the external diameter of the transmission case needs to be considered when selecting the motor dimensions since it is assumed that the motor will be located between the engine and transmission or inside the transmission case. Also, although this type of motor is typically cooled using the transmission fluid, to allow for the possibility of water cooling, an external diameter of 245 mm was selected for the stator core to leave room for a water jacket to be fitted around the exterior of the motor.

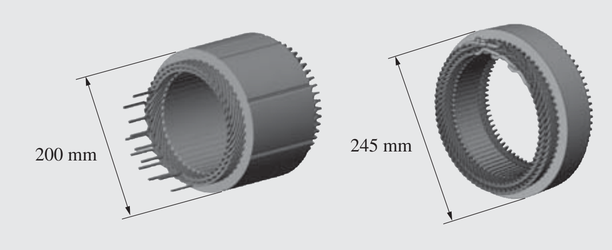


Fig. 2—Dimensions of Standard Motor.
The two standard stator core diameters selected were 200 and 245 mm.

By standardizing these two stator core diameters based on these considerations, Hitachi was able to make development more efficient (see Fig. 2).

MOTOR SPECIFICATIONS AND FEATURES

IPM synchronous motors are widely used for vehicle drive, with advances in motor control

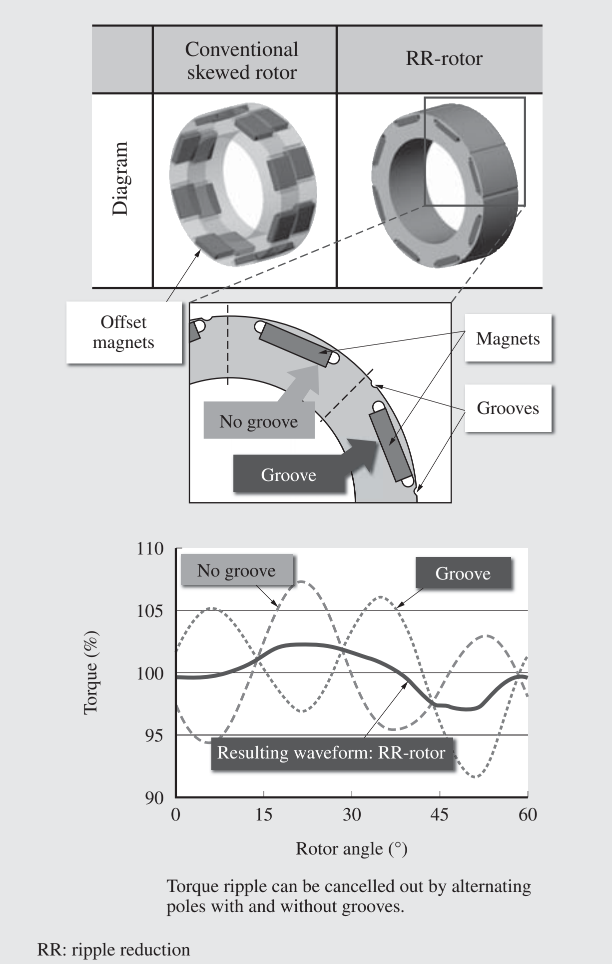


Fig. 3—RR-rotor.
By adding grooves to alternating poles around the circumference of the rotor, torque ripple can be reduced without splitting the magnets in the axial direction.

techniques in recent years delivering smooth driving performance. However, a structurally inherent feature of these motors is that the torque they produce includes a torque ripple component. This ripple can be a cause of pulsation at low speed or noise and vibration at high speed. The following sections describe proprietary techniques adopted by Hitachi for the rotor and stator respectively to minimize these effects.

RR-rotor

The conventional method for minimizing the torque ripple due to the rotor of an IPM motor is the offset skew technique in which the magnets are split and offset along the length of the rotor core (see Fig. 3). However, this approach increases costs because the greater number of magnets increases magnet machining costs and makes rotor assembly more difficult. In its place, Hitachi has devised the ripple-reduction (RR) rotor that reduces ripple without the use of skewing.

Torque ripple is pulsation of the output torque that results from variation in the intensity of magnetic flux. It occurs because of the interaction between the magnetic flux produced by the stator winding and that produced by the magnets. Also, the geometry of the stator slots and rotor poles are contributing factors. Accordingly, it is possible to cancel out the ripple in the output torque waveform by generating an opposite-phase ripple in the torque.

To generate this opposite-phase torque waveform, Hitachi modified the rotor geometry to create structurally induced variation in the flow of magnetic flux and produce a consequent linkage in the flow of magnetic flux at the stator. Specifically, by adding grooves in the rotor surface on each side of the magnets for alternating poles, the torque ripple waveform produced by the poles with a groove is opposite in phase to the torque ripple waveform produced by the poles without a groove (see Fig. 3). The result is reduced torque ripple due to the two ripple waveforms canceling each other out[1].

HR-winding

Hitachi devised the harmonic reduction (HR) winding technique for stators as a means of reducing torque ripple and achieving quiet operation. Reducing the harmonic components of the magnetomotive force and induced voltage play an important role in reducing electromagnetic hum and torque ripple in motors. Accordingly, Hitachi devised a new winding technique designed to achieve these goals (see Fig. 4).

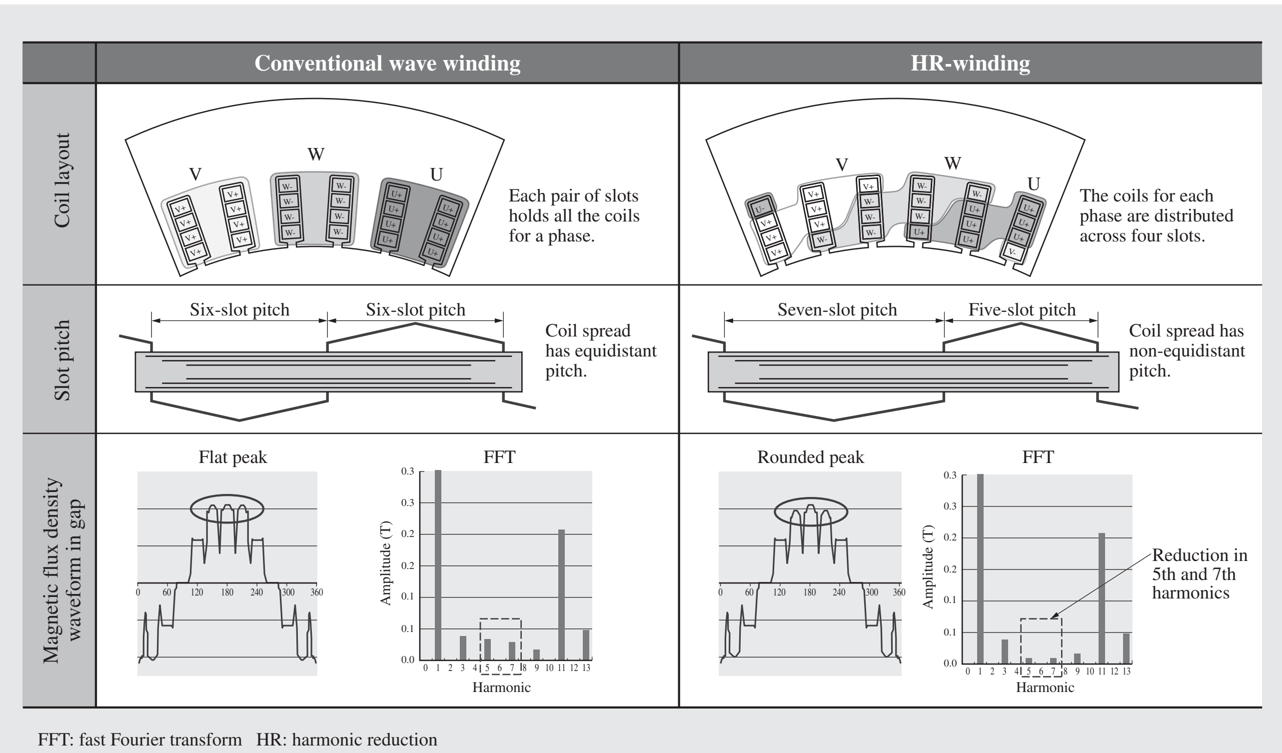


Fig. 4—HR-winding.
Low torque ripple and quiet operation can be achieved by reducing the harmonic components of the magnetomotive force and induced voltage.

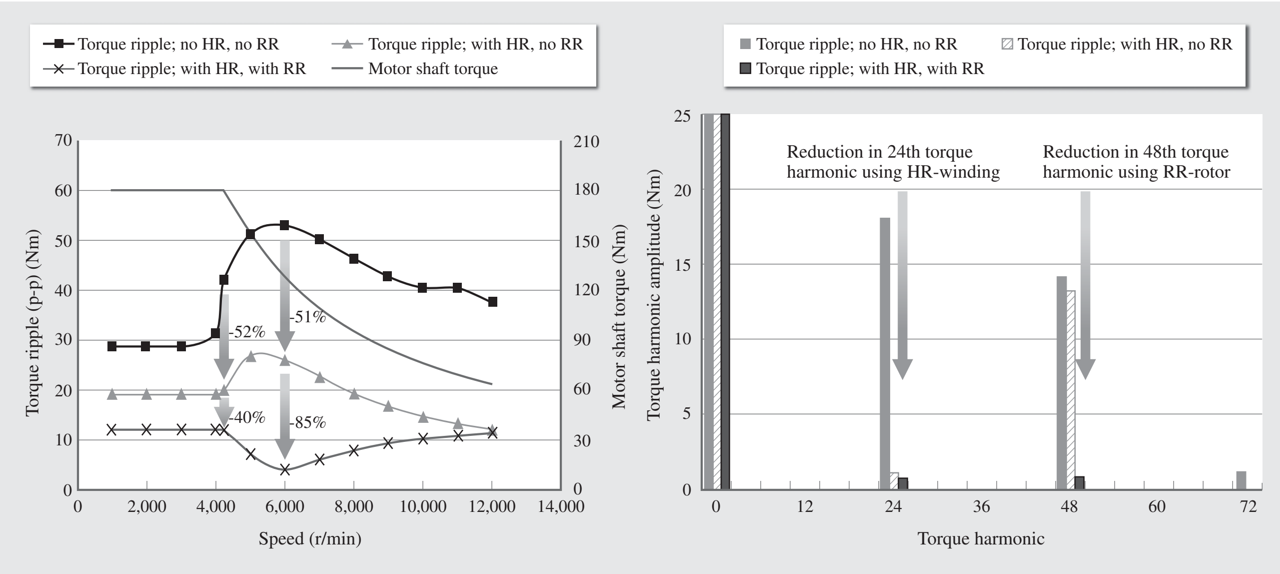


Fig. 5—Benefits of Torque Ripple Reduction.
A magnetic field simulation was used to demonstrate the benefits of the HR-winding and RR-rotor for a motor with maximum torque of 180 Nm. Use of HR-winding reduces torque ripple by 51% and use of the RR-rotor reduces torque ripple by 85%. Note that these results were calculated assuming a sinusoidal current waveform.

Previous winding techniques used the same slot pitch for all coils, with a stator cross-section in which all of the coils for each phase were located together in two slots. In contrast, the new HR-winding technique uses coils with seven-slot and five-slot pitches to distribute the coils for each phase across four slots and spread the magnetic flux produced by the coils over a wider area. This creates a rounded peak at the leading edge of the magnetic flux waveform in the gap between the inner circumference of the stator and outer circumference of the rotor and makes the overall waveform closer to a sine wave, thereby suppressing the harmonic component by reducing the amplitude of the fifth and seventh harmonics.

Benefits of RR-rotor and HR-winding

To demonstrate the benefits of the RR-rotor and HR-winding, Fig. 5 shows the results of using a magnetic field simulation to calculate the torque ripple for a motor with maximum torque of 180 Nm.

The horizontal axis represents motor speed and the vertical axis represents torque ripple. Use of HR-winding reduces torque ripple by up to 51% compared with that of previous designs. If the RR-rotor is also used, it is anticipated that torque ripple will be reduced by up to 85% compared with when HR-winding is used on its own. Meanwhile, fast Fourier transform (FFT) analysis of the torque waveform showed that the harmonic at which the benefits occur is different in each case, with HR-winding reducing torque ripple for the 24th harmonic of rotation and the RR-rotor reducing it for the 48th harmonic.

OUTPUT ADJUSTMENT FOR STANDARD MOTOR

While two different stator core diameters (200 mm and 245 mm) were selected for the standard motor, because customers' motor performance requirements are diverse, Hitachi also intends to use the two motor performance adjustment methods described below to satisfy these various requirements (see Fig. 6).

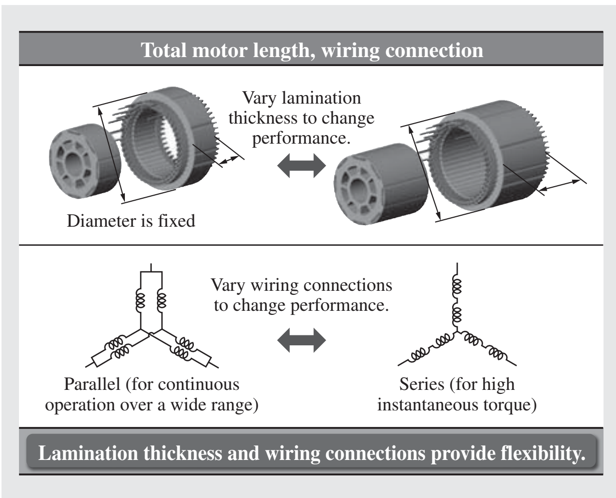


Fig. 6—Stator Variations.
Motor performance can be changed by varying the lamination thickness and wiring connections.

Torque Adjustment by Changing Lamination Thickness

The workload for motor design and development is significantly increased if the magnetic circuit (motor cross-section shape) from the core shape for each new set of customer requirements. On the other hand, once the magnetic circuit design of the motor cross-section is complete, the performance calculation associated with varying the length of the motor (core lamination thickness) is comparatively simple. Moreover, the production equipment can be adapted more easily to changes that consist solely of varying the length of the motor without changing its cross-section shape when using wave winding with square-profile wire than it could when using the distributed windings with circular-profile wire in the past.

For these reasons, Hitachi has chosen to use changes to the core lamination thickness (as shown in the top part of Fig. 6) as a means of varying the torque and other motor performance parameters, without changing the cross-section shape of the core.

Torque Adjustment by Changing Winding Wire Connections

The motor output range and time rating requirements differ for different vehicle models and gear ratios of the associated reduction gear. Because an EV is powered by the electric motor on its own, it needs to be able to operate continuously over a wide range. In the case of an HEV motor, on the other hand, because it provides torque-assist to the engine, it is used to generate high torque over short durations. To satisfy these different requirements, Hitachi uses a standard winding wire configuration but changes the wiring connections in the stator, as shown in the lower part of Fig. 6.

For an EV motor, end-point connections are used to form two winding circuits in parallel and provide low-torque and high-speed motor output characteristics that are matched to the reduction gear ratio. This provides for continuous operation over a wide range when operating in the frequently used medium to low torque range.

HEV motors require high-torque and low-speed motor output characteristics. Accordingly, to deliver high torque, the two winding circuits are connected in series to increase the number of winding loops. Although this results in a shorter permissible operating time because of the large temperature rise while current is flowing, it is adequate for the short-duration torque-assist that occurs in HEVs when accelerating from a halt, for example.

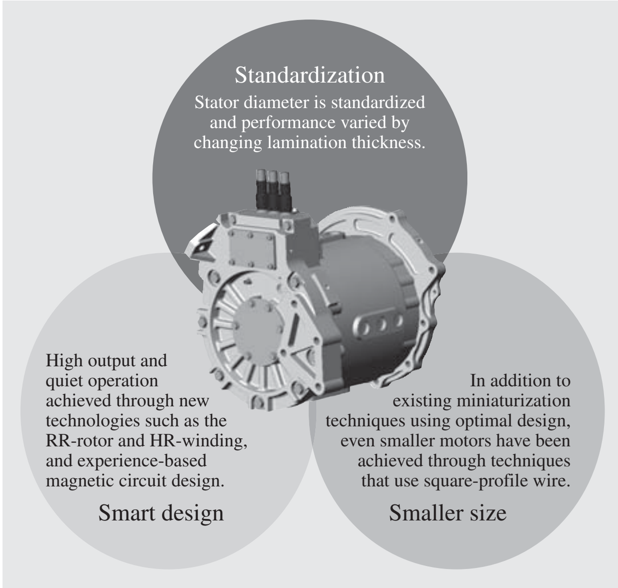


Fig. 7—Standard Motor Developed by Hitachi Automotive Systems, Ltd.
Hitachi is developing small motors that feature high output, high efficiency, and quiet operation, and that have standardized stator core diameters.

Based on these considerations, it is possible to produce a series of motors that share components such as cores, magnets, wires, and insulating paper, and that allow the standardization of production equipment and manufacturing practices.

CONCLUSIONS

Hitachi is currently working on the development of a standard motor for green vehicles that incorporates its proprietary technologies (see Fig. 7). While changes in environmental and fuel economy standards continue, it is anticipated that demand for vehicles with electric drive will increase, and that the technology for a next-generation standard motor described in this article will play a key role in satisfying the need for vehicle electrification.

REFERENCE

(1) S. Yoshihara et al., "Development of Technology for Electrically Driven Powertrains in Hybrid Electric Vehicles," Hitachi Review **58**, pp. 325–329 (Dec. 2009).

ABOUT THE AUTHORS

Hiroshi Hamano

EP Equipment Design Department, Powertrain Design Division, Powertrain & Electronic Control System Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of a traction motor for EVs and HEVs. Mr. Hamano is a member of the Society of Automotive Engineers of Japan (JSAE).

Yasuyuki Saito

EP Equipment Design Department, Powertrain Design Division, Powertrain & Electronic Control System Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of a traction motor for EVs and HEVs. Mr. Saito is a member of the JSAE.

Satoshi Kikuchi

MS3 Unit Department of Motor Systems Research, Hitachi Research Laboratory, Hitachi, Ltd. He is currently engaged in the development of a traction motor for EVs and HEVs. Mr. Kikuchi is a member of The Institute of Electrical Engineers of Japan (IEEJ) and the Japan Society of Refrigerating and Air Conditioning Engineers (JSRAE).

High-power-density Inverter Technology for Hybrid and Electric Vehicle Applications

Takashi Kimura
Ryuichi Saitou
Kenji Kubo
Kinya Nakatsu
Hideaki Ishikawa
Kaname Sasaki

OVERVIEW: Green vehicles have become familiar sights on the road in recent years, with growing sales of HEVs and the arrival of the first mass production BEVs. With environmental regulations on CO_2 (fuel economy) and exhaust emissions also becoming increasingly stringent, sales of these green vehicles are set to increase further in the future. Consequently, because electric drive systems are made up primarily of electric motors, inverters, and batteries, inverters are being called on to fulfill increasingly diverse roles and there is a need to decrease their size and cost while increasing their output. Along with supplying inverters for HEVs and EVs that are an ideal match with customer requirements, Hitachi also intends to continue contributing to progress toward a low-carbon society by developing technologies that will help make inverters more widely used.

INTRODUCTION

WITH the aim of creating a sustainable society, vehicle fuel economy standards are becoming progressively tighter year by year in order to reduce carbon dioxide (CO_2) emissions. It is forecast that the proportion of the total market accounted for by electric vehicles (EVs) and hybrid electric vehicles (HEVs) will grow significantly by 2020. HEVs have been commercialized in a variety of forms. Hitachi draws on its strengths in power electronics to supply inverters that suit diverse customer requirements.

There has been demand in recent years to increase the output and reduce the size of inverters so that they can fit into the limited space available in vehicles. In response, Hitachi has developed new power modules with double-sided direct cooling that deliver considerably higher power density than past models. Hitachi has also developed a standard power electronics platform for mounting these power modules, and has commercialized it in the form of a standard inverter.

This article describes the power modules with double-sided direct cooling used in automotive inverters, the configuration of the standard inverter, Hitachi's own direct current (DC) converter that is integrated into the inverter, and the steps Hitachi is taking to increase inverter output further.

PAST WORK

Automotive inverters accelerate or decelerate the vehicle by converting the DC power from the batteries to alternating current (AC) at the frequency required for vehicle speed and other system control to control the electric motor speed, drive torque, and power. The performance requirements for these electric drive systems for HEVs and EVs are small size (important for ensuring that the system can be installed in the vehicle), high efficiency to extend EV range, high output to provide suitable acceleration performance, and reliability to operate in the harsh environment inside a vehicle.

By utilizing its technologies for package structure of power module to develop a direct water cooling system, Hitachi has succeeded in delivering both small size and high performance. It is also working on making its inverters smaller still by adopting a double-sided cooling method with direct water cooling and fully immersed cooling fins (see Fig. 1).

Depending on the type of drive used, electric drive systems require an inverter capable of driving one or two electric motors. For compatibility with the motor and battery, they also need to operate at a variety of system voltages, such as 60 V or less, or 100 – 450 V. Hitachi commenced full-scale production of HEV inverters with direct cooling in 2005, producing models capable of driving one or two motors and operating at 42 V. Power modules with single-sided direct cooling were used up to the second generation, and double-sided direct cooling was adopted from the third generation onward. Hitachi has also developed its standard inverter to achieve greater sharing of parts between models (see Fig. 2).

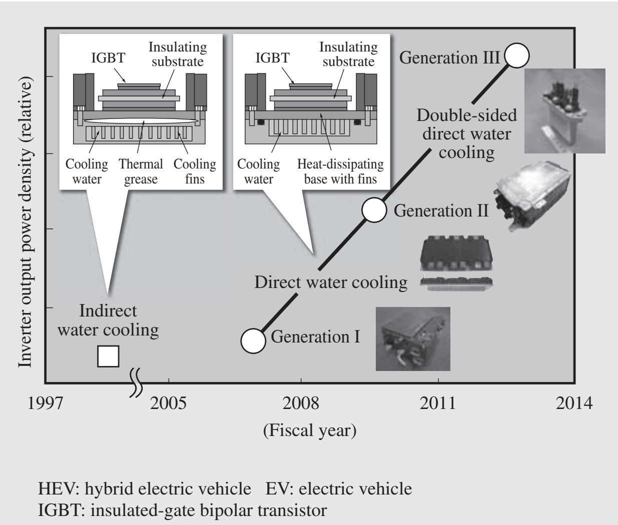


Fig. 1—Development Roadmap for HEV/EV Inverters.
To satisfy the diverse requirements for automotive use, Hitachi is achieving smaller size and higher performance by utilizing engineering and analytical technologies taken from numerous different fields, including the electric power, industrial, and consumer sectors, to develop direct water cooling.

TECHNOLOGIES FOR INVERTERS WITH HIGH POWER DENSITY

Features of High-power-density Inverter

The requirements for automotive inverters include control performance that extends from low to high motor speeds, robustness to withstand a harsh environment (heat and vibration), electromagnetic compatibility (EMC) performance to minimize the radiation of electromagnetic noise due to heavy current switching, ease of installation (small size and light weight), failsafe functions in the event of a fault, long life with respect to thermal fatigue, excellent water and dust proofing, and insulation performance at high altitude. The inverters also need to satisfy these demanding requirements at a low cost.

Automotive inverters incorporate a wide variety of components, including insulated-gate bipolar transistor (IGBT) power devices, power modules, high-voltage DC line capacitors, main circuit busbars, a power module drive circuit board, a motor control circuit board, three-phase current sensors, and DC and heavy-current AC connectors. Delivering the expected high performance has in the past required the use of special-purpose components. The components used in the high-voltage and heavy-current power sections of the inverter required a high level of insulation and the ability to withstand high voltages.

As a result, Hitachi has set out to reduce costs by standardizing components, and is seeking to satisfy diverse customer needs by designing inverters that use these standardized components.

The newly developed high-power-density inverter has the following features.

(1) Use of power modules with low thermal resistance, and IGBTs and diodes with low losses and high performance

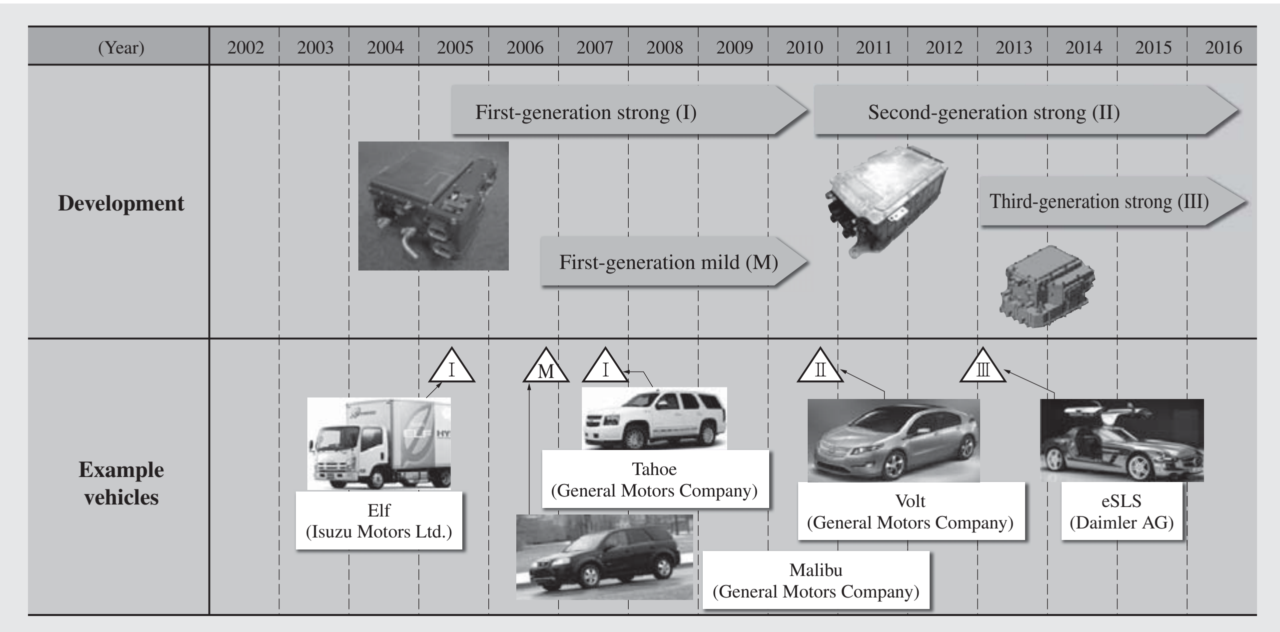


Fig. 2—Use in HEVs.
Hitachi commenced full-scale production of inverters with direct cooling in 2005, and has supplied three generations of high-output inverters to date.

(2) Design with a low-inductance main circuit and optimized DC capacitance
(3) Water channel design that combines efficient cooling with low pressure loss
(4) Use of an application-specific integrated circuit (ASIC) with built-in protection functions for gate drive
(5) Motor control circuit board designed for functional safety
(6) Compact package design with small size and light weight
(7) Miniaturized auxiliary inverter (option)

Double-sided Direct-cooling Power Module

Power Devices

The IGBT and freewheeling diode (FWD) power devices need to deliver the performance required by the vehicle when operating at its maximum limits. As power devices account for the bulk of losses in an inverter, they have a significant impact on electrical efficiency. Accordingly, the power devices need to have low losses. Hitachi has achieved low losses by adopting the latest device technology available at the time for each of its inverter generations (see Fig. 3).

As the maximum DC link voltage is about 400 V (assuming no voltage booster is used), IGBTs need to be rated for 650 to 700 V. Other likely design requirements are an effective current of 300 to 400 Arms and a carrier frequency of 5 to 12 kHz. To achieve low losses under these operating conditions, and to reduce inverter size, Hitachi has adopted field-stop, trench IGBTs for its third-generation models.

Power Modules

The requirements for power modules are to minimize inverter floor space and to get the best performance out of the power devices. Hitachi has been using direct cooling since its first- and second-generation models. For direct cooling, the fins on the base of the module are immersed in cooling fluid. This improves heat dissipation because it dispenses with the heat sink thermal resistance and the thermal grease used in the past between the base plate and heat sink (see Fig. 4).

The pin fin design is critical to direct cooling. While having more fins reduces the thermal resistance, it increases the pressure losses in the cooling water channels. Hitachi uses a genetic algorithm to optimize the design of its pin fins (see Fig. 5). The optimum pin fin design needs to be selected based on the required thermal resistance and the pressure loss determined by the requirements specified for the electric drive system's cooling system. By applying this optimization, the single-sided cooling systems used in the first- and second-generation inverters achieved a 30% improvement over indirect cooling, as measured by the thermal resistance from the device junction to the cooling fluid (for a flow rate of 10 L/min and a pressure loss of 20 kPa).

This cooling method was further developed in the third generation with the adoption of double-sided

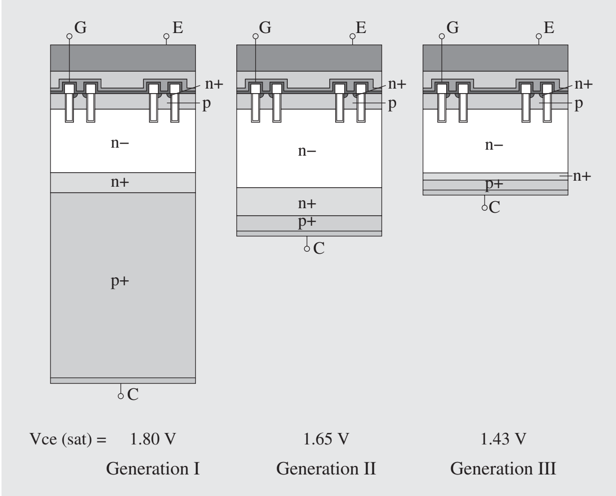


Fig. 3—Evolution of IGBT Device Structure and Vce (Saturation Voltage).
As IGBT losses account for the bulk of inverter losses, losses have been reduced with each successive generation. Non-punch-through devices were used for the first generation, punch-through devices for the second, and field-stop devices for the third.

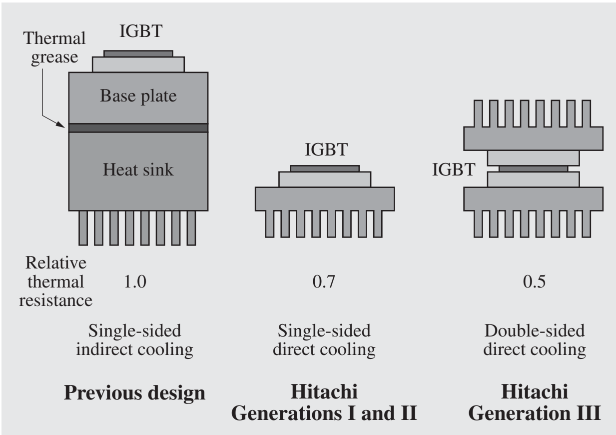
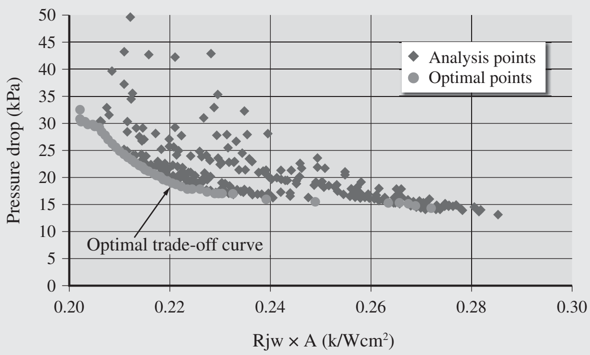


Fig. 4—Advances in Power Module Cooling Design.
Whereas past designs dissipated heat via grease to a heat sink, Hitachi has since its first-generation models adopted direct cooling in which the heat-dissipating fins are immersed in cooling water, allowing the IGBT current density to be increased. From the third generation onwards, Hitachi has developed a new double-sided cooling method in which fins are located on both sides of the chip.

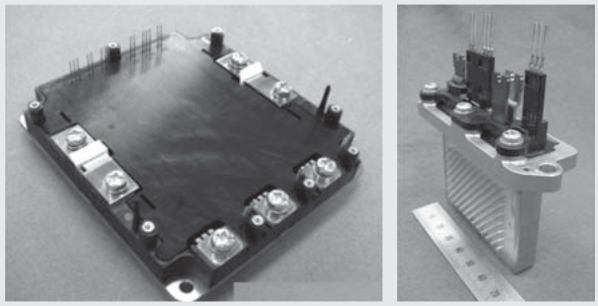


Pressure drop: Drop in pressure in cooling water channels for 50% long life coolant (LLC), 50% water
Rjw × A: Thermal resistance per unit area between junction temperature and cooling water temperature

Fig. 5—Pin Fin Optimization for Power Modules.
The thermal resistance of the power modules is improved at the expense of increasing the pressure loss in the cooling water channels. As this increases the resistance to water flow in the channels, the optimal point can be selected based on the cooling capacity. Hitachi used a genetic algorithm to determine the optimal curve for the fin shape parameters (number of fins, fin spacing, and fin height).

direct cooling (see Fig. 4). In place of the wire bonding used in the past, the lead frame for the emitter side of the IGBT is soldered and the lead frame is joined to the heat sink via insulating material. As the metal leads, insulators, and fins form a single structure, this dramatically reduces thermal resistance.

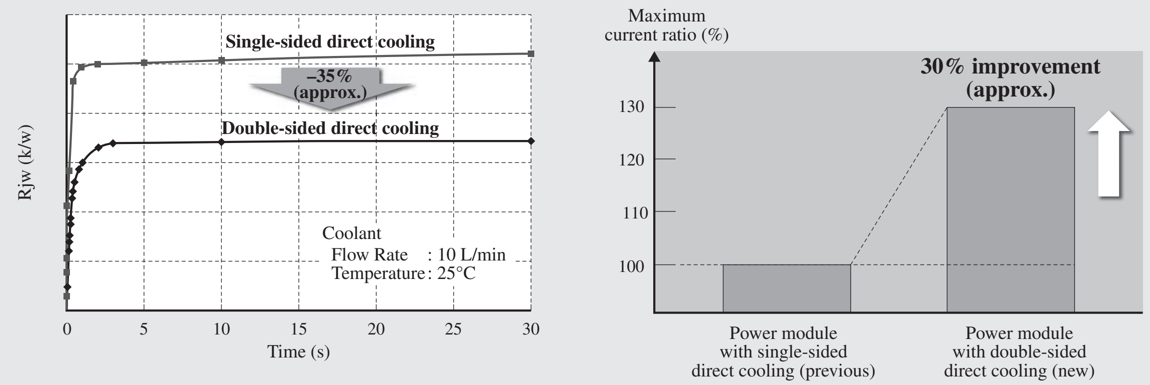
Also, the third-generation modules have a two-in-one configuration with one module for each phase of the three-phase current (UVW). This facilitates optimization of the inverter design because it provides greater flexibility in where to mount the module (see Fig. 6).



(a) Power module with single-sided direct cooling **(b) Power module with double-sided direct cooling**

Fig. 6—Power Modules.
A power module with single-sided direct cooling (a) was used for the second-generation inverters, and a power module with double-sided direct cooling (b) was developed for the third generation. The power module with double-sided direct cooling is rated for 700 V, has a maximum current of 325 Arms, and has an insulation resistance of 10 MΩ (500 Vdc) and 2,700 Vdc (1 minute). Its maximum current can also be up-rated to 400 Arms by changing the IGBT chip.

The power modules with double-sided direct cooling have approximately 35% better thermal resistance than the modules with single-sided direct cooling, providing a performance improvement of 30% or more in terms of current flow assuming use of power devices with the same chip size (see Fig. 7).



(a) Comparison of transient thermal resistance **(b) Comparison of maximum current ratios**

Rjw: Thermal resistance (degrees Kelvin/Watt) between junction temperature of power device and cooling water temperature

Fig. 7—Heat Dissipation Performance of Power Module with Double-sided Direct Cooling.
This comparison shows the heat dissipation performance of power modules with double-sided and single-sided direct cooling respectively, assuming the same IGBT chip size. The reduction of about 35% in Rjw thermal resistance increases the maximum current by approximately 30%.

Improvements in the performance of modules with double-sided direct cooling mean less rise in junction temperature, and because the inverter is able to operate with the cooling water at a higher temperature, this simplifies the dedicated inverter cooling system that was required in the past.

Cooling Water Channels, Main Circuit, and Capacitors

While reducing inverter losses requires lower gate resistance and higher switching frequency, these result in higher surge voltage. This means the main circuit inductance needs to be reduced. As the main circuit inductance consists of the module's internal inductance, busbar inductance, and capacitor internal inductance, reducing overall inductance is achieved by optimizing pin locations and overlaying the positive and negative busbar terminals of each component.

Film capacitors of 2.5 μm in thickness are used to improve DC capacitor reliability, and the cells and pin locations have been optimized to reduce the capacitors' internal inductance.

For inverters that use the power modules with double-sided direct cooling, Hitachi also optimized the design of the cooling water channels that house the modules to ensure that the level of pressure loss in these channels is appropriate.

The design also locates the DC capacitance in the space surrounded by the vertical cooling water channels that house the power modules with double-sided direct cooling so that the heat generated by these DC capacitors, which have a low heatproof temperature, is conducted away to the water-cooled jacket. Hitachi has also sought to dramatically simplify the wiring harness to make the inverters easier to assemble and more reliable. An efficient design is used, including the current sensors being mounted directly on the circuit board, eliminating harness and connector components, and significantly reducing the overall component count of the inverter (see Fig. 8).

Gate Drive Circuit Board

The gate drive circuit board is designed to suit the power module layout, with Hitachi having developed an ASIC that includes protection functions for detecting over-temperature and over-current, and that significantly reduces the component count. It has been standardized to obtain maximum performance from the power devices.

Motor Control Circuit Board

Internal permanent magnet synchronous motors (IPM-SM) are widely used in HEVs because of the need for the motors to operate at high torque and speed. Hitachi has developed standard control software and a standard motor control circuit board to implement vector control. These provide the key functions required for automotive inverters, including a resolver interface, dual control area network (CAN) interfaces, motor temperature detection, high-voltage detection, torque security, and fault diagnostics memory. As automotive electronics systems will need to comply with functional safety as defined by ISO 26262 in the future, Hitachi has pre-empted this by designing inverters that satisfy the Automotive Safety Integrity Level-C (ASIL-C) standard of functional safety. Hitachi also uses dual-core central processing units (CPUs) and provides the monitoring functions needed to satisfy functional safety requirements.

Standard Inverter

Fig. 9 shows Hitachi's latest inverter that utilizes the technologies described above for higher density. Second-generation inverters used modules with single-sided direct cooling and were able to drive two motors. The third-generation models use modules with double-sided direct cooling and feature a power density of 35 kW/L, 5.6 times that of first-generation models. Whereas in the past Hitachi has developed inverters that have been optimized for individual customers, for its third-generation models it developed a new standard inverter that drives a single motor. The aims are to simplify vehicle layout design and shorten development and design times. By using

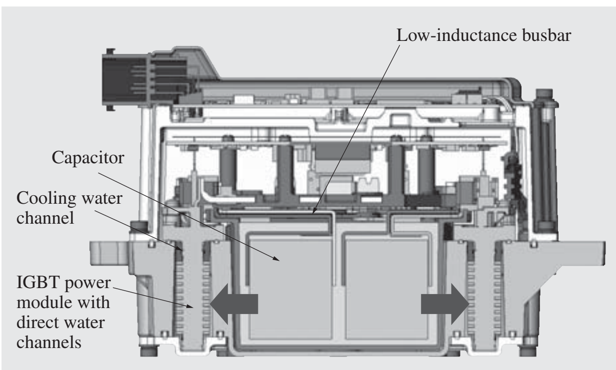


Fig. 8—Internal Design of Inverter Using Power Module with Double-sided Direct Cooling.
Locating the inverter power modules with double-sided direct cooling alongside the capacitors allows cooling of the film capacitors, which have a low heatproof temperature.

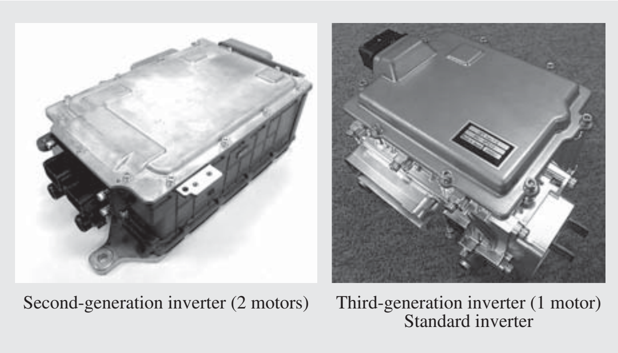


Fig. 9—Design of Latest Inverters.
Hitachi has developed a single-motor standard inverter to its own proprietary specifications. To maintain its general-purpose characteristics while also providing the flexibility to fit in various vehicle layouts, the new inverter uses a standard power section but allows the cooling pipework, heavy-current connectors, signal connectors, and housing (interface) to be designed to suit user requirements.

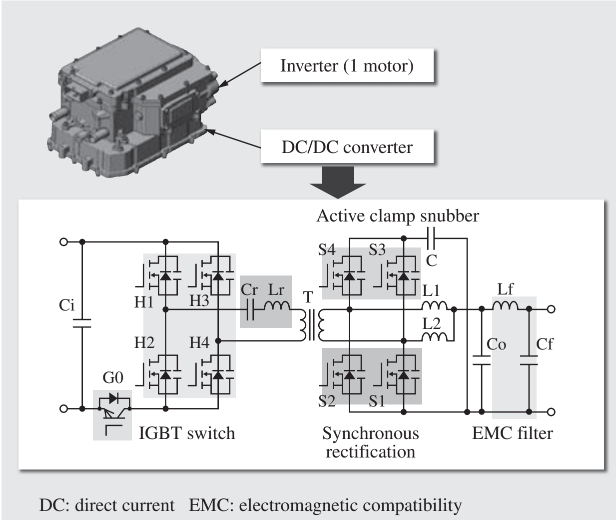


Fig. 10—Inverter with Integrated DC Converter, and DC Converter Main Circuit.
Hitachi has developed a DC/DC converter that can be integrated into the inverter. It achieves small size by sharing the inverter's cooling water channels.

power modules with double-sided direct cooling, the size of the new inverter has been shrunk to 3.5 L, making installation in vehicles significantly easier. By selecting from power modules with rated currents ranging from 300 to 400 Arms, the same package can be used to drive motors with a range of outputs, extending from HEVs to EVs.

DC/DC CONVERTER

As HEVs and EVs no longer have 12-V alternator systems, they require a DC/DC converter to supply power from the high-voltage (150- to 450-V) system to the low-voltage (12-V) system. In response, Hitachi has developed its own DC/DC converter that is integrated into the inverter so that it can share features such as the cooling system and high-voltage connectors, making it easier to install in the vehicle (see Fig. 10). This has included developing an active clamp circuit and IGBT switching method to produce a 3-kW DC/DC converter that achieves high efficiency (95% max., 92% or higher under rated conditions) and supports bidirectional operation (back and boost).

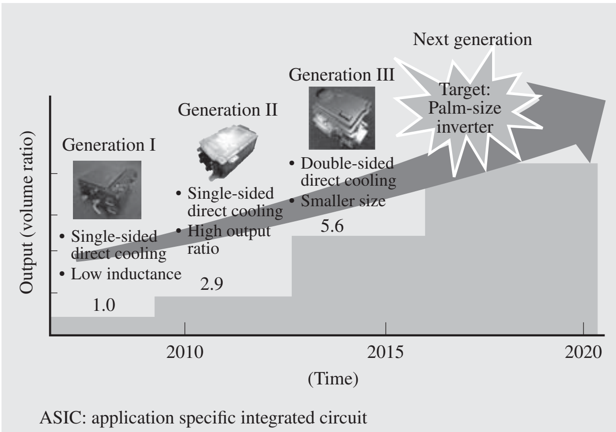


Fig. 11—Future Inverter Development.
To date, Hitachi has developed three generations of small inverters with high output. In the future, Hitachi intends to continue this trend toward higher output and to develop a next generation of ultra-small inverters small enough to fit in the palm of the hand.

CONCLUSIONS

This article has described the power modules with double-sided direct cooling used in automotive inverters, the configuration of the standard inverter, Hitachi's own DC/DC converter that is integrated into the inverter, and the steps Hitachi is taking to increase inverter output further.

In the future, Hitachi intends to continue making advances in automotive inverters primarily through advances in power devices and the design of power modules. As indicated by its inverter roadmap, Hitachi intends to continue making its inverters smaller and to increase their output, with the aim of making the next generation of systems small enough to fit in the palm of the hand (see Fig. 11). It is anticipated that the future of automotive inverters will see new technical innovations made possible by silicon carbide (SiC) and other wide-band-gap semiconductors, and further system integration to reduce in the overall cost of drive systems.

REFERENCES

(1) H. Hamada et al., "Development of Fuel-efficient, Environmentally-friendly Hybrid Electric Vehicle Systems," Hitachi Review **53**, pp. 177–181 (Nov. 2004).

(2) S. Yoshihara et al., "Development of Technology for Electrically Driven Powertrains in Hybrid Electric Vehicles," Hitachi Review **58**, pp. 325–329 (Dec. 2009).

(3) K. Ide et al., "Power Electronics Component Technologies for Green Mobility," Hitachi Review **60**, pp. 310–315 (Oct. 2011).

(4) K. Nakatsu et al., "Development of Technologies to Cut in Half Floor Space Required for Power Modules on Inverters for Electric and Hybrid Automobiles," Hitachi Review **61**, p. 80 (Aug. 2012).

(5) K. Nakatsu et al., "Next-generation Inverter Technology for Environmentally Conscious Vehicles," Hitachi Review **61**, pp. 254–258 (Nov. 2012).

(6) R. Saito et al., "High power density inverter technology for automotive applications," Ingénieurs de l'Automobile, No. 825 (2013).

ABOUT THE AUTHORS

Takashi Kimura

Inverter Design Department, Electronics Device Design Division, Powertrain & Electronic Control Systems Division, Hitachi Automotive Systems, Ltd. He is currently engaged in design and development of automotive inverters. Mr. Kimura is a member of the Society of Automotive Engineers of Japan (JSAE).

Kenji Kubo

Inverter Design Department, Electronic Device Design Division, Powertrain & Electronic Control Systems Division, Hitachi Automotive Systems, Ltd. He is currently engaged in design and development of a DC/DC converter and automotive power electronic components. Mr. Kubo is a member of the IEEJ and JSAE.

Hideaki Ishikawa

Inverter Design Department, Electronic Device Design Division, Powertrain & Electronic Control Systems Division, Hitachi Automotive Systems, Ltd. He is currently engaged in design and development of automotive inverters and DC/DC converter. Mr. Ishikawa is a member of the JSAE.

Ryuichi Saitou

Inverter Design Department, Electronics Device Design Division, Powertrain & Electronic Control Systems Division, Hitachi Automotive Systems, Ltd. He is currently chief engineer engaged in inverter development of automotive. Mr. Saito is a member of The Institute of Electrical Engineers of Japan (IEEJ) and JSAE.

Kinya Nakatsu

Department of Power Electronics System Research, information and Control Systems Research Center, Hitachi Research Laboratory, Hitachi, Ltd. He is currently engaged in the research and development of automotive inverters, industrial inverters, and power modules. Mr. Nakatsu is a member of the IEEJ, JSAE, and IEEE.

Kaname Sasaki

Inverter Design Department, Electronic Device Design Division, Powertrain & Electronic Control Systems Division, Hitachi Automotive Systems, Ltd. He is currently engaged in design and development of inverters for EV/HEV applications. Mr. Sasaki is a member of The Japan Society of Mechanical Engineers (JSME) and JSAE.

Lithium-ion Battery for HEVs, PHEVs, and EVs

Fumihiro Namiki
Toshikazu Maeshima
Kosuke Inoue
Hidemasa Kawai
Shoji Saibara
Toshiyuki Nanto

OVERVIEW: Hitachi Vehicle Energy, Ltd. commenced the full-scale production of lithium-ion batteries for hybrid vehicles in 2005. As of the end of 2012, its cumulative sales of battery packs was sufficient to supply approximately 80,000 vehicles. In addition to commencing the production of generation-3.5 battery packs in July 2013, the company is also working on the development of new generations of technology in anticipation of significant growth in the market for xEVs. By meeting customer needs with technologies for high reliability as well as other advanced technologies that it has built up through involvement in the market, Hitachi is working to reduce exhaust emissions by encouraging the wider use of xEVs.

INTRODUCTION

ACCORDING to the United Nations, global warming has been occurring faster than ever since 2001. Sea levels are rising at roughly twice their previous rate, and the number of deaths associated with heat waves has increased approximately 20-fold. There are also parts of the world where atmospheric pollution, as measured in terms of the particulate matter 2.5[*1] (PM2.5) concentration, is becoming more severe. Vehicle exhaust gas is one of the major causes of these environmental problems. The number of vehicles is set to continue increasing in future, particularly in emerging economies. For these reasons, it is no exaggeration to say that reducing the load that vehicles place on the environment is a major global challenge.

MARKET ENVIRONMENT AND PAST INVOLVEMENT

Market Forecasts for xEVs

As environmental awareness grows, countries are tightening their regulations pertaining exhaust emissions (see Fig. 1). Europe has set a target of reducing the amount of carbon dioxide (CO_2) emitted per kilometer driven from 130 g at present to 95 g in 2020. This is not a target that can be achieved solely by improving the fuel efficiency of gasoline engines, and will require the full-scale introduction of electrically powered vehicles such as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and electric vehicles (EVs). Meanwhile, market forecasts for the sales of electrically powered vehicles continue to be revised downward.

*1 Particles with a size of 2.5 μm or less (1 μm = one-thousandth of a millimeter) suspended in the atmosphere.

Having forecast in 2012 that the market for electrically powered vehicles would reach 13 million in 2020, Fuji Keizai Co., Ltd. has now reduced this figure to 9.6 million. The main reasons for the change include a poorer outlook for sales of EVs and PHEVs, and concerns such as the short range of EVs and lack of charging facilities. Despite this, strong growth is still forecast for HEVs, with the market expected to grow four-fold between 2012 and 2020 to 7 million vehicles.

Past Involvement by Hitachi Vehicle Energy, Ltd.

Hitachi Vehicle Energy, Ltd. led the world by commercializing a lithium-ion battery for vehicles in 1999. Its total sales to date are approximately 4.2 million cells, enough for about 80,000 vehicles.

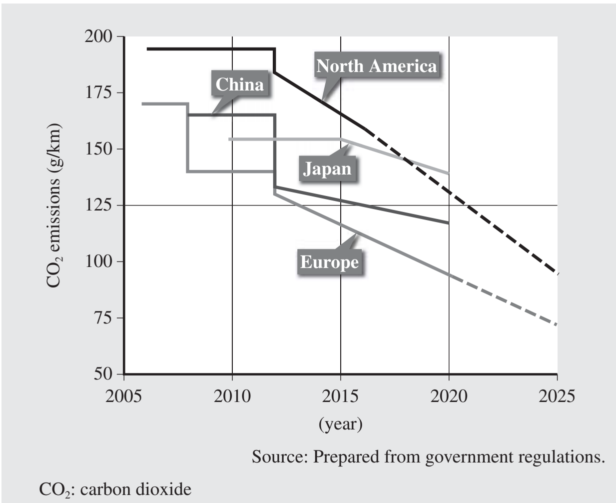


Fig. 1—Trends in Regulations Exhaust Gas.
The graph shows the expected levels of permitted emissions in different markets up to 2025.

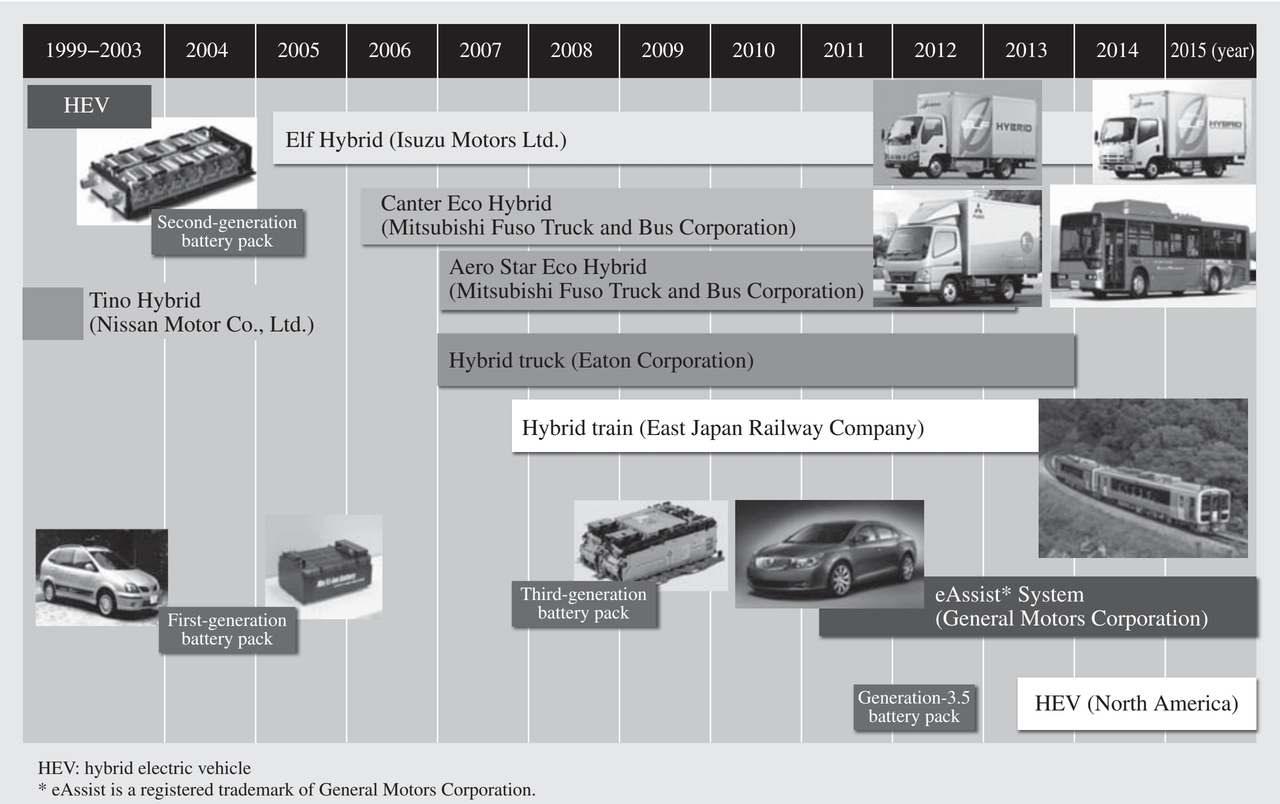


Fig. 2—Use of Hitachi Lithium-ion Batteries in Electric Vehicles.
These are the main examples of vehicles that have used products from Hitachi Vehicle Energy, Ltd. between 1999 and the present day.

Its second-generation battery packs are widely used in applications such as commercial vehicles and hybrid trains operated by the East Japan Railway Company. Its third-generation battery packs are used in HEVs made by the General Motors Corporation, with a total of more than 65,000 units shipped to date. Based on the quality and safety that are underpinned by these many years in the market, Hitachi commenced production of generation-3.5 battery packs in July 2013 (see Fig. 2).

DEVELOPMENT OF GENERATION-3.5 BATTERY PACKS

Hitachi has developed a generation-3.5 battery pack for use in cars supplied to the North American market in 2013. The functions of the battery packs include providing power assist during acceleration and when starting the engine, and regeneration during deceleration and braking.

The batteries are produced at the Kentucky plant of Hitachi Automotive Systems Americas, Inc.

Battery Pack Design

The generation-3.5 battery pack is supplied in a box housing that includes battery modules made up of cylindrical cells, a battery management system (BMS), a junction box used for electrical switching of the heavy current circuits, and a manually operated service disconnection switch for physically isolating the heavy current circuits. Fig. 3 shows the design of the battery pack.

The three battery modules are connected together by a wire harness. Table 1 lists the main battery pack specifications.

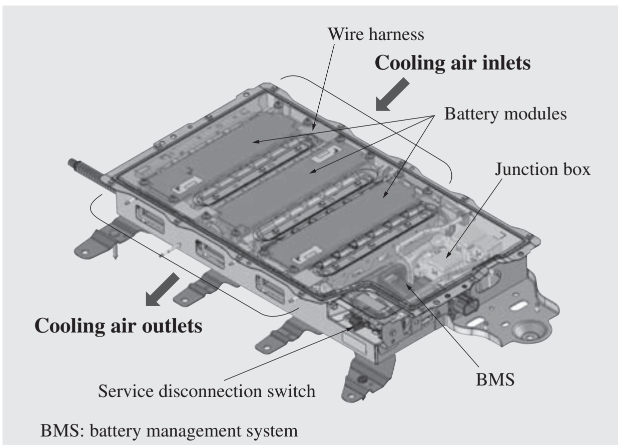


Fig. 3—Battery Pack Components.
The new battery pack includes battery modules and a BMS, junction box, and service disconnection switch.

Table 1. Main Battery Pack Specifications
These are the specifications of the generation-3.5 battery pack.

Parameter	Specification	Remarks
Energy capacity	634 Wh	
Capacity	4.4 Ah	
Voltage	144 V	50% SOC
Input power	19 kW	25°C, 50% SOC, after 10 s
Output power	17 kW	25°C, 50% SOC, after 10 s
Operating temperature	–30°C to +60°C	
Mass	29 kg or less	
Dimensions	744 (W) × 427 (D) × 93 (H) mm	

SOC: state of charge

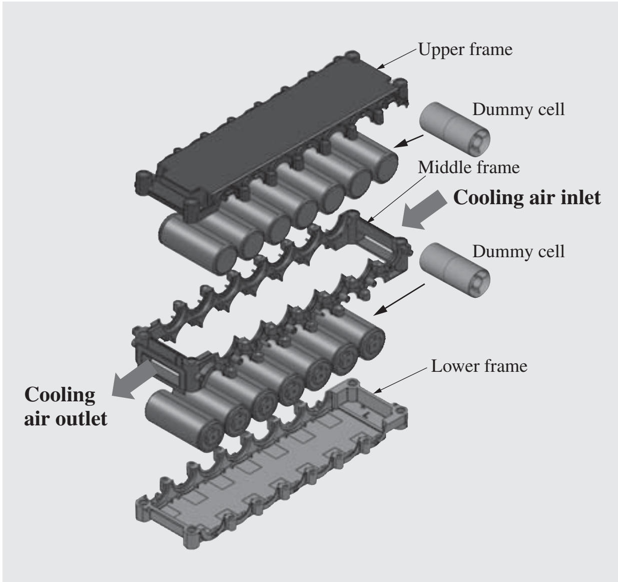


Fig. 4—Module Components.
Based on cooling considerations, the module consists of three frames (upper, middle and lower) and the battery cells.

Battery Module

The battery modules are housed in metal boxes, with 12 to 14 battery cells per module. Fig. 4 shows how the battery module components fit together. The low-profile design sandwiches the battery cells between three plastic frames (upper, middle, and lower), with the upper and lower rows of batteries arranged in a staggered formation to keep the total height down to only about 93 mm. To ensure sufficient cooling, air channels are provided between the battery cells. A battery pack consists of a row of three modules with air channels branching off from the cooling air inlets (see Fig. 3). Also, copper plates are fitted between the battery cells with welded joints connecting the cells together in series.

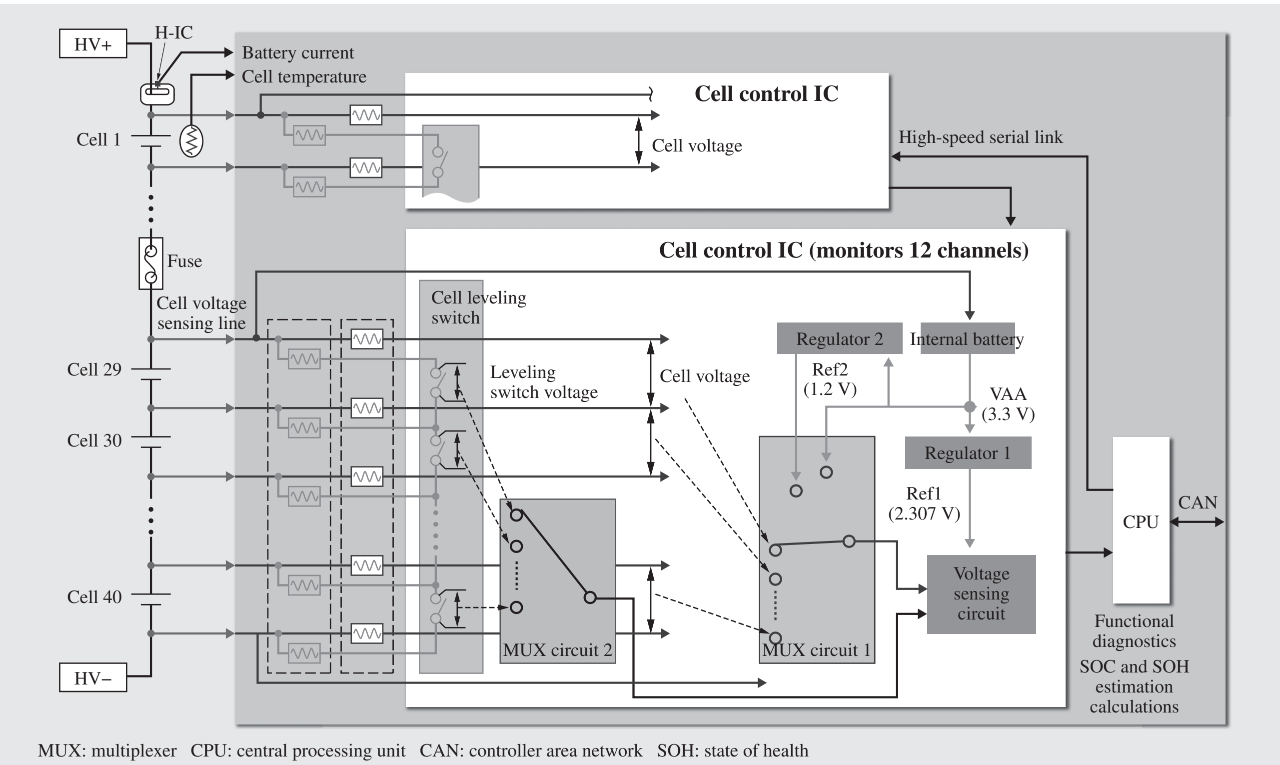


Fig. 5—BMS Block Diagram.
The functions of the BMS consist of monitoring the status of the battery cells, estimating the states of the battery cells, leveling cell voltage, performing diagnostics, and communicating with diagnostic tools.

BMS

The BMS sends information from the battery pack and battery cells to controller in the vehicle via a controller area network (CAN), and controls the battery pack and battery cells based on the commands it receives in response. Fig. 5 shows a block diagram of the BMS. The functions of the BMS consist of monitoring the status of the battery cells (voltage, current, and temperature), monitoring state of charge (SOC) and state of health (SOH) to estimate the states of the battery cells, leveling cell voltage, performing diagnostics, and communicating with diagnostic tools. To comply with Onboard Diagnosis II (OBD-II), a North American standard for self-diagnosis, Hitachi has also developed additional functional diagnostics, including for circuit faults and the rationality diagnosis of measured and estimated signals. Furthermore, Hitachi has developed functions for supporting diagnostic tools. These provide compatibility both with the diagnostic tools used by specific vehicle manufacturers and also the generic scan tool (GST) specified in OBD-II.

Lithium-ion Battery Cells for HEVs

The cylindrical cells used in the generation-3.5 battery packs were designed specifically to deliver both high performance and safety in HEVs, and commenced production in 2011[1]. As a result of this development, the battery packs have also been adopted by new customers who recognized their commercial success in cars.

Cell Assembly Line

With the aim of optimizing its electrode supply chain, Hitachi has constructed a new production facility for cylindrical cells in Oyamazaki Town, Otokuni District, Kyoto Prefecture (see Fig. 6). The achievements of this new battery production line include roughly twice the investment efficiency and half the operating costs of existing lines. The construction of this new production line lifts Hitachi's total capacity for cylindrical cells to more than one million per month and provides competitive and efficient production infrastructure. Drawing on this experience of setting up a manufacturing plant that is geographically separated from the design and development facility, Hitachi intends to expand its operations globally.

Battery Pack Assembly Line

In December 2012, Hitachi built a battery pack assembly line at the Kentucky plant of Hitachi Automotive Systems Americas, Inc. (see Fig. 7). Introduction of the battery packs proceeded on the basis of mutual cooperation between the USA and Japan and involved the initial prototypes being produced in Japan before shifting to North America to start full-scale production with subsequent gradual introduction of locally sourced parts. Following production trials that commenced in January 2013, commercial production started in July. This approach in which a production line was established with a short lead time through mutual cooperation between the USA and Japan will serve as the foundation for the future launch of new products, and also for the site selection of production facilities around the world to fulfill "local production for local consumption" requirements.

BATTERY CELL TECHNOLOGY

This section describes a prismatic cell currently under development for use in the next generation of lithium-ion battery cells.

Fig. 6—New Cell Assembly Line Building.
Artist's impression of cell assembly line building in Oyamazaki Town, Otokuni District, Kyoto Prefecture.

Fig. 7—Battery Pack Assembly Line.
The battery pack assembly line at the Kentucky plant of Hitachi Automotive Systems Americas, Inc.

Parameter	Specification
Size (mm)	120 × 85 × 12.5
Mass (kg)	0.25
Rated capacity (Ah)	5.3
Specific power (W/kg)	3,400
Specific energy (Wh/kg)	76
Positive electrode material	Newly developed manganese-based material
Negative electrode material	Amorphous carbon

Fig. 8—Prismatic Lithium-ion Battery for HEVs.
This prismatic battery for HEVs is designed for higher output.

Development of Lithium-ion Battery Cells for HEVs

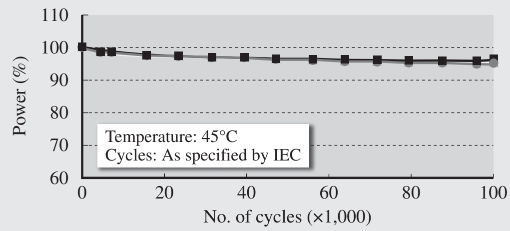
In addition to the cylindrical cells described above, Hitachi has also developed prismatic cells in response to the growing diversity of vehicle types. Hitachi has taken the technologies it has built up through its work on cylindrical cells and applied them to prismatic cells, including the adoption of new materials produced using techniques such as the control of crystal growth for optimized grain design to improve power characteristics in colder climates. Hitachi is also seeking to improve power by using thinner electrodes and other means to reduce reactive resistance. Fig. 8 shows the battery and lists its main specifications. Fig. 9 shows the results of performance testing which indicate that the new prismatic cell has long life and high reliability similar to those of the cylindrical cells, with power still at 95% after 100,000 cycles.

Fig. 10 shows the power at an ambient temperature of –30°C. The low-temperature power is 1.3-fold that of the previous battery used for comparison.

Lithium-ion Battery Cells for PHEVs and EVs

Hitachi is also developing a high-energy prismatic cell for use in PHEVs and EVs. Able to operate in both EV and HEV modes, PHEVs are recognized for their potential to achieve significant improvements in fuel economy and exhaust gas emissions. To power PHEVs, Hitachi is developing a battery cell that combines high energy (for EV mode) and high power (for HEV mode). Although these objectives conflict, a battery design that combines the two can be achieved by adopting a low-resistance structure and optimizing the composition of the active electrode material and the electrode thickness. Fig. 11 shows the battery and lists its specifications. Other measures adopted by Hitachi to ensure that the battery remains safe despite its higher energy capacity include the use of ceramic separators and the development of new electrolyte additives.

Note that, Hitachi Vehicle Energy, Ltd. and Hitachi, Ltd. are participating in the "Advanced Technology Research Project for the Application and Commercial Use of Lithium-ion Batteries" run by the New Energy and Industrial Technology Development Organization (NEDO), and are jointly undertaking some of the development of the next generation of high-energy batteries.



IEC: International Electrotechnical Commission

Fig. 9—Battery Life.
Power remains at 95% after 100,000 cycles.

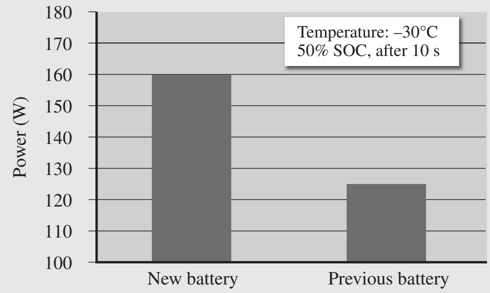


Fig. 10—Power at Low Temperature.
Low-temperature power is 1.3-fold that of the previous battery.

Parameter	Specification
Size (mm)	148 × 91 × 26.5
Mass (kg)	0.72
Specific power (Ah)	28
Specific energy (W/kg)	2,300
Energy density (Wh/kg)	140

Fig. 11—Lithium-ion Battery for PHEVs and EVs.
This prismatic battery for PHEVs and EVs features a high level of safety as well as combining both high energy (for EV mode) and high power (for HEV mode).

CONCLUSIONS

This article has described Hitachi's generation-3.5 battery packs and the newly developed battery control system technologies they incorporate, and also the new generation of high-power cells and high-energy cells currently under development.

Through these next-generation battery cells and battery control system technologies, and also the establishment of production systems designed for global deployment, Hitachi is seeking to pave the way for the wider adoption of electrically powered vehicles and deliver automotive lithium-ion batteries with higher levels of cost-performance.

REFERENCES

(1) "Latest Technologies for Battery and Electric Drive Components," Hitachi Review **60**, pp. 17–21 (Feb. 2011).

(2) S. Takahashi et al., "Lithium Ion Battery and Materials Technology for Low-carbon Society," Hitachi Hyoron **95**, pp. 358–363 (May 2013) in Japanese.

ABOUT THE AUTHORS

Fumihiro Namiki

Business Planning Department, Hitachi Vehicle Energy, Ltd. He is currently engaged in planning for the lithium-ion battery business.

Toshikazu Maeshima

BBX Development Division, Hitachi Vehicle Energy, Ltd. He is currently engaged in the development of lithium-ion batteries.

Kosuke Inoue

Production Engineering Department, Production Division, Hitachi Vehicle Energy, Ltd. He is currently engaged in the development of lithium-ion battery production lines. Mr. Inoue is a Professional Engineer of mechanical engineering.

Hidemasa Kawai

Battery Design Department, Battery Design & Development Division, Hitachi Vehicle Energy, Ltd. He is currently engaged in the development of lithium-ion cells for HEVs.

Shoji Saibara

Battery Design Department, Battery Design & Development Division, Hitachi Vehicle Energy, Ltd. He is currently engaged in the development of lithium-ion cells for PHEVs and EVs.

Toshiyuki Nanto

Battery Design & Management Division, Hitachi Vehicle Energy, Ltd. He is currently engaged in design management for lithium-ion battery products.

Developments in Precision Power Train Sensors

Keiji Hanzawa
Shinobu Tashiro
Hiroaki Hoshika
Masahiro Matsumoto

OVERVIEW: The fuel economy and emissions performance demands on vehicle power trains are becoming more stringent for reasons relating to global environmental protection and the rising price of oil. There has also been a change in thinking on the measurement of emissions and fuel economy toward allowing for conditions where the temperature and humidity are closer to real driving conditions. Other changes include the electrification of power trains, such as in hybrid vehicles, and improvements in the running efficiency of internal combustion engines that result in more frequent use of engine operating modes in which sensor operation is more difficult, such as the Atkinson cycle. Hitachi Automotive Systems, Ltd. is supporting ongoing progress in power train control by making further improvements in sensor accuracy.

INTRODUCTION

HITACHI supplies customers around the world with a variety of systems for the driving, cornering, and braking of vehicles. By using a range of different sensors to determine conditions in the power train, vehicle body movements, and what is happening around the vehicle, these systems ensure a driving experience that is safe and comfortable, and that is conscious of the global environment (see Fig. 1).

Automotive power trains have made rapid progress on electrification and reducing fuel consumption in recent years. This article describes advances in the performance of the sensors used in these power trains, looking at micro electromechanical system (MEMS) air flow sensors that reduce the error in intake pulsation, the integration of air intake relative humidity sensors and pressure sensors, and the adoption of digital signal output for sensors with network connectivity.

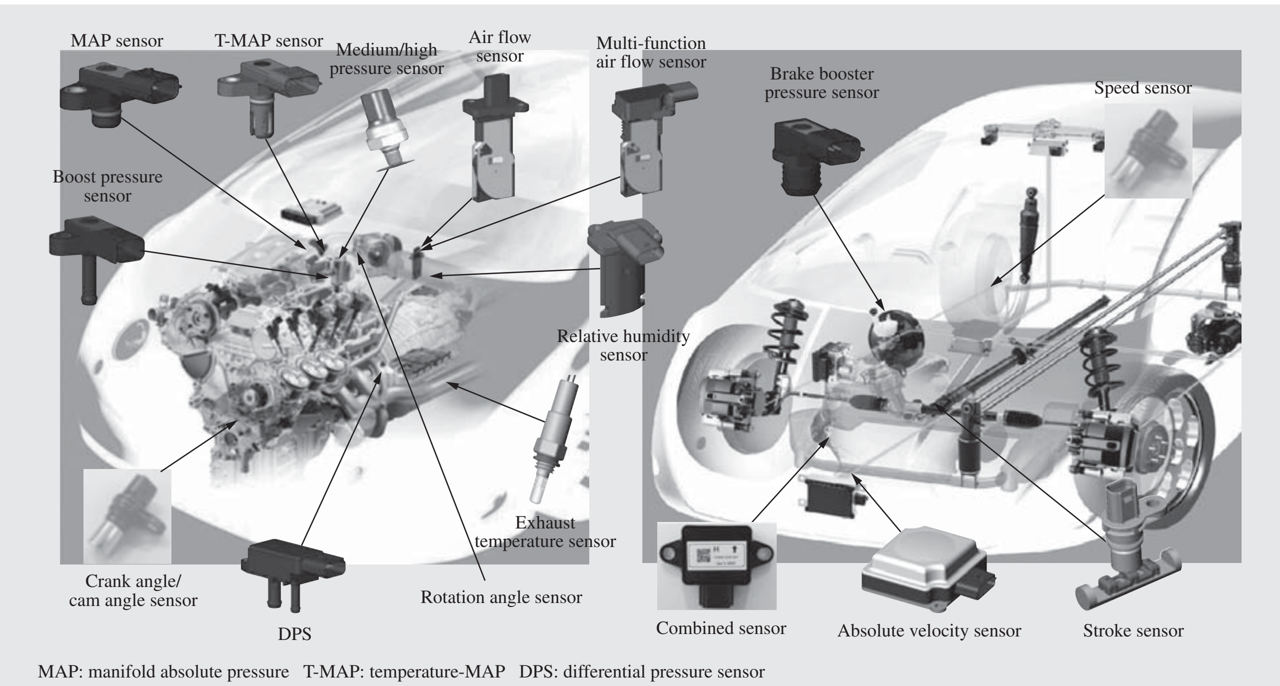


Fig. 1—Hitachi Power Train Sensors.
Modern vehicle power trains incorporate a variety of sensors that are used by control systems to deliver maximum environmental performance. Improvements in sensor accuracy lead directly to better control system performance.

MEMS AIR FLOW SENSORS

Since commercializing its first hot-wire air flow sensor in 1981, Hitachi has supplied a total of 200 million air flow sensors of various types over numerous generations. These have included the MEMS air flow sensors(1) introduced in 2005 that use a silicon diaphragm detection element to measure air flow in both directions. The second generation of these sensors currently in production operate the detector at a higher temperature for better anti-fouling and use 5-V drive to reduce power consumption. The third generation of sensors are currently being set for production. They are designed for lower cost and to achieve high precision when operating at a high level of intake pulsation.

Sensors for Engines with High Level of Intake Pulsation

The functions and performance sought in MEMS air flow sensors depend to a large extent on advances in the engines in which they are used.

When engines used the Otto cycle, the intake air flow remained unidirectional (into the engine) over most operating conditions. Modern engines, however, have features that include reduced pumping losses through the use of a high exhaust gas recirculation (EGR) ratio, and use of the Miller cycle (a variation on the Atkinson cycle) to provide a high expansion ratio. A consequence of this is that reverse flow (air flow out from the engine) is very common.

In Miller type Atkinson cycle engines, for example, which use valve timing control (VTC) to significantly delay the intake valve close (IVC) timing angle, most of the in-drawn air is expelled again by the piston, resulting in reverse flow and stronger pulsation. Also, when an engine's EGR ratio is raised, assuming the same total volume of air-fuel mixture is supplied to the cylinder, the amount of air is reduced by the amount of exhaust gas used. For the sensors that measure the air flow rate, this means that even if the size of the pulsations remains the same, they become larger in relative terms because of the reduction in mean air flow (see Fig. 2).

Hitachi divides the pulsation amplitude by the mean forward air flow to quantify it as the pulsation amplitude ratio. If the pulsation amplitude ratio exceeds 200%, this indicates that there is a period in which the air flow is fully reversed. As improvements are made in engine performance, this pulsation amplitude ratio is rising with each new vehicle generation (see Fig. 3).

As advances in engines and engine control result in a strongly pulsing flow in the vicinity of the air flow sensors, techniques for reducing error are important even in the case of MEMS air flow sensors that can cope with bidirectional flow.

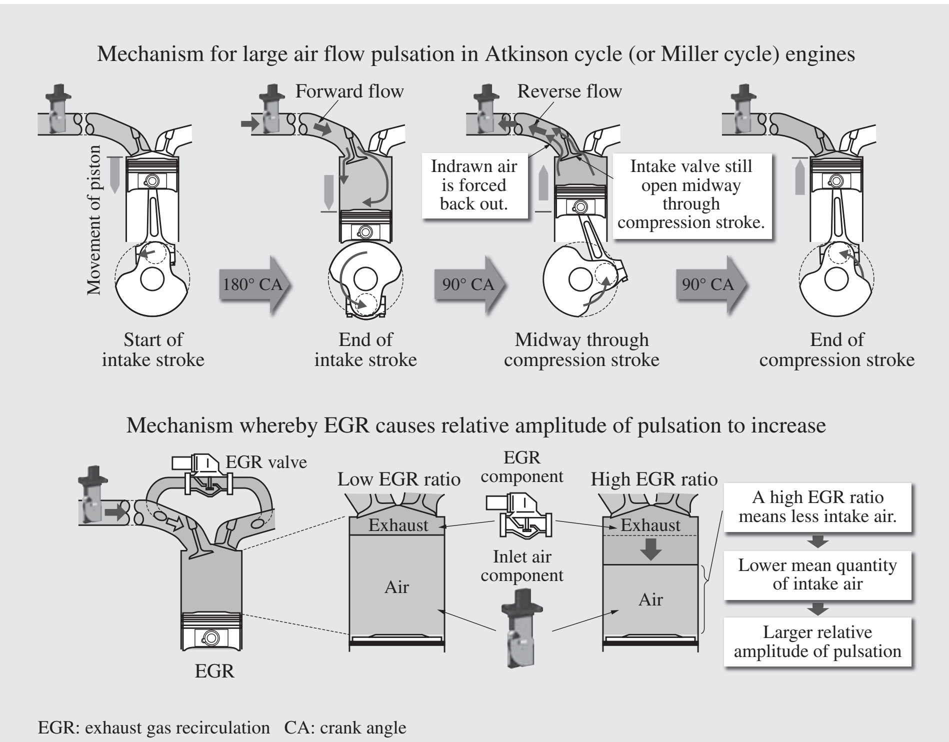


Fig. 2—Flow Pulsation Mechanism.
As Miller type Atkinson cycle engines delay the intake valve close timing until the middle of the compression stroke, a large amount of air is forced back out the inlet, resulting in large pulsations. If a large EGR is used, the increased use of recirculated exhaust gas reduces the amount of air taken in, making the pulsations larger relative to the intake air.

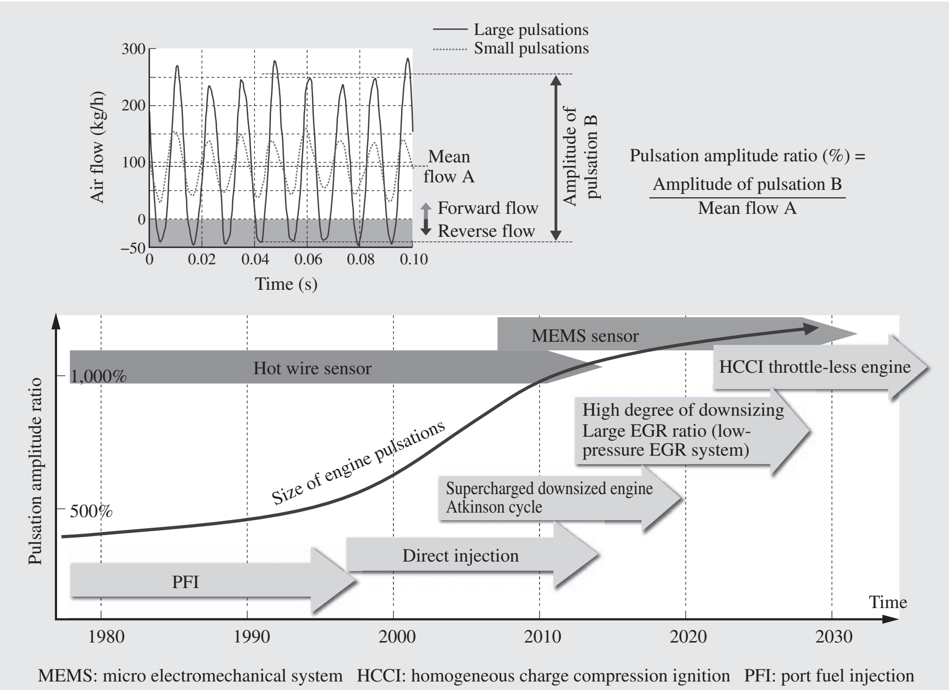


Fig. 3—Flow Pulsation Mechanism.
For quantitative measurements, Hitachi defines the size of pulsations in terms of their amplitude as a proportion of mean air flow. This pulsation amplitude ratio is increasing as engines become more advanced, and the accuracy of air flow measurement under pulsation conditions is closely related to advances in engine control.

Techniques for Reducing Air Flow Measurement Error Due to Pulsation

The error that occurs when inlet pulsations are large is due to a number of causes. The output signal of the air flow sensor is required to always represent the mean forward air flow. Accordingly, however accurate the sensor may be at measuring the forward air flow, the overall sensor error will be large if there is a measurement error in the reverse flow component or if this is not compensated for appropriately. Pulsation error has a variety of causes which are always interrelated, the main ones being the flow detector having a response that is too slow, non-linearity error (due to non-linear characteristics), and turbulence error (when turbulence in the air flow sensor itself causes suction when the flow reverses).

While this has been dealt with in the past using correction measures such as conventional signal filter processing or by the shape of the bypass channel in the air flow sensor, these provide inadequate correction for air flows with a very high level of pulsation.

To solve this problem, Hitachi Automotive Systems, Ltd. and Hitachi Research Laboratory jointly developed an application-specific integrated circuit (ASIC) digital signal processor (DSP) specifically for use in air flow sensors. The air flow sensor significantly reduces pulsation error by utilizing the high-speed computing capabilities of the DSP to process the signal internally. This includes performing separate signal correction for the forward and reverse directions, linearity processing in which the flow rate signal is converted to its physical amount before applying correction, and precise temperature compensation for the pulsation characteristics.

By optimizing the length of the secondary channel (the bypass through the sensor) and the inlet for reverse flow (outlet) to stabilize the air flow in the detector, Hitachi has succeeded in providing sufficient accuracy for trouble-free engine operation even under high levels of pulsation, such as pulsation amplitude ratios approaching 1,000% at which the sensor signal was unable to be used in the past (see Fig. 4).

MULTI-FUNCTION AIR FLOW SENSORS

While the predominant configuration has long been to connect different single-function sensors to the engine control unit (ECU), there is also growing demand for combining multiple sensors in a single multi-function package and performing mutual correction to improve their overall accuracy. In 2011, Hitachi became the first supplier to commence production of a multi-function air flow sensor that also included a relative humidity sensor and pressure sensor (see Fig. 5).

Hitachi is also working on the development of a new generation of devices that use a digital interface to improve the accuracy of the sensor signal passed to the ECU, incorporate network connectivity to reduce wire harness requirements, and provide more flexible onboard diagnostics (OBD).

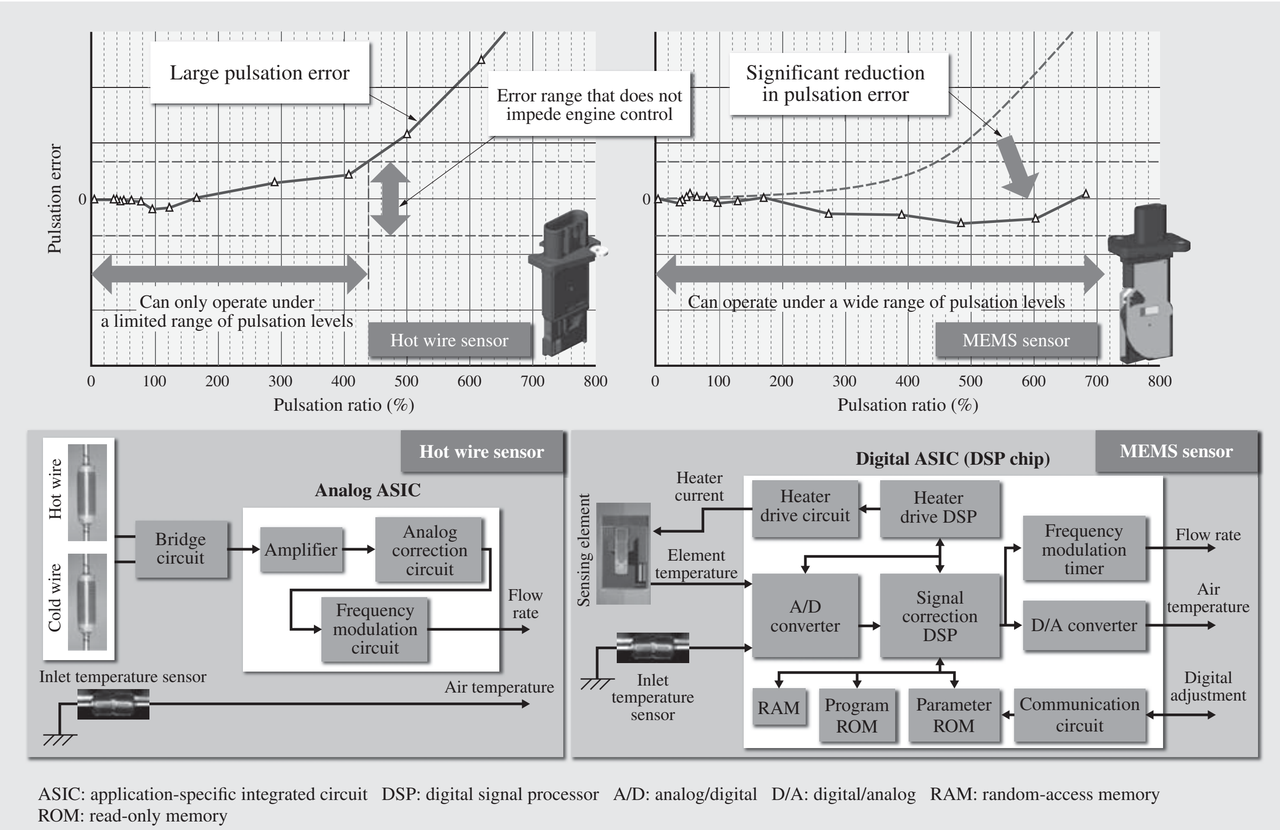


Fig. 4—Reducing Error in Air Flow Measurement Due to Pulsation.
As there is a limit to how accurately a pulsing flow can be measured using analog circuits, MEMS air flow sensors include a special-purpose DSP for internal digital signal processing to ensure sufficient accuracy to prevent any loss of engine control performance even when there is a very high level of flow pulsation.

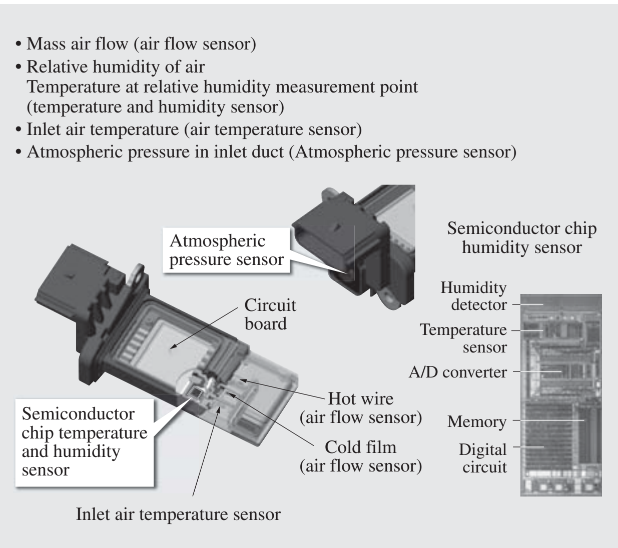


Fig. 5—Multi-function Air Flow Sensor.
In addition to its air flow sensor function, this sensor also measures the relative humidity and the pressure in the inlet duct. This allows the engine control to adapt to changes in weather, driving, and other conditions, and means that the engine control margins previously included to allow for changes in humidity can be allocated instead to fuel economy or other improvements.

Use of Multiple Sensors to Improve Control Accuracy

In addition to the mass air flow traditionally measured by sensors, the physical properties of the air taken in by the engine also include such things as moisture content (water vapor) and the pressure at the measurement point. Changes in these properties will cause an error in the mass air flow measured by the sensor that can be as high as several percent at low flow rates. This is because both hot wire and MEMS sensors work on the principle of detecting the transfer of heat by the air, and therefore are influenced by moisture-induced changes in the physical properties of the air.

Also, engine factors such as ignition performance, EGR limit, and fuel temperature are affected by the amount of moisture in the intake air, and these result in large changes in outcomes such as fuel consumption and the amount of pollutants produced. Accordingly, a key factor in improving environmental performance is to control the engine, along with exhaust gas treatment and other systems, in accordance with changes in the moisture content of the intake air.

While the existence of these errors was known in the past, the regulatory levels were not sufficiently tight for them to be a problem. With the market's emphasis on low fuel consumption and steadily more stringent regulations, however, semiconductor-chip-based relative humidity sensors have been added to multi-function air flow sensors to correct for the error caused by the moisture in intake air.

Relative humidity sensors are capacitive sensors. They consist of a capacitor with a dielectric made of moisture-sensitive polymer with a permittivity that varies as it absorbs water molecules from the air, the extent of which can be detected from the variation in the sensor's capacitance. These relative humidity sensors also incorporate a highly accurate temperature sensor. The absolute humidity of the air can then be calculated from this temperature and the relative humidity.

As the relative humidity varies with pressure, it is possible to obtain a very accurate measurement of the moisture being taken into the engine by using information from the built-in pressure sensor to correct for this effect.

The sensor also includes a microprocessor to provide the flexibility to work with various different engine control systems, allowing output of both the raw uncorrected sensor signals and the corrected values (see Fig. 6).

Accuracy Improvements in Sensor Signal Transmission

Improving sensor accuracy is pointless if the accuracy is degraded during signal transmission. Traditionally, most sensor signals have either been analog voltage outputs or frequency-modulated outputs that worked by varying a pulse frequency. However, this results in degradation of the final accuracy of the sensor signal due to errors that occur during signal transmission, such as fluctuations in the ground potential or the temperature characteristics of the modulation reference frequency, or due to conversion error in the analog-to-digital converter (ADC) in the ECU that converts the analog signal to a digital value.

As a result, high-precision sensors are increasingly converting signals to digital form to avoid these errors. Single-edge nibble transmission (SENT) communications is one example of a method for converting sensor signals to digital form. It can send two sensor signal channels over a single wire and can include use of cyclic redundancy check (CRC) error detection[(2)].

As it is also possible to multiplex multiple signal channels, the technique is suitable for applications like the multi-function air flow sensor that require the output of a number of sensor signals.

The SENT protocol provides one-way (sensor to ECU) communications and works by converting a

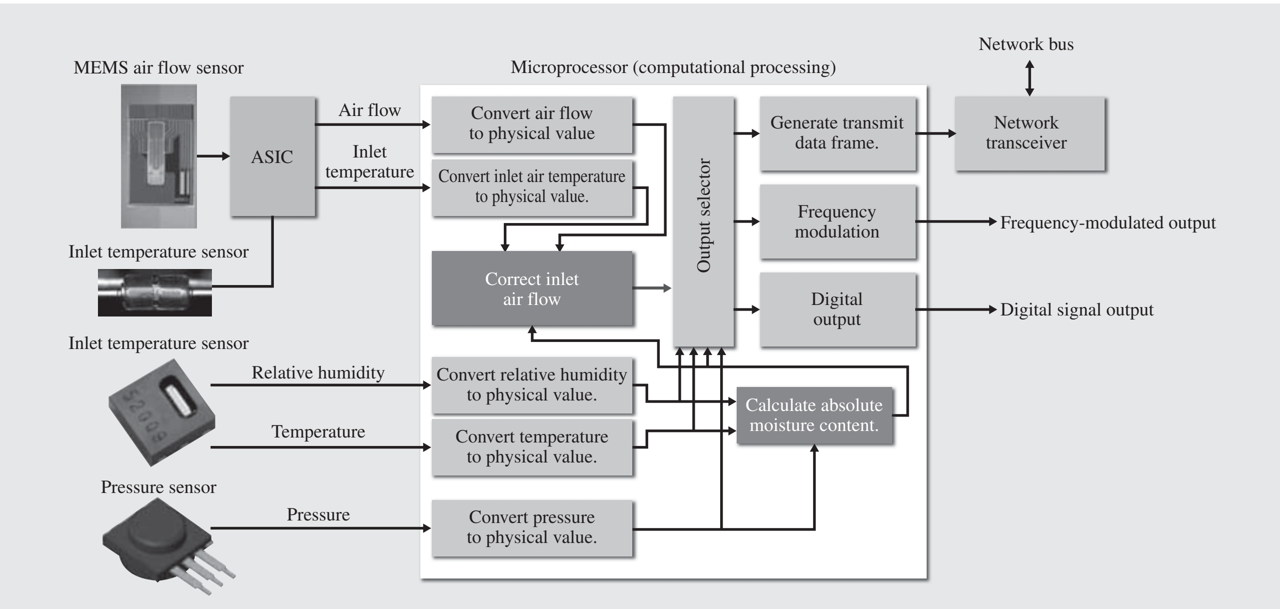


Fig. 6—Use of Multiple Sensors to Improve Accuracy (Multi-function Air Flow Sensor).
Use of multi-function sensors can improve overall signal accuracy because it means that information from certain sensors can be used to correct other sensor signals. This example shows how the relative humidity measurement can be corrected using pressure to calculate the absolute humidity. This can then be used to correct the inlet flow rate.

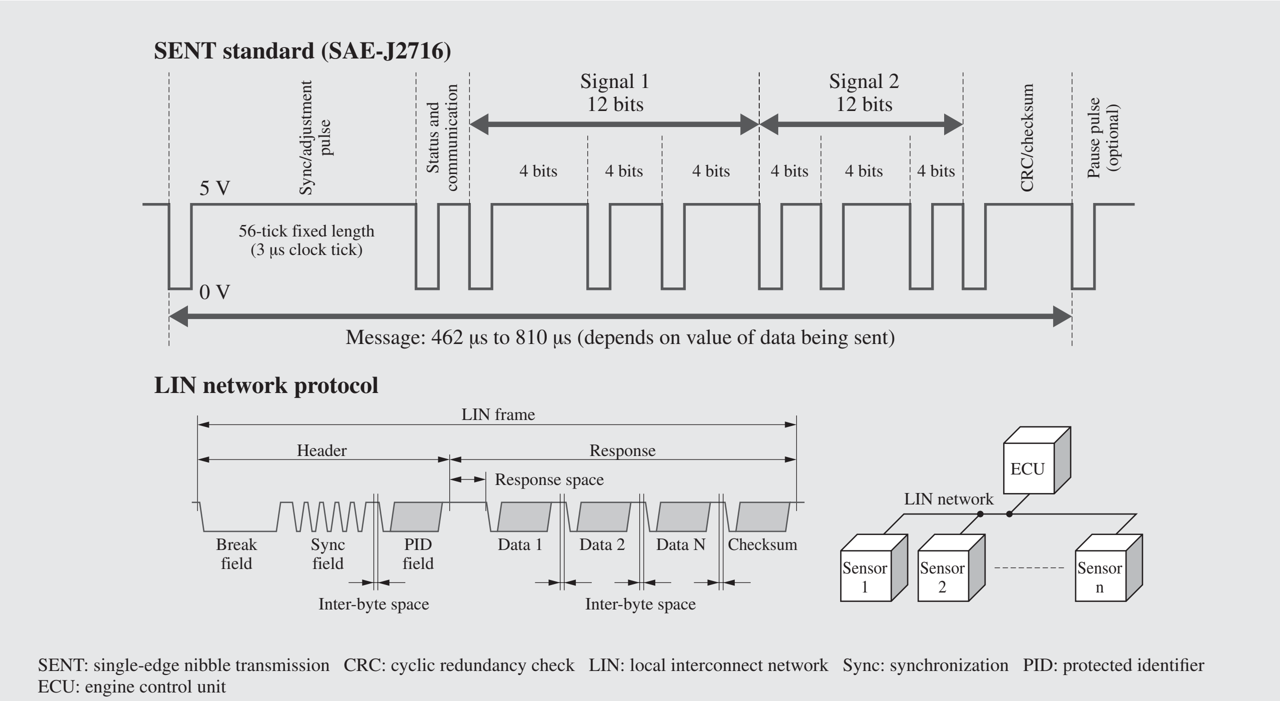


Fig. 7—Digitization of Sensor Output Signal.
The ability of SENT to transmit two signals per message with a cycle time of less than 1 ms makes it a suitable protocol for digital sensor signals. Already used for angle sensors, it is anticipated that its simplicity will see it used more widely in future. LIN, meanwhile, is a low-speed network that is already widely used in vehicle electronics, and it is starting to be used in power trains because of its flexibility and its ability to provide bidirectional communications over a single wire.

conventional analog signal to digital form. In addition to SENT, the sensors currently under development will also support the local interconnect network (LIN) protocol[3] (see Fig. 7). Hitachi is working on sensors that combine higher accuracy with flexibility, such as by taking advantage of the ability to communicate in both directions to improve accuracy by only activating those sensors that are required at particular time, as specified by a request from the ECU. Because converting sensor signals to digital form and providing network capabilities improves flexibility while reducing the loss of accuracy in the signal transmission process, this is the best type of interface for precision sensors.

CONCLUSIONS

This article has described advances in the accuracy of automotive sensors, including improvements in the measurement accuracy of MEMS air flow sensors under conditions of high pulsation, the integration of multi-function sensors, and the use of digital signals for sensor output.

The benefits of using precise, high-performance sensors to determine conditions such as those in the power train, vehicle body movements, or what is happening around the vehicle include improving the safety of vehicles and their power trains, resource saving, and global environmental improvement.

REFERENCES

(1) M. Kimata et al., “The latest trend in sensors for automobiles,” CMC Publishing (Feb. 2009) in Japanese.
(2) “SENT–Single Edge Nibble Transmission for Automotive Applications,” SAE-J2716 (2006).
(3) “LIN Specification Package Revision 2.1,” LIN Consortium (2006).

ABOUT THE AUTHORS

Keiji Hanzawa
Electronic Device Design Division, Powertrain & Electronic Control Systems Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of sensors and sensing systems. Mr. Hanzawa is a member of The Society of Automotive Engineers of Japan (JSAE).

Shinobu Tashiro
Electronic Device Design Division, Powertrain & Electronic Control Systems Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of sensors and sensing systems.

Hiroaki Hoshika
Electronic Device Design Division, Powertrain & Electronic Control Systems Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of sensors and sensing systems. Mr. Hoshika is a member of The Society of Automotive Engineers of Japan (JSAE).

Masahiro Matsumoto
Department of Green Mobility Research, Hitachi Research Laboratory, Hitachi, Ltd. He is currently engaged in the development of sensors and sensing systems. Mr. Matsumoto is a member of The Society of Instrument and Control Engineers (SICE).

Advanced Vehicle Safety Control System

Hiroshi Kuroda, Dr. Eng.
Atsushi Yokoyama
Taisetsu Tanimichi
Yuji Otsuka

OVERVIEW: Hitachi has been working on the development of integrated control systems for advanced vehicle safety since the latter half of the 1990s. Hitachi has already commercialized an ADAS controller incorporating a system that uses an "environmental recognition" stereo camera and data from various sensors for vehicle control. Development of the stereo camera included works on improving accuracy and increasing speed. Development of the ADAS controller, meanwhile, included creating an architecture that facilitated the inclusion a wide range of different functions to suit different vehicle models and markets. Building on these developments, Hitachi is now working on creating safer and more comfortable vehicles through the development of integrated vehicle control technologies designed to achieve 360° collision avoidance, and easy-to-use human-machine interfaces.

INTRODUCTION

ADAPTIVE cruise control (ACC) systems that use vehicle-mounted "environmental recognition" sensors (sensors for detecting objects in the region around the vehicle) to control the distance between preceding vehicles were first commercialized by DaimlerChrysler AG (now Daimler AG) in 1999. The vehicle control system was subsequently enhanced to apply the brake automatically in order to minimize damage in situations where a collision cannot be avoided outright, and a version was released that could prevent low-speed collisions. Another new function assists with the horizontal movement of the vehicle by detecting features such as road lanes.

Systems like these are called advanced safety systems. In addition to sensor technology for detecting objects in the region around the vehicle, they also require the fusion of control techniques for processing information from various other sensors with technology for using actuators to control the vehicle.

This article describes the environmental recognition stereo camera sensor, the advanced driver assistance system (ADAS) controller, and the integrated control system for advanced safety.

STEREO CAMERA

The following sections focus on the stereo camera jointly developed with Fuji Heavy Industries Ltd.

Overview of Stereo Camera

A stereo camera consists of separate left and right cameras. It can be used as an environmental recognition sensor capable of determining the position and three-dimensional shape of an object from the difference between the images of the object captured simultaneously by the two cameras (disparity)[1]. While other forms of environmental recognition sensors include laser radars, millimeter wave radars, and monocular cameras, the inherent strengths of stereo cameras include their ability to detect objects regardless of their composition or shape, and their high spatial resolution of depth and horizontal angle. On the other hand, stereo cameras also present a number of specific technical challenges before they can be adopted as vehicle-mounted sensors, including aiming and calibrating the optical axis, taking account of factors such as deterioration over time, and achieving fast and accurate image matching to determine disparity.

Fuji Heavy Industries, manufacturer of the Subaru brand of vehicles, has been working on the research and development of stereo cameras for many years. Hitachi Automotive Systems, Ltd. has been collaborating with the company on joint development since 2004, and through this work has overcome the problems mentioned above. The resulting stereo camera has been installed in numerous different models since first appearing on the Subaru Legacy in May 2008[1].

Design of Stereo Camera

The stereo camera consists of the left and right cameras and a main processing unit that handles image signal processing (see Fig.1).

The images from the left and right cameras are input to an image processing application-specific

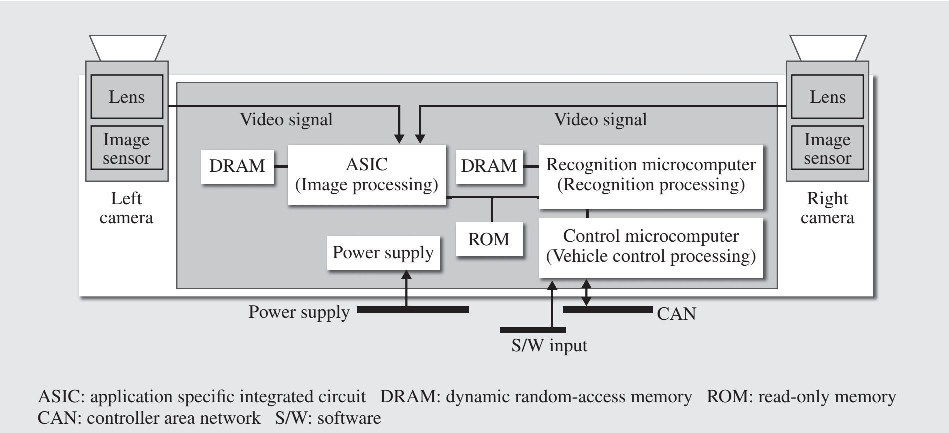


Fig. 1—Block Diagram of Stereo Camera.
This stereo camera jointly developed with Fuji Heavy Industries, Ltd. uses an ASIC to increase the speed of the disparity and other computationally intensive calculations.

integrated circuit (ASIC). The ASIC corrects distortion and peripheral darkening (lower light intensity around the edge of the lens) and then matches the two images to generate the disparity image. Here, a disparity image means one in which the disparity has been emphasized so that the distance can be determined for each pixel. The disparity image and other information required for recognition is stored in dynamic random-access memory (DRAM) by the recognition microcomputer. The recognition microcomputer then uses this information to detect obstacles such as other vehicles and pedestrians, identify white lines, and so on. The control microcomputer outputs control commands based on the recognition information, such as a command to issue a warning or apply the brakes.

Fig. 2—ADAS ECU Hardware.
The vehicle is controlled by a dedicated ECU designed for use with ADASs.

Future Development

While the stereo camera needs to be made smaller and lighter if it is to be adopted on a wider range of vehicle models, this raises problems such as a reduced range of object recognition if making the unit smaller results in a shorter baseline length (distance between left and the right cameras).

With the aim of producing small stereo cameras, Hitachi is working on the development of new image processing techniques that can reliably detect preceding vehicles in far distance.

ADAS CONTROLLER

The next section describes the design concepts and technologies used in an ADAS controller supplied to Nissan Motor Co., Ltd.

Overview of ADAS Controller

The ADAS controller is a dedicated electronic control unit (ECU) designed for implementing advanced safety control applications, something that has become an increasingly frequent feature of vehicles in recent years (see Fig. 2).

The first such applications, used for ACC, appeared around 1999. These were followed by the introduction of pre-crash safety systems, with a further series of new systems emerging around 2005, including lane departure prevention (LDP), lane departure warning (LDW), lane keep assist (LKS), forward collision warning (FCW), traffic sign recognition (TSR), intelligent head lamp control (IHC), and curve overshoot prevention (COP). Initially, each of these systems was implemented on a different ECU, as shown in Table 1.

While these systems use the same software functions regardless of vehicle model or market, the controllers on which they run are often different, depending on factors such as model, market, and date of commencing production. Changing to a different controller means the software functions needs to be ported, and this results in increased cost in terms of both

TABLE 1. ECUs Used for Different Systems

Different systems for advanced safety control have run on different ECUs.

System	ECU
ACC, FCW Pre-crash safety system	Radar
LDP, LDW, LKS, TSR, and IHC	Monocular camera
COP	ESC

ECU: electronic control unit ACC: adaptive cruise control
FCW: forward collision warning LDP: lane departure prevention
LDW: lane departure warning LKS: lane keeping system
TSR: traffic sign recognition IHC: intelligent head lamp control
COP: curve overshoot prevention ESC: electric stability control

time and money because the software functions must be retested on the new ECU even if no changes were made during this porting process. The aims in developing the ADAS controller included minimizing this problem and providing more flexibility in the choice of sensors and actuators, so that system cost would be reduced.

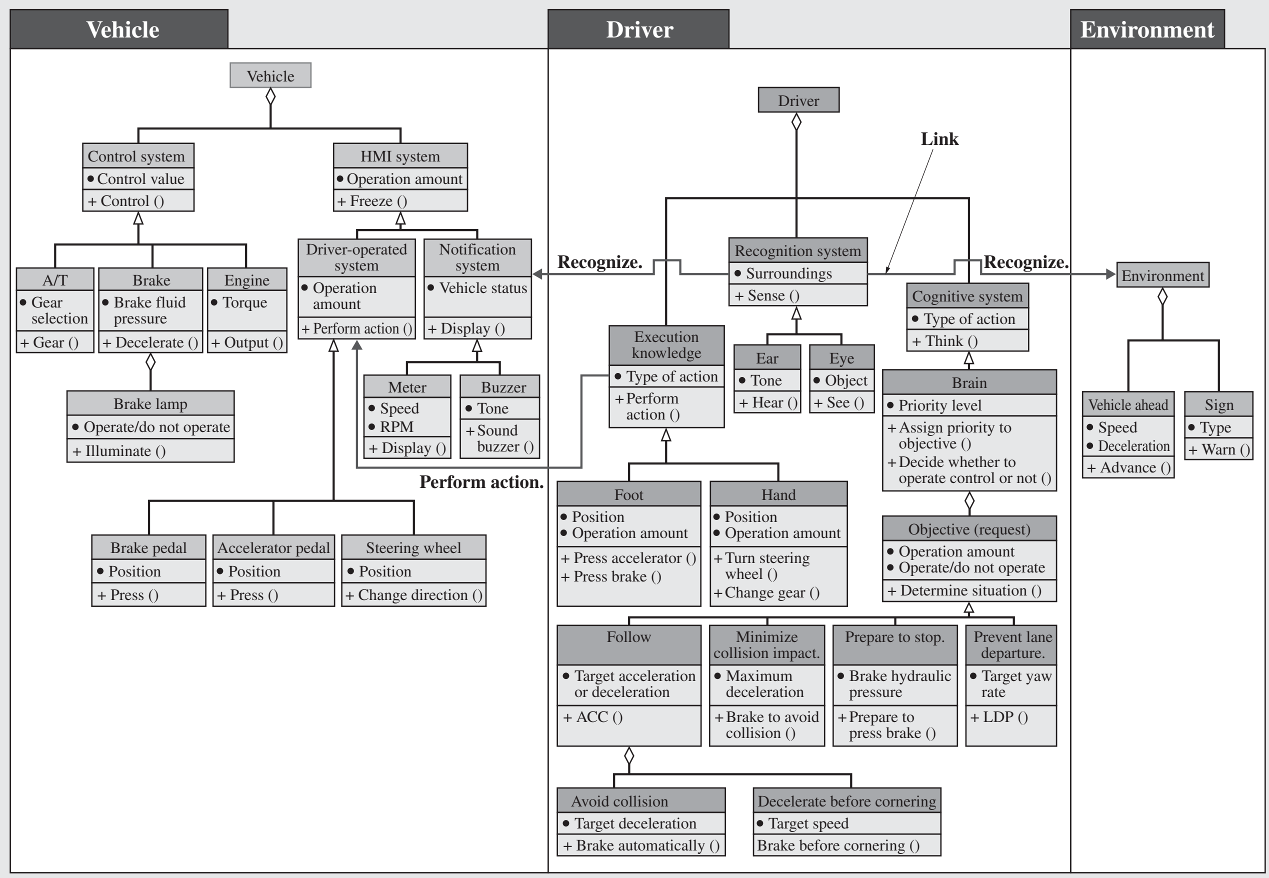
Development of ADAS Controller

The application software used on the ADAS controller has often been developed at different times and with different sensors, actuators, and other external devices in mind. This has resulted in complex interdependencies between different software systems, and with the sensors and actuators.

To deal with this, Hitachi undertook an analysis to determine which functions to include in the ADAS controller (see Fig. 3). To clarify the relative priority of each function and identify which functions were universal, the analysis used a class diagram to collate the functions that govern the movement of the vehicle, including those of the vehicle and driver.

The analysis succeeded in classifying functions into four categories. These are the sensor interface that encapsulates the functions dependent on sensors, the system section that provides the application's control functions, the arbitration section that handles the interdependencies between systems, and the output interface that provides the functions dependent on actuators.

Based on these results, the application software was structured along functional lines and re-implemented on the ADAS controller (see Fig. 4). This new structure



HMI: human machine interface A/T: automatic transmission RPM: revolution per minute

Fig. 3—Analysis of ADAS Systems.

The class diagram collates the functions that govern the movement of the vehicle, including those of the vehicle and driver.

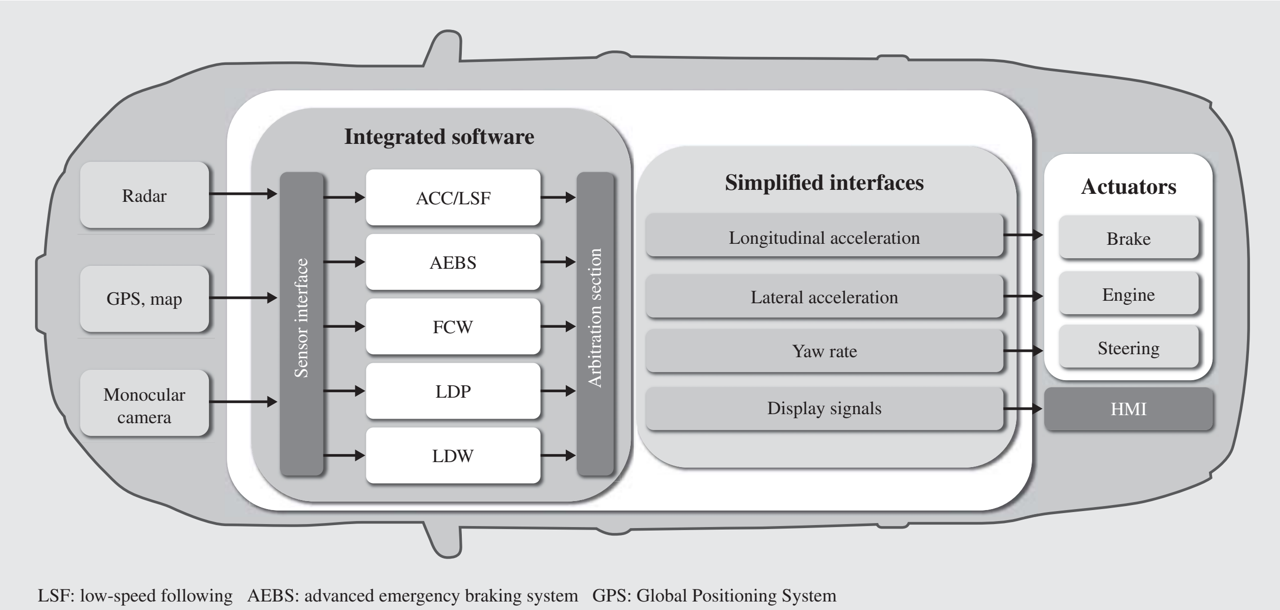


Fig. 4—Block Diagram of ADAS Controller.
The ADAS ECU is a general-purpose ECU used to consolidate software distributed around the vehicle into a single ECU.

minimized the dependencies between each part of the software and simplified the job of combining different systems and a variety of different sensors and actuators.

Future Development of ADAS Controller

It is anticipated that the ADAS controller will be further developed to become the "brain" of the vehicle in place of the driver, ultimately becoming a controller for autonomous vehicles. To this end, Hitachi is working on development that will be required in the future. These are (1) support for faster communication networks to allow the real-time acquisition of large amounts of information from around the vehicle, (2) more extensive functions for connecting to infrastructural communication systems to acquire information about areas not visible from the vehicle, and (3) incorporation of a real-time database able to select, in real-time, necessary information acquired by (1) and (2).

INTEGRATED CONTROL OF ADVANCED SAFETY

The integrated control system for advanced safety assists the driver by combining environmental recognition sensors, controllers, and actuators to partially replace the human functions of recognizing, deciding, and operating. Hitachi is working on expanding the functions of advanced safety systems, with a central role for its stereo cameras and ADAS controller.

Most advanced safety systems that have been developed to date are based on the combination of a forward-looking sensor, such as a stereo camera, with the engine, brake, and steering subsystems. In the future, however, the systems will require the integration of omnidirectional sensing systems such as radar or monitor cameras with a wide range of actuators, including inverters, electric motors, and suspensions.

One technique being pursued by Hitachi for expanding the range of sensing is the inclusion of an obstacle detection function in monitor cameras. Hitachi has already commercialized a function for detecting nearby obstacles that applies a recognition function to images from a rear-view camera or a bird's-eye-view (overview) image, and has implemented systems that issue a warning upon detecting a situation such as lane departure or a vehicle approaching from behind[2] (see Fig. 5).

In addition to expanding the sensing range of vehicle-mounted sensors, Hitachi is also developing car-to-X (C2X) systems for car-to-car or car-to-infrastructure communications. C2X technology can be used to develop safer driver assistance systems by providing drivers with information that was previously unavailable, such as the location of nearby cars at an intersection with poor visibility.

Development is also proceeding on G-Vectoring control, an advanced technology for enhancing vehicle driving performance. This control technique

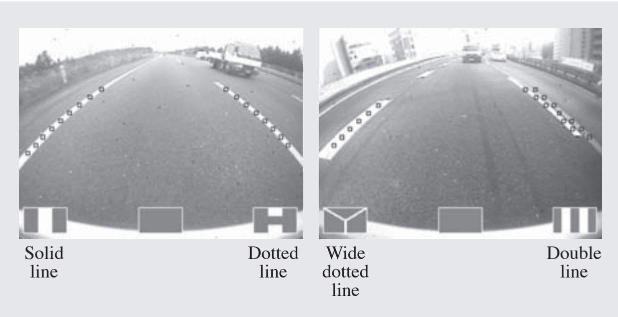


Fig. 5—Example of Road Marking Detection Using Rear Camera.
The system not only detects road marking but also determines their type.

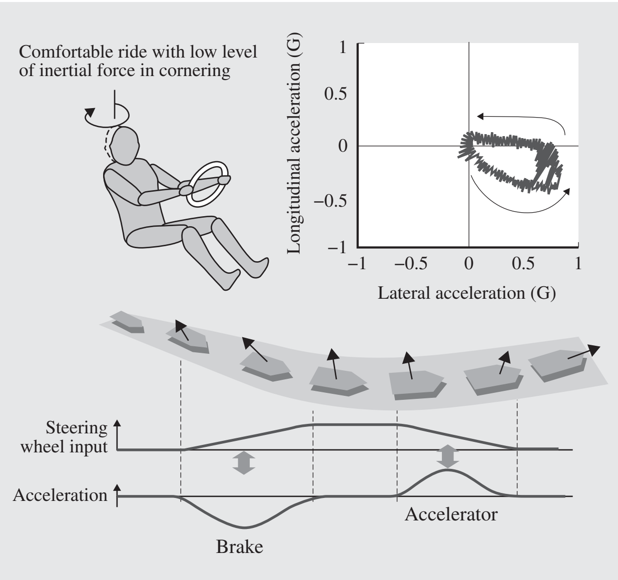


Fig. 6—G-Vectoring Control.
G-Vectoring provides smooth cornering by controlling the change in vehicle acceleration such that it traces a circular path.

achieves smooth and stable cornering by automatically decelerating through the corner in accordance with the driver's steering input(3) (see Fig. 6). There are also moves toward developing this into Preview G-Vectoring control whereby information about corners is obtained from map data and used to brake automatically before entering the corner(4).

Autonomous driving systems are progressive type of advanced safety system likely to be commercialized in the future. Whereas technologies such as ACC and LKS can be considered to be types of autonomous driving systems, manual and autonomous driving will continue to coexist until driving is completely automated from the time a passenger gets into the car until the time they get out. Because the human driver remains in charge of driving during this intermediate phase in the shift to autonomous driving, it is

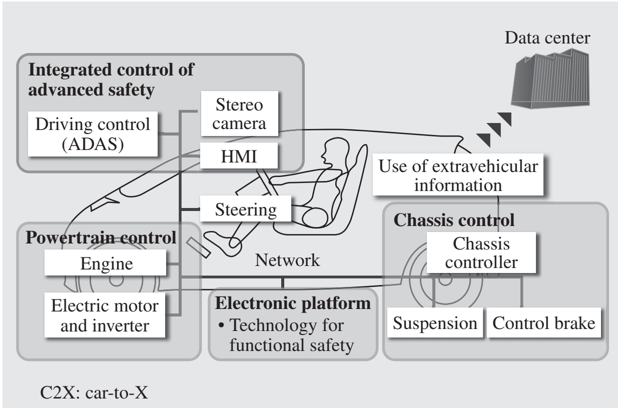


Fig. 7—Integrated Control System for Advanced Safety that Combines C2X and HMI.
A high level of performance in terms of safety, comfort, and the environment is achieved by integrating control of C2X with the HMI.

important that the system maintains an understanding of the driver's circumstances and presents appropriate information. Based on human-machine interface (HMI) technology that it has applied in fields like navigation systems and monitor cameras, Hitachi has proposed advances in HMIs for use in autonomous driving and is working on the implementation of comprehensive integrated control systems for advanced safety (see Fig. 7).

CONCLUSIONS

Autonomous driving will require environmental sensors able to cover the full 360° region around the vehicle along with the development of technologies that can process information and control vehicles safely while also using communications to handle the exchange of remote information not directly visible from the vehicle. The development of these technologies will need to include an understanding of the human functions of recognizing, deciding, and operating on the basis that the driver remains the one responsible for the driving.

REFERENCES

(1) S. Katahira et al., "Development of Hardware for a Driving Assistant System Using Stereo Image Recognition," The 14th Symposium on Sensing via Image Information, No. IN2-15 (Jun. 2008) in Japanese.

(2) M. Takemura et al., "Improvements to Durability of Lane Departure Warning System Using Rear-mounted Fish-eye Cameras," ViEW2012 Practical Workshop on Vision Technology, IS1-B5 (Dec. 2012) in Japanese.

(3) M. Yamakado et al., "Proposal of the Longitudinal Driver Model in Coordination with Vehicle Lateral Motion Based upon Jerk Information," Transactions of the Society of Automotive Engineers of Japan, Vol. 39, No. 3, pp.53–58 (May 2008) in Japanese.

(4) J. Takahashi et al., "A Study of Acceleration/Deceleration Model Based on the Time Variation of Road Curvature Ahead," Transactions of the Society of Automotive Engineers of Japan, Vol. 43, No. 1, pp.7–14 (Jan. 2012) in Japanese.

ABOUT THE AUTHORS

Hiroshi Kuroda, Dr. Eng.

Advanced Development Center, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of the advanced vehicle safety control system. Dr. Kuroda is a member of The Institute of Electronics, Information and Communication Engineers (IEICE) and the Society of Automotive Engineers of Japan (JSAE).

Atsushi Yokoyama

Department of Green Mobility Research, Information and Control Systems Research Center, Hitachi Research Laboratory, Hitachi, Ltd. He is currently engaged in the development of a chassis control system. Mr. Yokoyama is a member of the JSAE.

Taisetsu Tanimichi

Advanced Development Center, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of the advanced driving assistant system. Mr. Tanimichi is a member of the Information Processing Society of Japan (IPSJ) and the Society of Instrument and Control Engineers (SICE).

Yuji Otsuka

Advanced Development Center, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of image processing software for stereo cameras. Mr. Otsuka is a member of the IEICE and JSAE.

Chassis Control Systems for Safety, Environmental Performance, and Driving Comfort

Tadahiko Nogami
Motohiro Higuma
Yasuhiko Amari
Fumiyuki Yamaoka
Mitsuo Sasaki

OVERVIEW: Chassis subsystems, such as suspensions, steering, and brakes, play an important role in determining driving, cornering, and stopping performance of a vehicle. Hitachi supplies a wide range of such products and has drawn on technologies, which have built up with conventional products to incorporate electronics and electric drive into these systems. By drawing on capabilities from throughout Hitachi, including making further enhancements to cooperative control techniques for electric powertrains of HEVs and EVs and for engine-driven powertrains (a field in which progress is being made on improving fuel economy), integrating information and recognition systems such as car navigation and cameras, and developing systems for integrated control of chassis subsystems and for autonomous driving, Hitachi is seeking to be a supplier that can provide the entire world with vehicles that are safer, greener, and more comfortable.

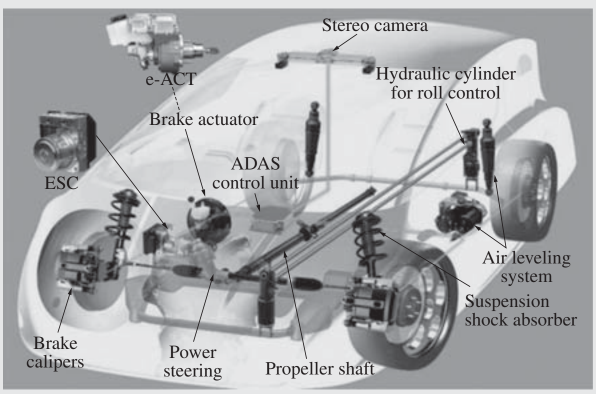
INTRODUCTION

ELIMINATING traffic accidents is an ever-present objective for society, and factors such as aging drivers are behind stronger demand for accident prevention systems. Along with electronic stability control (ESC) for preventing skidding, there are also moves toward mandating systems that brake automatically in emergent situations.

Meanwhile, hybrid electric vehicles (HEVs) and electric vehicles (EVs) are entering wider use in response to growing environmental awareness prompted by global warming. These electrically powered vehicles require systems that cooperatively control friction and regenerative braking (braking using electric motor), and also electric drives for subsystems such as power steering and braking to avoid relying on drive force or vacuum provided by engine. Progress is also being made on innovative techniques for improving fuel economy of engine-powered vehicles, with growing demand for systems that can turn off engine not just during idling, but also prior to stopping or when coasting.

Semi-active and active suspensions not only enhance ride comfort and improve handling, they also help make evasive action more effective and reassure passengers by maintaining stability when trying to avoid an accident.

Development continues on further improvements to safety, achieved by utilizing information such as map data from car navigation systems, recognition data from cameras and radar, and information acquired via car-to-car communications and car-to-infrastructure communications, with growing activity in the development of technology that has potential for use in autonomous driving systems. Through integrated control involving the cooperative interoperation of these technologies with chassis control systems, Hitachi is picking up the pace of development for systems that further enhance safety, environmental performance, and driving comfort of vehicles (see Fig. 1 and Fig. 2).



ESC: electronic stability control e-ACT: electrically-assisted actuation
ADAS: advanced driver assistance system

Fig. 1—Chassis Control System Products.
Hitachi supplies a variety of products for chassis systems, which play an important role in determining the driving, cornering, and stopping performance of a vehicle.

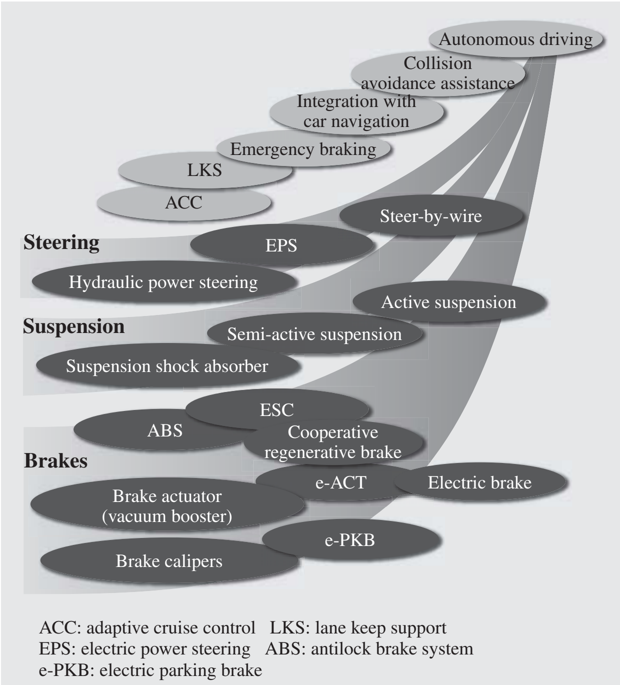


Fig. 2—Advances in Chassis Control Systems.
By drawing on technologies it has developed with conventional products to incorporate electronics and electric drive and enhance cooperative control techniques, Hitachi is creating vehicles that are safer, have better environmental performance, and are more comfortable.

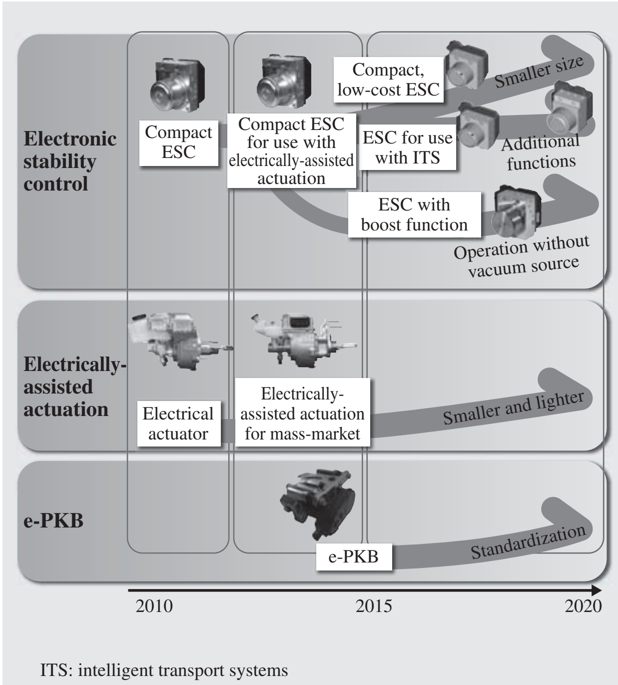


Fig. 3—Roadmap for Controlled Brakes.
With a product range that includes skidding prevention systems, electric actuator, and e-PKBs, Hitachi supplies brake systems that cover everything from normal driving conditions to extreme cases.

This article describes the current state of development of chassis control systems and the outlook for the future.

BRAKE SYSTEM

Developments in Brake Technology

Brake systems can be broadly divided into the "service brake" that decelerates a moving vehicle when the driver applies the brake pedal and the "parking brake" that prevents a stationary vehicle from moving. In addition to braking and parking, brake systems are also being required to provide greater safety, with antilock brake systems (ABSs) that prevent wheel lock and ESC that prevent vehicle spin and drift-out that becoming standard features. The safety, comfort, and environmental performance of vehicles have also been improved through optimal control of the braking force, with greater use being made of electric drive in parking brake mechanisms and devices for boosting the braking force applied by the driver. Controlled brakes have become critical parts when considering the performance of modern vehicles. Against the background of these trends, Hitachi is developing ESC, electrically-assisted actuation, and electric parking brakes (see Fig. 3).

ESC

ESC systems use sensors to monitor for behavior of vehicle instability (tire lock, wheel spin, vehicle spin, and drift-out), and control the braking force at each wheel to stabilize the vehicle. Hitachi has been commercializing the pressure sensor-less compact ESC systems since 2003. Next generation compact ESC system was released in 2007 with additional functions that included active rollover protection control and hill start assist control. The growing demand for ESC system is to reduce the size and weight and extend functionality, Hitachi is currently developing a low-cost ESC system that is 20% smaller and lighter than the current model. That target is emerging markets and small vehicles.

Meanwhile, the function controls the brake force to stabilize the vehicle behavior and the function of autonomous brake cooperates with camera, radar and/or other sensors operate not only the emergency condition but normal driving condition. Because of the need, ESC should be quieter, more responsive, and more durable, Hitachi is developing a system that utilizes its own gear pump technology.

As small vehicles, HEVs, EVs, and fuel-efficient green vehicles are being more widely adopted, and so there is growing demand for brake boost mechanisms that do not rely on vacuum from the engine. Hitachi is currently developing a compact ESC system for small vehicles that includes the boost function. Because the overall brake system has been made smaller and lighter through the integration of functions, making it easier to fit inside a vehicle, Hitachi anticipates that the new system will be widely adopted.

e-ACT

As an alternative brake actuation, Hitachi has been the first in the world to develop and commercialize its own electric brake actuator that uses a servo mechanism that does not rely on vacuum from the engine. Instead an electric motor assists the pedal force provided when the driver operates the brake pedal.

This electrically assisted actuation (e-ACT) includes a function for working in cooperation with the regenerative brake on an HEV or EV (see Fig. 4). It helps improve fuel economy by utilizing the superior control performance provided by an electric motor to obtain the optimal level of braking force from the friction brake, thereby significantly increasing energy regeneration by the regenerative brake. It also enhances vehicle safety and driving comfort by utilizing the precise control performance of e-ACT to implement automatic braking and other intelligent transport system (ITS) functions in conjunction with sensors such as cameras or radar. With an ability to modify the pedal feel by software, the system also provides added value not available on conventional brake system.

The popularization of HEVs, EVs, and ITS functions is driving growing demand for brake actuator with a high level of controllability. To improve fuel economy, safety, and driving comfort, Hitachi is developing and promoting low-cost e-ACT products that feature small size, light weight, and ease of installation to allow this technology to be utilized by a larger number of vehicle models in the future.

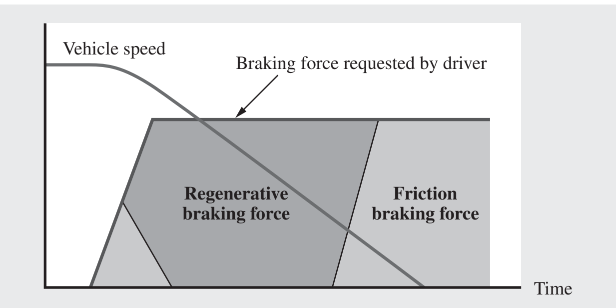


Fig. 4—Cooperative Control of e-ACT and Regenerative Brake.
e-ACT works in conjunction with the regenerative brake, adjusting the friction brake and controlling the two mechanisms in tandem to provide the driver with the intended braking force.

e-PKB

There is an ongoing trend toward the use of electric parking brakes (e-PKBs) with the aim of providing simpler operation and greater flexibility in interior layout. To make automatic parking brakes possible, Hitachi has minimized brake noise, increased the speed with which the parking brake can be released, and adopted its own actuators, which combine transmission efficiency with an ability to maintain clamping force. Through these initiatives, Hitachi is considering safety and the environment by reducing the weight of the overall brake system, making the calipers and motor smaller and lighter, and also ensuring that the system works with idling stop systems and collision prevention and minimization systems.

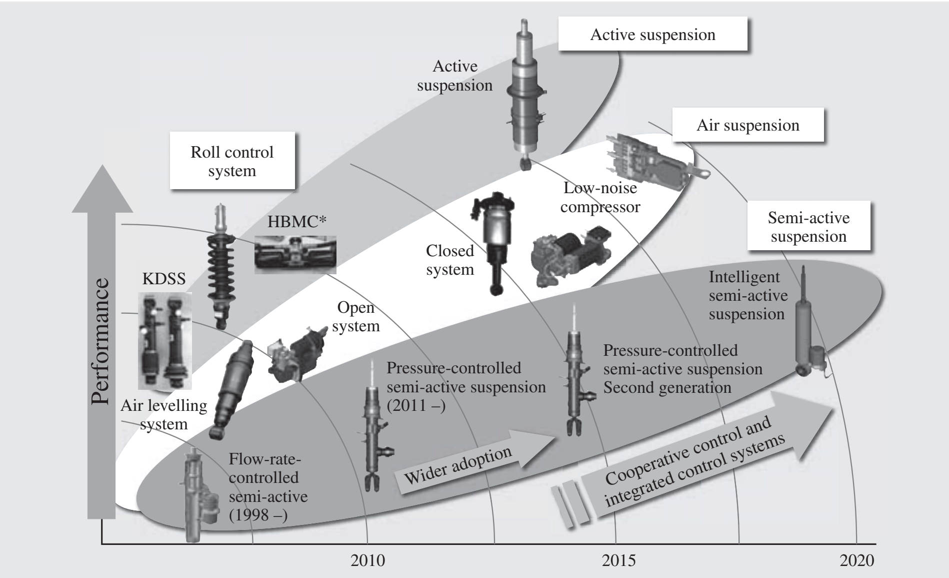
SUSPENSION SYSTEMS

Developments in Suspension Technology

Through its influence on ride comfort and handling, the suspension is an important system for ensuring driving comfort by providing a sense of stability and reassurance and by being less tiring for the driver. In particular, controlled suspensions provide a high level of both handling and ride comfort. At the same time that greater use is being made of these in small, low-cost vehicles, mainly in the form of semi-active suspension, progress also continues on improving performance through integrated control and cooperative operation with other chassis control systems (see Fig. 5).

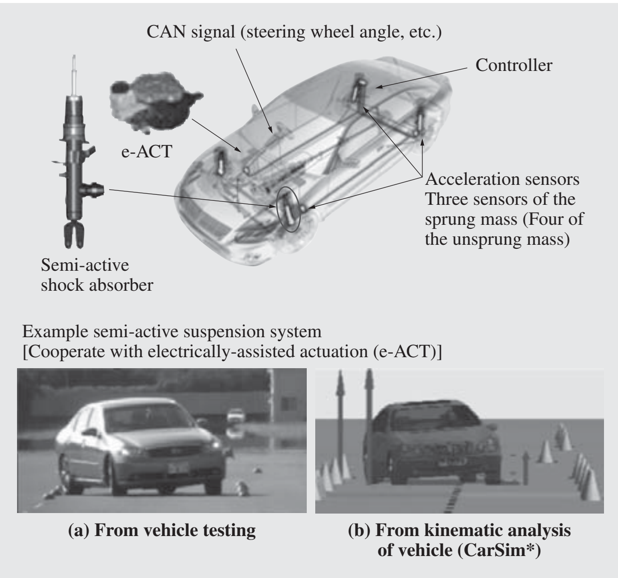
Semi-active Suspension

Semi-active suspension controls the damping force characteristics of shock absorbers on the basis of vehicle body movement to reduce vibration in the 2 Hz–8 Hz range, to which people are most sensitive (becoming nauseated), while also suppressing other low-frequency shaking of the vehicle body. Hitachi has used its own control valve designs to develop shock absorbers for semi-active suspension that provide a wide range of damping forces and quick response. These shock absorbers have been adopted in an increasing number of vehicles, primarily high-end models. In addition to reducing the size and cost of the shock absorbers so that they will be used more widely, Hitachi's plans for the future include developing cooperative control systems that work with controlled



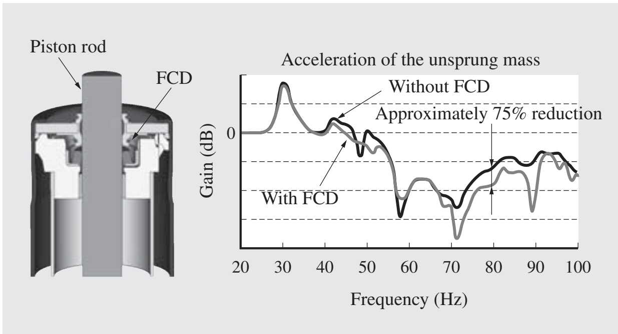
KDSS: kinetic dynamic suspension system HBMC: hydraulic body motion control
*HMBC is a product name of Nissan Motor Co., Ltd.

Fig. 5—Roadmap for Controlled Suspension.
Use of semi-active suspension, in particular, is extending beyond top-end models to also include small, low-cost vehicles, with performance improvements being achieved through integrated control in cooperation with other chassis control systems.



CAN: controller area network
* CarSim is a trademark or registered trademark of Mechanical Simulation Corporation of the USA.

Fig. 6—Cooperative Control System for Semi-active Suspension and Controlled Brake.
Cooperative control of the semi-active suspension and brake (e-ACT) can improve vehicle stability when taking evasive action.



FCD: friction control device

Fig. 7—Structure and Benefits of FCDs.
Fitting FCDs significantly reduces high-frequency vibrations of the unsprung mass with major benefits for ride comfort.

brakes and other subsystems with the aims of making evasive action to prevent an accident more effective and providing reassurance (see Fig. 6).

Improvements to Ride Comfort

This section describes friction control devices (FCDs), a technology for improving ride comfort. FCDs are useful for reducing vibrations in the high-frequency range (30 Hz and higher), which are difficult to control through hydraulic damping force and yet are an important aspect of improving ride comfort. FCDs help achieve better ride comfort, with specific benefits that include smooth standing starts, reducing the shock of driving over bumps, and less tire pattern noise. Their uses in recent years have included light vehicles, where they provide a means of preventing the harsh ride that results when using a set of fuel-efficient tires whose inflation pressure is tipically higher than normal tires, and run-flat tires to improve ride comfort and reduce pattern noise while still improving safety. Hitachi has already been producing FCDs for more than a decade, during which time they have entered wider use, and has developed improved versions to satisfy the rising level of expectation for ride comfort (see Fig. 7).

Along with advances in electronically controlled suspension, improving on technologies like this one is an important challenge, and Hitachi is working on products that match customer needs by further developing and combining both electronically controlled systems and mechanical techniques.

STEERING SYSTEMS

Developments in Steering Technology

Use of electric power steering (EPS) has grown steadily since it was first adopted in light vehicles in the late 1980s, with a forecast that approximately 50% of all vehicles manufactured in 2015 will have EPS. This is a consequence of how the high price of oil and growing environmental awareness in recent years have focused attention on fuel economy, and also, EPS provides estimated fuel savings of approximately 3% to 4% is the reason. In Japan, where the number of models available as HEVs or with idling stop is growing, it is estimated that approximately 80% of 2015 vehicles will use EPS. Given these circumstances, Hitachi has focused its product range on pinion EPS (PEPS), and is also developing dual-pinion EPS (DEPS) and belt-drive EPS (BEPS) for higher output and better steering feel (see Fig. 8).

EPS with Better Steering Feel

With an increasing number of vehicles including EPS as standard equipment in recent years being in their second or third generation, there are growing demands for EPS to provide better steering performance and to minimize minor steering uncomfortable behavior transmitted from the vehicle. Hitachi has developed the logics for achieving this. Fig. 9 shows effectiveness of the disturbances suppressing control. By using control logic of minimizing the steering wheel vibration caused by juddering or kickback from the road surface, the steering wheel vibration was reduced about 30%. Also, Fig. 10 shows an example of applying the control logic of friction compensate in the EPS's mechanical systems, where almost 66% of the steering wheel torque in starting to turn was reduced. This gives drivers an easier steering feel, requiring less effort to make small steering angle adjustments. The control logic can also be modified for use with active steering based on steering inputs from other systems and corrections for assist curve characteristics, and the interfaces and software structure having a system configuration that can handle diversified requirements.

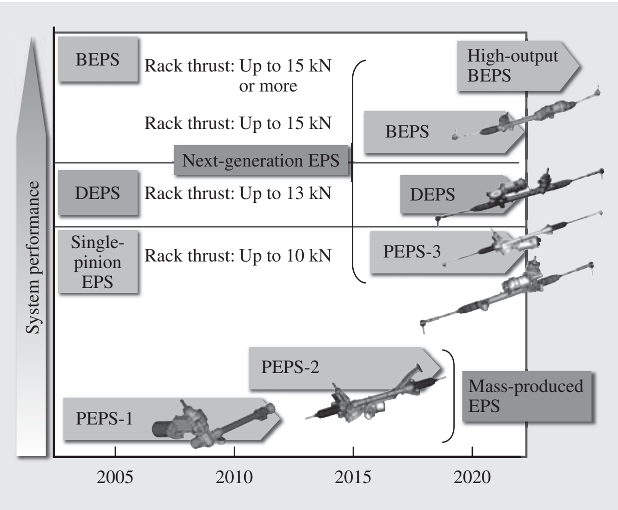


Fig. 8—Roadmap for EPS.
In addition to PEPS, Hitachi is also developing DEPS and BEPS to suit a wider range of vehicles.

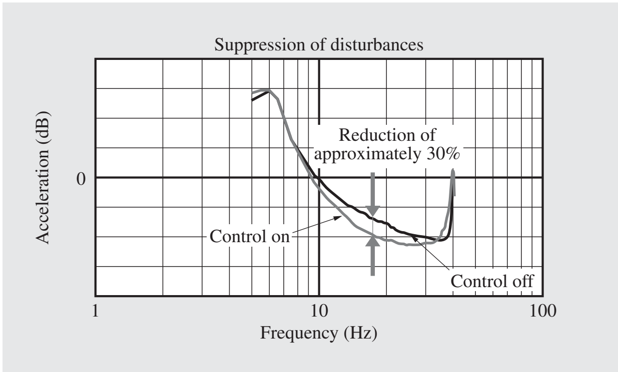


Fig. 9—Effectiveness of Control Technique for Suppressing Disturbances.
The control technique improves the feel of steering by reducing the transmission to the steering wheel of kickback from the road surface and of unpleasant vibrations.

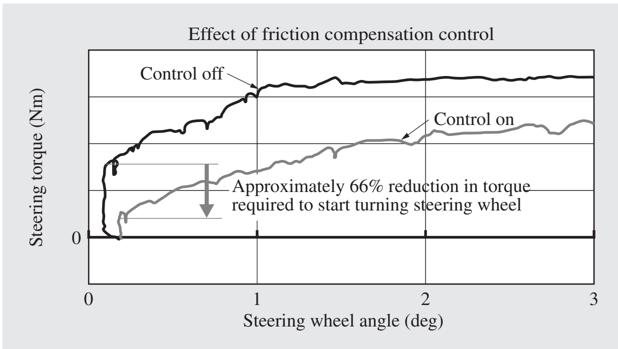


Fig. 10—Effectiveness of Friction Compensation Control.
A control system that compensates for friction in mechanical systems provides a smoother feel to the steering by significantly reducing the torque required to start turning the steering wheel from the center position.

Functional Safety

The ISO 26262 international standard for functional safety was published in 2012 and Original Equipment Manufacturers (OEMs) and suppliers globally introduce to this safety concept into products development. As the global consensus is that the automotive safety integrity level (ASIL) that applies to EPS is level D, the top level of safety design is required. To achieve the requirement, redundancies are adopted for crucial sensors and dual-core and lock-step configurations are used in microcomputers. There has also been growing demand recently for a "keep assist" feature that keeps the steering assist function working in the event of a breakdown. Hitachi intends to develop systems in the future that will satisfy even higher safety requirements.

CONCLUSIONS

This article has looked at brakes, suspensions, and steering, describing the current state of development for chassis control systems and the outlook for the future.

Chassis control systems include many safety-critical components, with each subsystem requiring high reliability. A high level of functional safety performance is also essential if these are to be controlled in an integrated way through interoperation with other systems. Advances in integrated chassis control systems can provide vehicles with a high level of safety, environmental performance, and driving comfort.

REFERENCES

(1) Y. Nemoto et al., "Development of Automotive Systems towards Environmental Protection and Safe Driving," Hitachi Hyoron **91**, pp. 755–759 (Oct. 2009) in Japanese.

(2) Y. Ohtani et al., "Development of an Electrically-Driven Intelligent Brake Unit," SAE, 2011-01-0572 (Jan. 2011).

(3) R. Hirao et al., "Improvement in limit Region Performance of a Vehicle with Damping Force Control based on G-Vectoring Concept," Proceedings of Technical Conference of the Society of Automotive Engineers of Japan, No.145 – 11 (Oct. 2011) in Japanese.

(4) Yano Research Institute, "Electric Power Steering Systems Market 2010," (Sept. 2010) in Japanese.

ABOUT THE AUTHORS

Tadahiko Nogami

Technology Development Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of automotive technology. Mr. Nogami is a member of The Japan Society of Mechanical Engineers (JSME).

Motohiro Higuma

Technical Center, Hitachi Automotive Systems Europe GmbH. He is currently engaged in the development of ESC. Mr. Higuma is a member of the Society of Automotive Engineers of Japan (JSAE).

Yasuhiko Amari

Brake Design Department, Design Division, Drive Control Systems Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of e-ACT.

Fumiyuki Yamaoka

Chassis Control System Design Department, Engine Components & Control Brake Design Division, Engine Components Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of control suspension systems. Mr. Yamaoka is a member of the JSAE.

Mitsuo Sasaki

Design Department, Power Steering Design Divsion, Hitachi Automotive Systems Steering, Ltd. He is currently engaged in the design of safety for EPS. Mr. Sasaki is a member of the JSAE.

Car Information System for Added Value in Connected Cars

Akira Yano
Toyota Honda
Akio Hayashi
Hirohisa Miyazawa
Haruhiko Sawajiri

OVERVIEW: Along with the interest in recent years in building a smart society in which people can live in harmony with the environment, easy-to-use driving support systems with benefits such as reducing congestion have been commercialized with the aim of providing safe, secure, and comfortable mobility. Amid these developments, and taking advantage of the spread of smartphones and advances in mobile communications, work on "connected cars" that connect vehicles to the Internet to create new value has gathered pace. Clarion Co., Ltd. supplies both telematics services and in-vehicle infotainment systems designed for these "connected cars." In developing new services that utilize car information from "connected cars," Hitachi is undertaking work that takes account of automotive security. In the future, Hitachi intends to utilize its know-how in fields such as in-vehicle infotainment systems and vehicle control technology to investigate services that create new value.

INTRODUCTION

ALONG with environmental changes such as global warming in recent years, growing interest in building a smart society in which people can live in harmony with the environment has led to measures being adopted in a variety of fields[1].

With the aims of providing safe, secure, and comfortable mobility, new services have been introduced in the automotive field that utilize intelligent transport systems (ITSs) to help alleviate traffic congestion and make driving more pleasant, for example by delivering information on congestion through vehicle information and communication systems (VICSs) and using it in car navigation (including taking account of congestion in route selection), and electronic toll collection (ETC) systems to provide quick passage through toll booths. Amid these developments, and taking advantage of the rapid spread of smartphones and advances in mobile communications, progress is being made in the provision of smart mobility that is safe, secure, comfortable, and ecological, with increasing work on "connected cars" that connect vehicles to the Internet to create new value[2].

In the area of in-vehicle infotainment systems, integration with smartphones is making it possible for the systems to do things such as interfacing with smartphone applications and accessing content from the Internet. Progress is also being made in the development of new services that utilize not only vehicle location but also other car information, including sensor information for supporting safe driving, car insurance, and remote on-board diagnostics (OBD).

This article describes the Clarion Telematics Service and its use of smartphones, and also use of car information and its application in automotive security.

CLARION TELEMATICS SERVICE

Clarion supplies telematics services that integrate smartphones with in-vehicle infotainment systems such as car navigation, displays, and audio equipment to make driving more pleasant by utilizing center services and content on the Internet.

Advances in Connected In-vehicle Infotainment Systems

(1) Linking in-vehicle infotainment systems to center systems

By using a network to link in-vehicle infotainment systems to a center system, some of the in-vehicle functions can be implemented instead on the center system (see Fig. 1).

Because it simplifies access to new information and the upgrading and adding of new functions to the in-vehicle infotainment system, users can be provided with new value.

(2) Use of cloud services

By combining large amounts of diverse cloud-based information, such as information that is held at the center, updated in real time, or obtained from sources such as social networking services (SNSs), it is possible to use the in-vehicle infotainment system

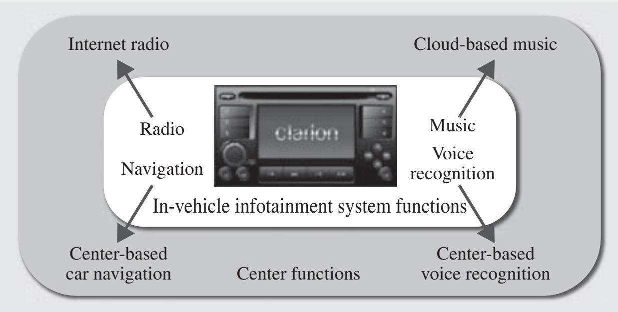


Fig. 1—In-vehicle Infotainment System Functions and Center Functions.
The functions provided by the in-vehicle infotainment system can be implemented at the center.

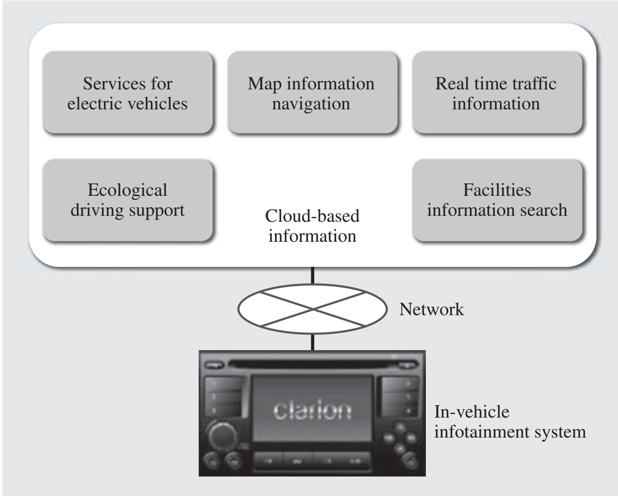


Fig. 2—Provision of Services that Use Cloud-based Information.
Comfort, security, and convenience can be achieved by providing drivers with cloud-based information.

as a conduit for providing the driver with services that are easy to use, safe, and convenient (see Fig. 2).

Taking advantage of this potential, Clarion has developed and launched cloud information network services for vehicles while also supplying the networked in-vehicle infotainment systems that can connect to these services.

Services Provided by Clarion Telematics

(1) System solution services

Clarion Telematics supplies system solution services that are specific to vehicles. These include infotainment services (such as news, weather, SNSs, and Internet radio), a map update service for car navigation systems, a software update service, a center-based voice recognition service, and a service for providing drivers with vehicle information and information from dealers(3).

(2) Center-based voice recognition service

This important service can provide an input mechanism suitable for use when driving. It uses Google*1 technologies for center-based voice recognition and search in combination with Clarion's own center-based voice processing technology (see Fig. 3).

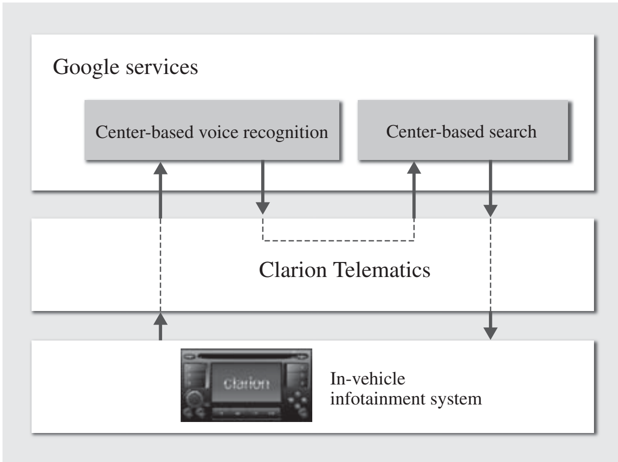


Fig. 3—Block Diagram of Center-based Voice Recognition.
Timely information can be delivered to drivers using center-based voice recognition and search functions.

Center-based voice recognition is intended to improve recognition accuracy and make in-vehicle use of car navigation functions such as destination search easier. The search function can also use natural language voice recognition. For example, the user can say "I want to eat Italian" to search for Italian restaurants near their current location or destination.

(3) Safety considerations

Clarion has also utilized the know-how it acquired in the development of in-vehicle infotainment systems to provide safe services suitable for use from vehicles. The operation of the in-vehicle infotainment system is designed to be easy for the driver to use while in the vehicle, and Clarion Telematics also includes a function to enable or disable operation of the system while the vehicle is moving.

Structure of Clarion Telematics

(1) Overall structure of Clarion Telematics Service

The Clarion Telematics Service is a network service that supplies information to vehicles and includes the content management, security measures, and content required to deliver the service. To ensure flexibility and optimal delivery, the service operates

*1 Google is a registered trademark of Google Inc.

from Clarion's own center and draws on other cloud services as required.

(2) Connection between in-vehicle infotainment systems and smartphones

As smartphones are used to relay communications between the in-vehicle infotainment system and center, the choice of connection type is important.

Clarion Telematics supports both an "image transfer method" for transmitting smartphone image data to the in-vehicle infotainment system and a "content transfer method" for transfer of other data (see Table 1).

The "image transfer method" allows the driver to use the in-vehicle infotainment system screen to operate and view applications developed for the smartphone. The "content transfer method" is characterized by minimal dependence on the type of smartphone but requires data processing to be performed on the in-vehicle infotainment system.

Which of the two methods to use can be selected to suit the application or service concerned.

(3) Network connection procedure

The in-vehicle infotainment system can connect to the network via methods such as a telematics communication unit (TCU) or by Wireless Fidelity (Wi-Fi)*2.

(4) Hypertext markup language (HTML) support on in-vehicle infotainment systems

Services are implemented using HTML content to facilitate the standardization of service content, the addition of new functions, and maintenance, and to allow the rapid release of new services. Incorporating support for HTML into the in-vehicle infotainment system means that the center can send content to the in-vehicle infotainment system in HTML format (see Fig. 4).

Further Development of Clarion Telematics

Hitachi is working on expanding the range of services for the targeted delivery of information to drivers, including the provision of information intended to suit the needs of drivers. The center-based voice recognition service improves the interface with the driver by combining functions for the analysis and understanding of the speaker's intentions with the use of functions such as interactively narrowing down the intended meaning. By implementing these services and functions, Hitachi is providing drivers with comfort, security, and convenience.

TABLE 1. Smartphone Connection

The connection between an in-vehicle infotainment system and the center is split into separate "image transfer method" and "content transfer method" mechanisms.

Connection type	"Image transfer method"	"Content transfer method"
Summary	Transfers smartphone images to the in-vehicle infotainment system.	Transfers data from the smartphone to the in-vehicle infotainment system for processing.
Character-istics	• Provides access to a wide range of smartphone applications. • Provides access to the resources of the smartphone.	Minimal dependence on the model of smartphone.

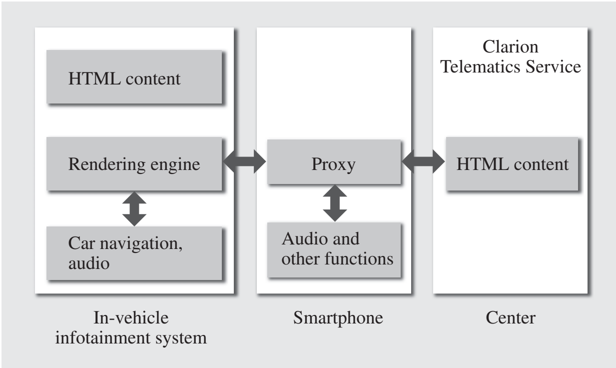


Fig. 4—Provision of Services Using HTML Content.
The provision of new services and the addition of new functions is facilitated by the use of HTML content to implement in-vehicle infotainment system functions.

In further developments, Hitachi will proceed with the use of mobility-related big data relating not only to vehicles but also to other sources such as people and public transportation agencies, and will adopt its global services to suit regional needs.

USE OF CAR INFORMATION AND AUTOMOTIVE SECURITY

Uses for car information that have been implemented to date include obtaining probe traffic information from vehicle location data and supporting safe driving based on parameters such as speed and acceleration collected from digital tachometers.

The emergence in recent years of "connected cars" has seen the launch of services that provide new value to drivers and other users through such things as smartphone applications that use car information or the use of car information by center systems (see Fig. 5).

The emergence of "connected cars" also means that, because vehicles are now connected to a network

*2 Wi-Fi is a registered trademark of the Wi-Fi Alliance.

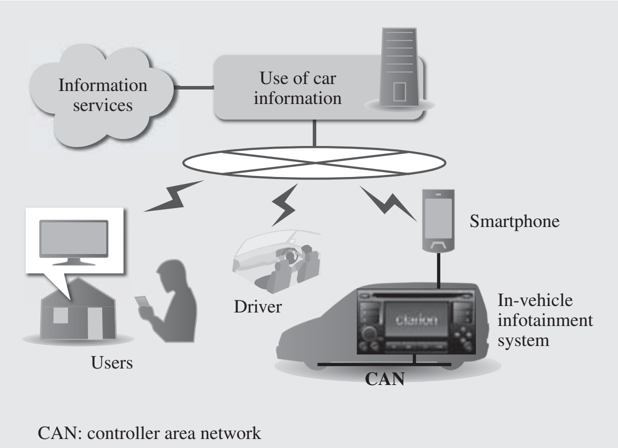


Fig. 5—Block Diagram of Service System Using Car Information.
Services that are safe, secure, comfortable, and ecological are provided to drivers and other users through the generation of knowledge from CAN and other car information at center systems.

rather than being the standalone systems they were in the past, it has become important for them to have the same sort of security measures as other digital devices.

Services that Use Car Information

(1) Insurance service

Insurers are beginning to offer options such as pay-as-you-drive (PAYD) insurance based on distance traveled and pay-how-you-drive (PHYD) insurance based on driving behavior. These services link insurance rates to risk assessments based on driving behavior, which consider factors such as distance traveled, speed, acceleration, and where and when the driving occurs.

(2) Remote OBD

Measures such as trials in the USA are in progress and aimed at providing a quicker way of identifying vehicles that are non-compliant with exhaust gas regulations through the periodic wireless collection of vehicle OBD information.

(3) Applications that use controller area network (CAN) data

Along with the spread of smartphones, service applications have appeared that utilize various CAN data by combining a smartphone with a CAN data collection unit.

These applications are in the form of systems that can use the smartphone to display information previously unavailable to the driver, including boost, fuel consumption, malfunction diagnosis information, and driving route logs.

Automotive Security

Projects in Japan, the USA, and Europe are studying the security risks associated with the use of CAN information, and also countermeasures[(4), (5)].

Preventing threats such as unauthorized access, spoofing, abuse, or information leakage is important for "connected cars," and work is underway on countermeasures that use security techniques from other information systems such as corporate systems and digital home devices.

(1) Definition of security requirements

Security requirements are defined by clarifying the information assets that need to be protected and where the threats are targeted, and by conducting threat analyses and risk assessments that extend from the design of vehicle systems to their use and dismantlement phases.

(2) Selection of security measures

Based on the security requirements, countermeasures that utilize security techniques such as cryptography, authentication, access control, and tamper-proof technology are incorporated into the system design.

(3) Execution of security measures

The steps decided on in the security requirements are executed in response to vulnerabilities identified during operation. This includes measures such as incident management and security supervision in cooperation with an incident response team (IRT).

In these ways, the Clarion Telematics Service implements measures that use techniques such as authentication and data encryption for the in-vehicle infotainment system, smartphone, and center systems.

CONCLUSIONS

The emergence of the "connected car" has been accompanied by the launch of services that enable safe, secure, comfortable, and ecological driving.

In the future, Hitachi intends to help create a smart mobility society that takes account of people and the environment through systems and services that utilize more information on automotive and social infrastructure.

In doing so, there is a need to investigate in-vehicle infotainment systems that utilize CAN information and other car information and their security measures, and also to investigate services that create new value by using car navigation, audio, and vehicle control technologies that have been built up over time.

REFERENCES

(1) Y. Yoshikawa et al., “Hitachi’s Vision of the Smart City,” Hitachi Review **61**, pp. 111–118 (May 2012).

(2) Nikkei Smart City Consortium: No.3, “Accelerating Initiatives for Smart Mobility,” http://bizgate.nikkei.co.jp/smartcity/technology/000611.html in Japanese.

(3) M. Kashiyama et al., “Cloud Telematics Service for Realtime Information in Vehicles,” Hitachi Review **62**, 5, p. 64 (Aug. 2013).

(4) “FY2011 Survey of Trends in Information Security for Vehicles,” Information-Technology Promotion Agency, Japan (May 2012) in Japanese.

(5) “FY2012 Survey of Trends in Information Security for Vehicles,” Information-Technology Promotion Agency, Japan (Mar. 2013) in Japanese.

ABOUT THE AUTHORS

Akira Yano

Technology Development Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of a Connected solution.

Toyota Honda

Advanced Development Center, Technology Development Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of a Connected solution.

Akio Hayashi

Smart Access Development Department, Smart Access Management Department, R&D Division, Clarion Co., Ltd. He is currently engaged in the development of the Smart Access service.

Hirohisa Miyazawa

System Planning Department, Marketing Strategy Division, Clarion Co., Ltd. He is currently engaged in planning for the Smart Access service.

Haruhiko Sawajiri

Smart Access Development Department, Smart Access Management Department, R&D Division, Clarion Co., Ltd. He is currently engaged in the development of the Smart Access service.

Advanced Electronic Platform Technologies Supporting Development of Complicated Vehicle Control Software

Yoshinobu Fukano, Dr. Sci.
Kosei Goto
Masahiro Matsubara
Yasuo Sugure, Dr. Eng.
Yoshihiro Miyazaki

OVERVIEW: The programs used by in-vehicle control software are increasing in size and complexity as vehicles adopt more advanced functions such as electric drive and collision prevention safety. There is also a need for techniques for the efficient development of software that has high levels of safety and reliability in accordance with the ISO 26262 international standard for functional safety in road vehicles published in 2011. In response to these challenges, Hitachi has been working on the development of platform software technology for functional safety and advanced software verification techniques.

INTRODUCTION

THE use of embedded systems in vehicles dates back to the 1970s when they were introduced to fulfill societal requirements such as road safety measures and the regulation of exhaust gas from motor vehicles. Nowadays, in-vehicle control software is used for the integrated control of the core vehicle functions of driving, cornering, and stopping, and in a variety of different components in the engine, powertrain, chassis, and other systems. The functional requirements of in-vehicle control software are becoming more advanced with each passing year, with the software set to become even larger and more complex(1).

This article describes the latest technology for the development of such large and complex in-vehicle control software.

TRENDS IN IN-VEHICLE CONTROL SOFTWARE DEVELOPMENT

Measured by lines of code, the total size of software used in a vehicle reached about two million lines in 2005. More recently, the scale and complexity of in-vehicle control software development has continued its steady rise due to factors such as the use of electric drive in hybrid and electric vehicles. It is estimated to reach 100 million lines of code by 2015.

In addition to control of the engine and powertrain, and chassis control covering systems such as brakes, power steering, and suspension, the in-vehicle control software for the next generation of vehicles will also include control of collision prevention safety and energy management. This is creating a need for more effective development capabilities for control and embedded software(2) (see Fig. 1).

As in-vehicle control software becomes larger and incorporates more advanced functions, there is a need to shorten development times without compromising software quality. There is also a need for safety design and verification in accordance with the requirements of the ISO 26262 standard for functional safety for road vehicles. Hitachi has developed platform software technologies and advanced verification techniques (formal verification and virtual microcontroller application simulation) that meet these requirements. The following section describes these technologies.

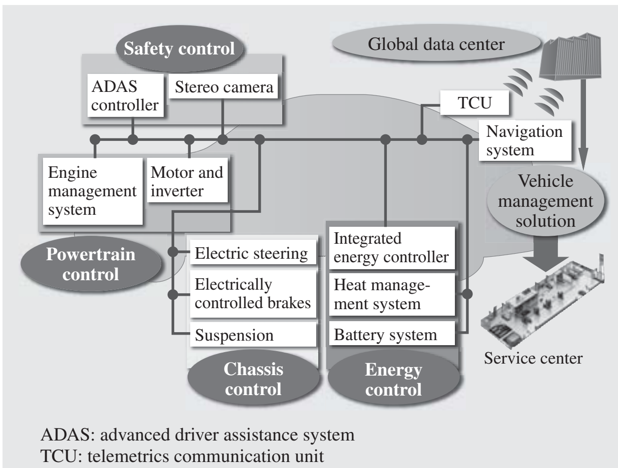


Fig. 1—Overview of In-Vehicle Control Software for Next-generation Vehicles.
In addition to the engine, powertrain, and chassis systems, the software needs to perform integrated management that also includes such things as collision prevention safety, energy control, and connections to external networks.

PLATFORM SOFTWARE TECHNOLOGIES FOR FUNCTIONAL SAFETY

Hitachi Automotive Systems, Ltd. is working on standard software platforms for significantly shortening the time taken to develop embedded software for vehicles while also reducing its cost and achieving higher reliability. Hitachi's standard platform software for compliance with functional safety standards and industry standardization [such as the Automotive Open System Architecture (AUTOSAR)] (see Fig. 2) can run on the microcontrollers used mainly for powertrain systems such as the engine or inverter, and for brakes and other chassis systems.

The structure of the standard platform software is based on the industry standard AUTOSAR specification (ICC1). Also, application layer software developed by Hitachi's customers or its product design departments interfaces with the platform software via a run-time environment (RTE). Accordingly, by complying with the RTE interface specifications, the application layer software can minimize the influence of differences in hardware such as the choice of microcontroller or the circuit design of control units.

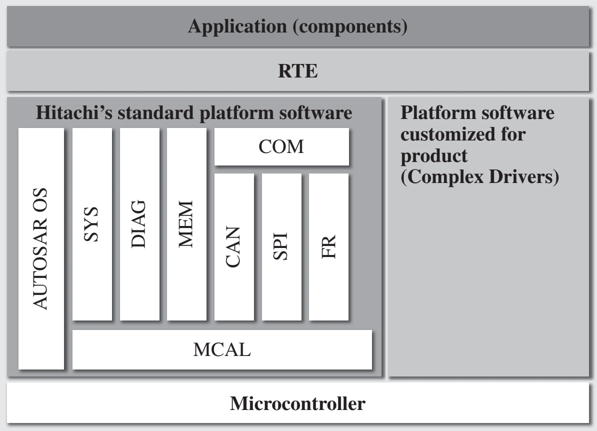
Also, to ensure the general applicability of the platform software, it has a layer structure in which the microcontroller and other hardware factors are hidden by the low-level microcontroller abstraction layer (MCAL).

For compliance with functional safety standards, the development process conforms to automotive safety integration level (ASIL) D stipulated by ISO 26262 to ensure that the platform software can be used for products with any safety level.

Implementing a freedom from interference (FFI) function is an important technology for complying with functional safety standards. The FFI function applies to situations when software with different safety levels (ASILs) coexists on the same microcontroller and prevents dependent failures propagating from software with a low ASIL to software with a high ASIL.

While the platform software developed by Hitachi has the highest ASIL-D level, the embedded application software used in vehicles may have various different levels, such as ASIL-A or ASIL-B, or may be subject to quality management (QM) that is outside the scope of functional safety.

Accordingly, the following protection functions are incorporated into the platform software to prevent the propagation of dependent failures from software with safety levels other than ASIL-D.



RTE: run-time environment
AUTOSAR: Automotive Open System Architecture
OS: operating system MCAL: microcontroller abstraction layer
CAN: controller area network SYS: system DIAG: diagnosis
MEM: memory COM: communications
SPI: serial peripheral interface FR: FlexRay

Fig. 2—Overview of Hitachi's Standard Platform Software.
The product-specific application layer is at the top and the platform software layer (standard software platform) at the bottom, with the RTE in between.

(1) Timing protection

This mainly involves using AUTOSAR operating system (OS) functions to monitor the timing of tasks and interrupts. Hitachi has also added functions it has developed itself to strengthen protection.

(2) Memory protection (memory partitioning)

This uses the AUTOSAR OS and the microcontroller's memory protection functions to protect the ASIL-D areas of memory. Hitachi has developed a high-speed memory partitioning technique that minimizes the overhead associated with switching the program execution mode between ASIL-D and other safety levels (context switching).

FORMAL VERIFICATION

The ISO 26262 standard for functional safety for road vehicles recommends the use of formal verification for ASIL-C and ASIL-D systems that have particularly high safety requirements. Hitachi has incorporated one such formal verification technique, called model checking, into its products to maintain and improve the reliability of vehicle software as it becomes increasingly large and complex. The motivation is to reduce the level of software defects to near zero by comprehensively testing all test paths through the source code as well as the conventional testing method of comparing the output produced by a particular input with the expected output.

Formal verification uses a precisely defined language to represent the requirements and associated design, and can verify that the two match through the use of mathematical theory. In the case of model checking, this verification is performed automatically. Model checking works by using a model of the software design and having a computer rigorously work through the potential states that can arise when the software is executing to determine whether there are any operations that are not in the specifications (operations that were not foreseen in the design process). The problem with this approach, however, arises when the number of software states is very large and the computer does not have enough resources to check them all. Despite improvements in computer performance, the scope of application for model checking has remained limited and its use on the large software used in production products has been problematic for many years.

To implement a practical form of formal verification (model checking), Hitachi has developed a technique that significantly reduces the number of states in the check model by analyzing the dependencies between variables that appear in the source code to identify which code is relevant to the variables in the software being checked, and then converting this into the check model (see Fig. 3). By doing so, Hitachi has succeeded in applying model checking to the complete software for electronic control units, even though such software may consist of as many as several hundred thousand lines(3). The size of the software being checked is approximately 10 times larger than other examples reported in the literature. The reasons why checking can be performed for such large program sizes is that the analysis technique features precision and high speed (100,000 lines or so of code can be analyzed in a few minutes on a standard PC), and because means have been provided for the software developers to select check points or adjust the range of software selected for conversion based on their design knowledge. Variable dependencies can be plotted on a graph to provide the software developers with visual ways of adjusting the scope of model conversion.

This technique was used to produce a tool to help with checking that makes the work more efficient by automatically generating the check model from the software's source code(4). This provides the infrastructure for applying formal methods (model checking) to product developments with the ASIL-C or ASIL-D level. Hitachi is proceeding with its progressive introduction.

VIRTUAL MICROCONTROLLER APPLICATION SIMULATION TECHNIQUE

This section describes the use of a virtual microcontroller application simulation technique for testing in-vehicle control software without the target hardware.

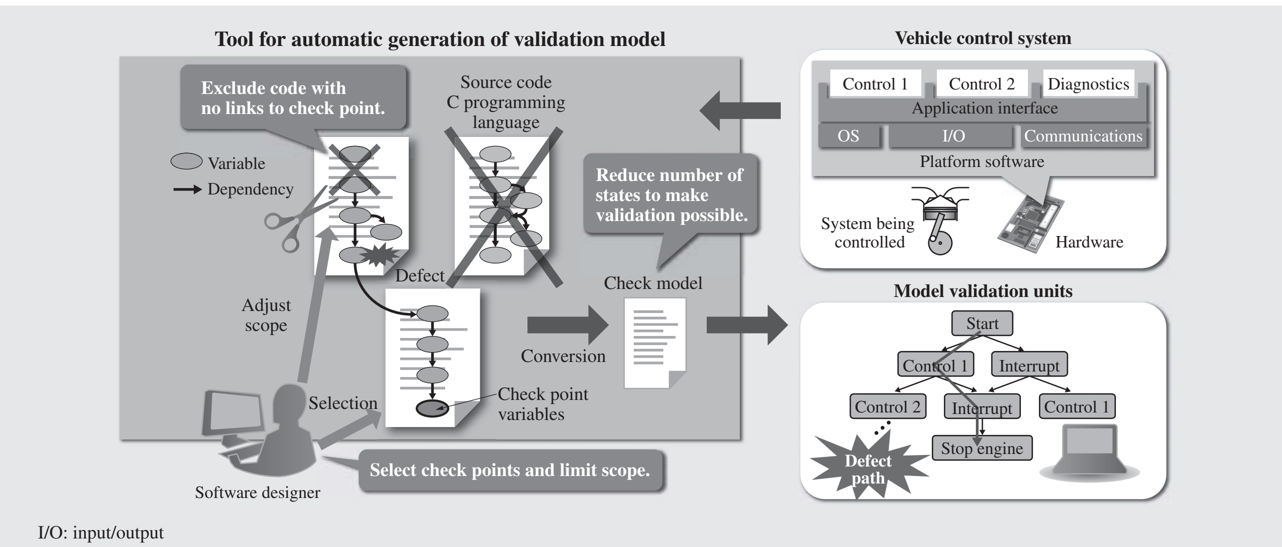


Fig. 3—Technique for Automatic Generation of Validation Model from Source Code.
Check point variables are those that are potentially affected by a defect. The tool automatically determines the links between these variables and other variables (dependencies) and identifies the relevant code with a high degree of precision. The software designers can also use their design knowledge to limit the scope of the source code to be converted to a model. Together, these techniques produce a model that can be used for validation.

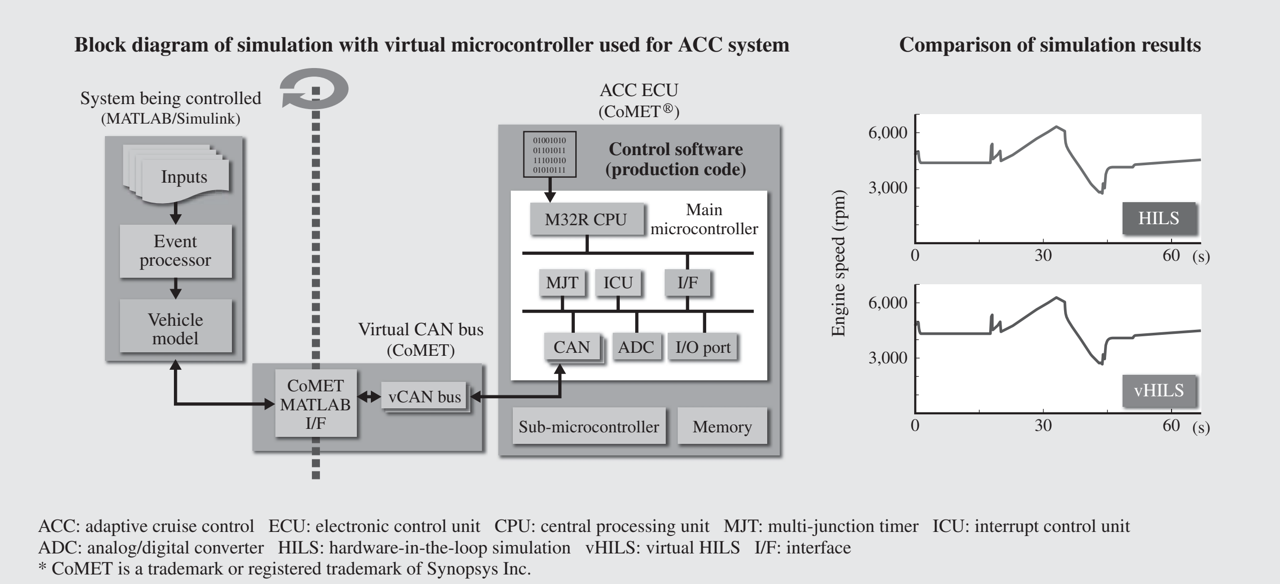


Fig. 4—Application of Simulation with Virtual Microcontroller to ACC System.
Validation of control software at the production code level was successfully conducted without using the target hardware by performing a joint simulation combining the MATLAB/Simulink models for the systems being controlled with the CoMET models for CAN communications and the ECU containing the microcontrollers.

The conventional practice for validating control software at the production code level in the past was to use hardware-in-the-loop simulation (HILS). This involved connecting the actual microcontroller hardware to a simulator that modeled the behavior of the system being controlled. However, use of the actual hardware brings with it practical restrictions. In response, Hitachi has developed virtual HILS (vHILS) to allow validation of control software without the target hardware. This uses a joint simulation consisting of a virtual microcontroller and a model of the system being controlled(5), (6), (7). vHILS can be used for validating control software at the production code level. The main benefits are, (1) software validation can be performed at times and places where the microcontroller and other parts of the target system are not available, and (2) faster validation achieved by performing large numbers of tests concurrently, which is made possible by the ease with which the validation environment can temporarily be replicated.

The vHILS technique was applied to an adaptive cruise control (ACC) system (see Fig. 4). The ACC system maintains a safe following distance behind the vehicle ahead by controlling the engine, brake, and other systems based on the distance to the other vehicle and its relative speed acquired using an external recognition sensor. The new validation system reused the MATLAB*/Simulink* models used in HILS for the electronic control units (ECUs) and the engine, brake, and other vehicle systems that they control. New models were produced, however, for the main microcontroller, sub-microcontroller, and memory in the ACC ECU, and for the controller area network (CAN) communications it uses to connect to other ECUs. In the case of CAN communications, the speed of simulation was increased without compromising accuracy by simulating the message-level communications, which is all that is needed to test the control software.

The same test cases used for the previous HILS testing were repeated on the vHILS system and the simulation accuracy and execution speed were assessed. The results shown in Fig. 4 indicate agreement for the logical operations such as the vehicle engine speeds and the speed change timings. Although equivalent accuracy was achieved, the execution speed was only 34% that of HILS. This indicates that equivalence with the target system can be achieved using a three-node configuration by executing a number of tests concurrently. Validation processing performance superior to HILS was also demonstrated by increasing the number of computing nodes. Results have also been obtained indicating that the amount of work required for pre-delivery testing can be reduced to 1/20 to 1/400 that of HILS by implementing the means to execute software validation automatically using cloud computing(7).

To promote the wider adoption of the vHILS technique described above through collaboration at all levels of the industry with an interest in vHILS (automotive manufacturers, parts makers, simulation tool vendors, semiconductor manufacturers, and research institutions), the Virtual ECU Model-Based Development (vECU-MBD) Working Group has been set up at the Japan Virtual Microcontroller Initiative (JVMI)[8].

CONCLUSIONS

This article has described platform software development technologies and advanced validation techniques for the next generation of in-vehicle control software development.

Hitachi Automotive Systems, Ltd. is working with the research divisions of Hitachi to devise platform technologies for in-vehicle control software development that extend beyond those described in this article. By integrating the technologies described here, Hitachi will be able to establish advanced development processes for the next generation of in-vehicle control software.

REFERENCES

(1) S. Kawana, “Current Status of Automotive Software Development (Software Engineering for Embedded System),” IPSJ Magazine **45**, No. 7, pp. 713–715 (Jul. 2004) in Japanese.

(2) “Growing Use of Simulation Technology in Automotive Software Development,” Nikkei Automotive Technology (27), pp. 68–73 (Nov. 2011) in Japanese.

(3) Hitachi News Release, “Development of Highly Reliable Verification Technology for Automotive Control Software Using Formal Methods” (Apr. 2013) http://www.hitachi.co.jp/New/cnews/month/2013/04/0416a.html in Japanese.

(4) M. Matsubara et al., “Application of Model Checking to Automotive Control Software with Slicing Technique,” SAE 2013 World Congress (2013-01-0436), (Apr. 2013).

(5) Y. Ito et al., “VIRTUAL HILS: A Model-Based Control Software Validation Method,” SAE 2011 World Congress (2011-01-1018), Int. J. Passeng. Cars -Electron. Electr. Syst. 4 (1):142-149 (Apr. 2011).

(6) Y. Sugure et al., “Failure Mode and Effects Analysis Using Virtual Prototyping System with Microcontroller Model for Automotive Control System,” 7th IFAC Symposium on Advances in Automotive Control (Sept. 2013).

(7) Hitachi News Release, “Development of Fully Virtual Simulation Technique for Railway, Automotive, and Other Embedded Software that Does not Require Actual System” (Oct. 2010) http://www.hitachi.co.jp/New/cnews/month/2010/10/1028.html in Japanese.

(8) vECU-MBD Working Group, http://www.vecu-mbd.org/en/

ABOUT THE AUTHORS

Yoshinobu Fukano, Dr. Sci.

System Development Engineering Department, Technology Development Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of model-based development technology for the in-vehicle control software development process. Dr. Fukano is a member of the Association for Computing Machinery (ACM) and the Society of Automotive Engineers of Japan (JSAE).

Kosei Goto

Electric Platform Development Department, Technology Development Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of standardized basic software. Mr. Goto is a member of the JSAE.

Masahiro Matsubara

GM4 Unit, Department of Green Mobility Research, Hitachi Research Laboratory, Hitachi, Ltd. He is currently engaged in the development of verification techniques for automotive control software. Mr. Matsubara is a member of the Information Processing Society of Japan (IPSJ).

Yasuo Sugure, Dr. Eng.

Platform Systems Research Department, Central Research Laboratory, Hitachi, Ltd. He is currently engaged in research of virtual prototyping systems using microcontroller models for automotive control systems. Dr. Sugure is a member of the Society of Automobile Engineers (SAE) and The Institute of Electronics, Information and Communication Engineers (IEICE).

Yoshihiro Miyazaki

Technology Development Division, Hitachi Automotive Systems, Ltd. He is currently engaged in the development of electronic platform technology for in-vehicle control systems. Mr. Miyazaki is a member of The Institute of Electrical Engineers of Japan (IEEJ), IPSJ, and JSAE.

Automotive Technologies for Smart Cities and their Global Deployment

Fumitoshi Emura
Mitsumasa Takayama
Hiroaki Sugita
Kouichi Hiraoka
Takamasa Yamazaki

OVERVIEW: In recent years, factors such as worsening environmental problems, including global warming and traffic congestion; resource and energy problems; population increases, primarily in emerging economies; and the aging of urban populations in developed economies have begun to bring major changes in the objectives of urban development. According to a survey by a research company, smart city projects aimed at overcoming these problems are underway at more than 400 locations around the world(1). In response to these new developments, Hitachi is actively involved in utilizing ICT and other advanced technologies to deliver innovation to social infrastructure such as energy, mobility, and water. As part of smart city projects in the mobility sector, Hitachi is working on demonstration experiments and projects such as the use of EVs in community energy management.

INTRODUCTION

IN response to fossil fuel scarcity and global warming, the automotive industry has been conducting research into alternatives such as hybrid vehicles, electric vehicles (EVs), and fuel cell vehicles for some time. With a series of these having already entered commercial production, they are recognized as having established an important role for themselves in society, and are on their way to wider use. In the field of smart cities, these new automotive developments are seen as a formative part of "smart mobility," and work is also ongoing on their use as part of energy and social infrastructure.

The smart city represents an approach to infrastructure and urban development that seeks to utilize information and communication technology (ICT) to improve energy efficiency and provide a comfortable way of life. As a business, it extends over a wide area, from the provision of hardware through to services.

This article presents examples of development for commercialization taking place worldwide that treats the automobile as part of the energy and social infrastructure, and as one of the elements that make up a smart city. It also describes the outlook for the future.

ROLE OF AUTOMOTIVE TECHNOLOGIES IN SMART CITIES

In the field of automotive technology, advances have been ongoing for some time in technologies for electrification and in research into new fuel technologies to reduce dependence on fossil fuels, with progress being made in basic performance (driving, cornering, stopping, etc.) to provide overall driving performance and the means for mobility and transportation. In the case of electrification, technologies for hybrids and EVs have been adopted from other fields, such as railways, where they are already in use, with remarkable progress having been made in the core technologies of motors, inverters, and batteries (see Fig. 1).

Advances in ICT, meanwhile, have allowed the social infrastructure to deliver new possibilities to consumers by becoming more tightly interconnected than in the past. This trend is also evident in the automotive sector, with growing use of ICT in vehicle and traffic infrastructure and moves toward using increasingly advanced automotive technology and the resources it provides as part of the energy and social infrastructure. Also, the large amount of operational data collected from different types of sensors is giving birth to services that use these data. Along with all these changes, the development of technologies for integrating vehicles into the social infrastructure is proceeding on a global scale.

Recognizing these trends, Hitachi is proceeding with demonstration experiments in Japan and elsewhere, establishing projects that use vehicles as part of the energy and social infrastructure.

Hybrids, EVs, and other electrically powered vehicles emit low levels of carbon dioxide (CO_2) and help reduce dependence on fossil fuels. To make

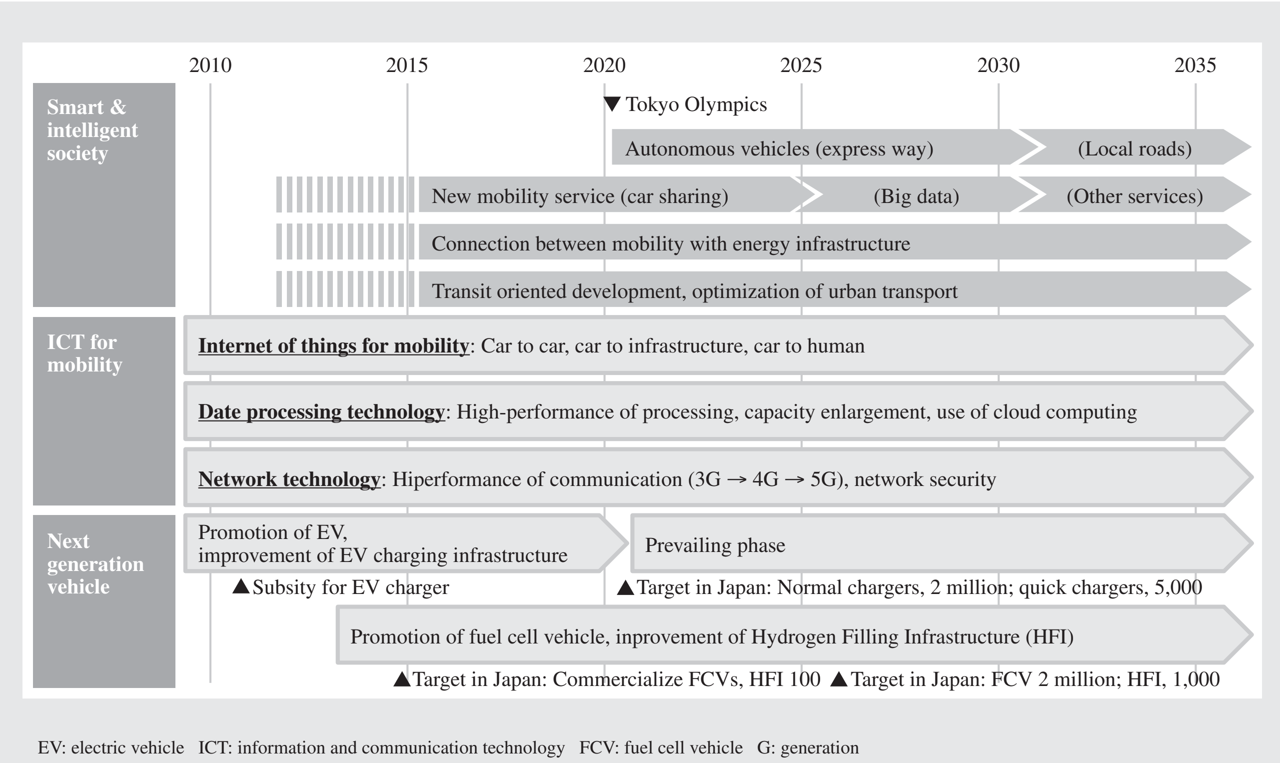


Fig. 1—Roadmap of Technical Developments Aimed at Fusion of Vehicles and Social Infrastructure.
The issues are being debated at a global level from a variety of considerations, including vehicles, infrastructure, fuel, and ICT.

the most of their potential to form part of the energy and social infrastructure, however, they require connections to the electric power supply infrastructure. The shorter range of current EVs compared to gasoline-powered vehicles means that charging infrastructure is also needed.

Rather than looking at the characteristics of EVs in direct comparison with gasoline-powered vehicles, Hitachi supplies a variety of EV solutions that can be used in ways that seek to make the most of these characteristics. The following sections describe some of these solutions.

EV Charger and EV Charging Management System

A variety of EV charging management solutions are required in order to suit the different scenarios for EV use. Hitachi supplies both normal chargers for use at homes or workplaces and quick chargers that allow the number of charging stations and their outputs to be configured based on the requirements of the site and its users. Hitachi is also working on the development of inductive charging technology that provides a non-contact means of charging from a power supply device built into the road, with ongoing development for the electric bus market.

Hitachi is also utilizing ICT to collect information on charger operation using charging management systems that provide centralized management of chargers via a network for the functions provided to EV users, and to implement mechanisms for member identification, billing, and settlement. Work is also proceeding on the energy and social infrastructure aspects of acquiring information about charger output in real time and utilizing it in community energy management.

V2H and V2G

Vehicle-to-X (V2X) initiatives aimed at using an EV connected to a charger as a stationary storage battery are taking place around the world. These use the charging or discharging of the EV's battery for purposes that include ensuring efficient use of electric power, power grid stabilization, and emergency power supply during disasters.

In demonstrations in Japan and elsewhere, Hitachi is building bidirectional mechanisms that utilize group control of EVs, photovoltaics (PV), and storage batteries to make effective use of the supply capabilities of these consumer resources. The aim is to provide load adjustability by timing power consumption and discharge so that it does not inconvenience consumers, and to do this by establishing EV virtual power plants (VPP) that perform integrated management and control of a number of EV batteries together with vehicle-to-home (V2H) and vehicle-to-grid (V2G) systems. The intended uses for these systems include reducing the high cost on outlying islands in particular for maintaining emergency generators that are used only a few times a year, and compensating for the fluctuating output of renewable energy. It is anticipated that systems like these will be installed in the future to achieve local production for local consumption and autonomous decentralized control.

Car Sharing

Because the EV fleet needs to reach a certain size before these vehicles can be used as part of the energy and social infrastructure, the wider adoption of EVs is the key to their use for this purpose. Car sharing is being introduced as a policy that can help achieve this. It is a system for sharing particular cars between a number of people in which each participant pays for their share of the operating costs, such as fuel, insurance, parking, and tax, in accordance with their level of use. Car sharing typically involves allocating vehicle use over shorter periods of time than car rental, with users able to access the service for as little as a few hundred yen each time in the case of brief trips. It also allows users to make reservations via methods such as the Internet and to pick up and return vehicles at the appointed times through a trouble-free automated and unstaffed process.

In Europe and America, car sharing is contributing to a decline in total car ownership and distance traveled, thereby providing benefits that include helping to alleviate urban traffic congestion, promote greater use of public transportation, improve air quality and other urban environmental problems, reduce city parking problems, and prevent global warming.

Hitachi is developing car sharing services that use technologies such as ICT, machine-to-machine (M2M) communications, and the use of non-contact-type integrated circuit (IC) cards for personal identification, and is seeking to expand the use of services that take advantage of affinities with EV features such as short range and low fuel costs.

Utilization of Big Data in Automotive Sector

With wider use of technologies such as M2M communications and sensors, the infrastructure is being put in place for the high-speed processing of large amounts of data. Work is also starting on the utilization of vehicle-based traffic volume, congestion, and other information in the form of big data.

Hitachi is developing services that are optimized for car owners, such as analyzing and processing vehicle information (including driving distance, fuel consumption/power consumption, and state of charge) at a data center based on a contract between the vehicle owner and manufacturer to provide environmental and driving safety assessments based on driving history.

EXAMPLE APPLICATIONS IN DEMONSTRATION EXPERIMENTS AND PROJECTS

It is anticipated that the use of automotive technology in energy and social infrastructure will continue to expand. This section describes some of the demonstration experiments and projects being conducted by Hitachi in Japan and elsewhere that provide leading-edge examples of this trend.

In addition to verifying the technology, these projects are being undertaken in close collaboration with local infrastructure companies, regional and local governments, and academic institutions in the regions concerned and present a model of building business concepts from the upstream stage. However, the actual services being introduced are primarily being implemented from the downstream perspective of users and consumers, requiring the establishment of business models that are more flexible than those of the past.

Okinawa EV Charging Management Service

As of July 2013, this service operates 385 EVs and 31 quick charging stations in Okinawa Prefecture. The provision of charging infrastructure is being handled by AEC Co., Ltd., a company in Okinawa Prefecture, and the service uses Hitachi Solutions, Ltd.'s EV charging management system.

AEC Co., Ltd. and Hitachi Solutions, Ltd. took advantage of Okinawa Prefecture's demonstration project to develop the Smart EV Navi (provisional name) cloud service that combines route search and energy management. The demonstration experiment commenced in February 2013. For EVs to gain wider acceptance, they will need to overcome users' range anxiety. This requires judgments on when and where drivers can charge their EV so that they can keep driving without running out of battery power, and how they can make their own decisions reflecting both vehicle range and information about nearby charging stations. When a driver uses a navigation application on a device such as a smartphone or tablet to search for their destination, the cloud service automatically determines the state of charge of their EV and the available range, and uses this to calculate the route. The route calculation provides the fastest route, one that includes the location of the most convenient charging stand in the case when charging is required, and advises on the estimated arrival time.

Hitachi is currently considering the development of an additional waypoint search function along with greater integration with tourist and other local information. It plans to conduct a further demonstration in Okinawa Prefecture in February 2014.

Demonstration Experiment in Yokohama

In Yokohama, Hitachi is participating in The Yokohama Smart City Project and a car sharing project using ultra-light mobility (EVs). The Yokohama Smart City Project is an energy management system for charging stations that coordinates EVs together with storage batteries, PV generation systems, and chargers installed at charging stations. Its aim is to perform appropriate management and control of the various equipment and systems (see Fig. 2). Following its launch in October 2013, it is expected that the service will manage around 100 ultra-light mobility (EV) vehicles and serve 10,000 members in the future. The car sharing project is a new EV business model that includes one-way travel between stations.

Model Project for Electric Bus Operation in Hitachi City

To promote the use of electric buses in smart cities, Hitachi is participating in a demonstration in Hitachi City as part of the Next-generation Energy Technology Demonstration Projects of the New Energy Promotion Council.

The aim is to build a solution for electric buses based on an electric bus operation management system that includes a driving status monitoring function and forecast power consumption function to support activities such as scheduling, operational management, charging management, and battery optimization for electric buses.

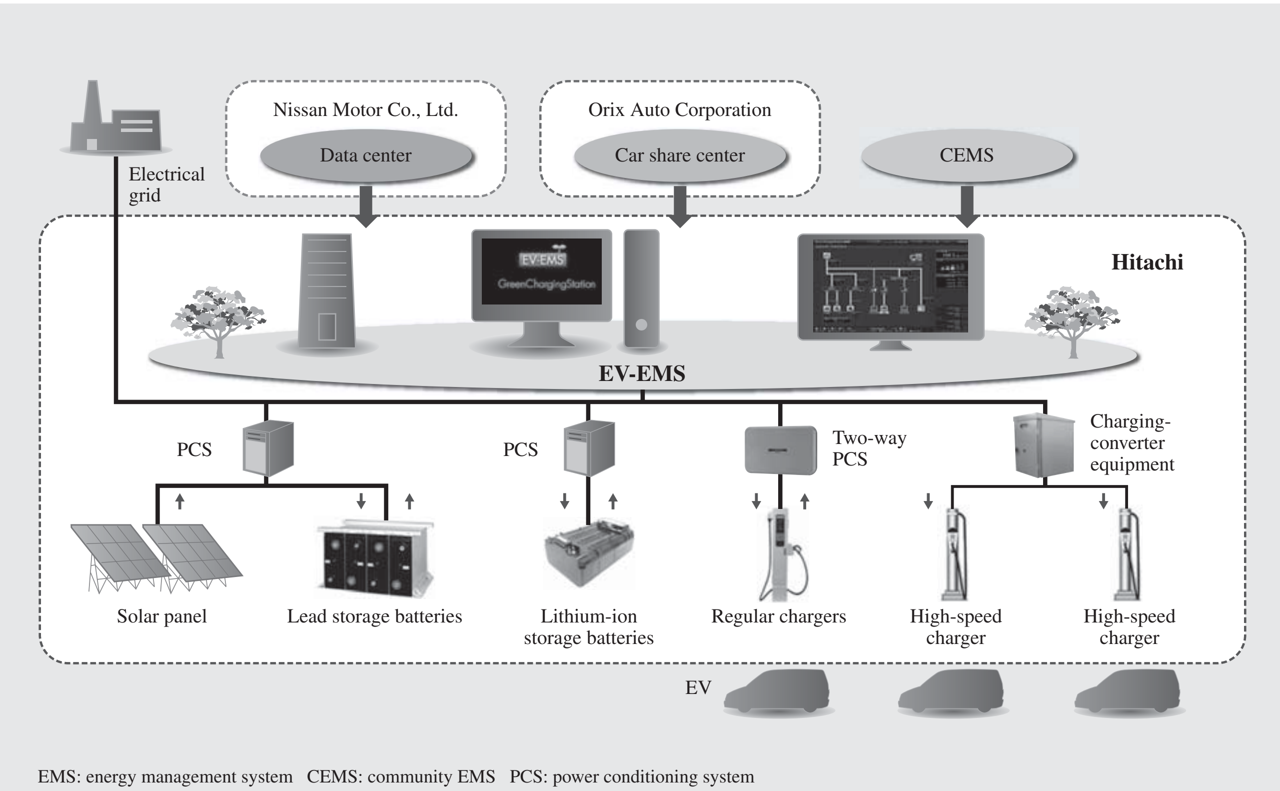


Fig. 2—Overview of The Yokohama Smart City Project.
The project is developing a charging system that incorporates photovoltaic power generation and storage batteries, and energy management that coordinates EVs and charging systems.

As electric buses fitted with large-capacity batteries can also serve as a power supply source at times of emergency, the project will undertake activities aimed at realizing smart mobility through the coordination of the electric bus operation management system, community energy management systems (CEMSs), EV chargers, EV charging management systems, and other resources.

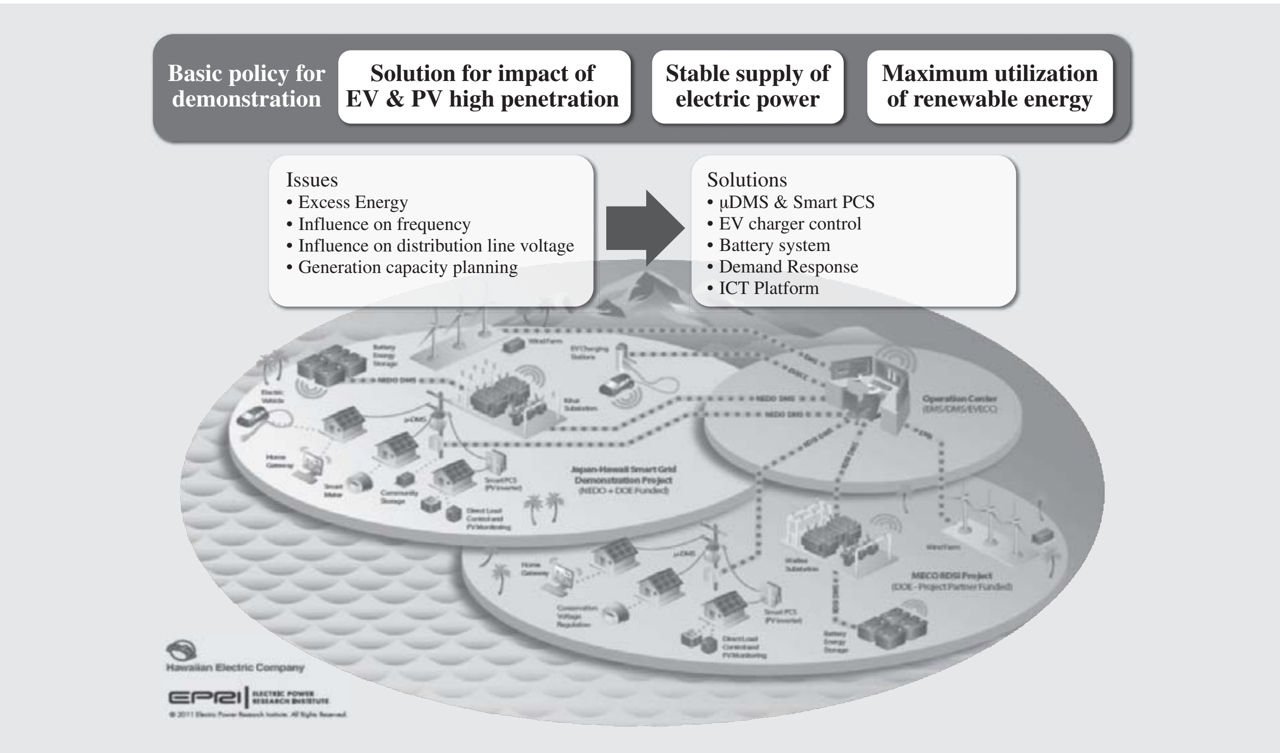
Smart Community Demonstration Project in Spain

Together with Mitsubishi Heavy Industries, Ltd. and Mitsubishi Corporation, Hitachi has been entrusted by the New Energy and Industrial Technology Development Organization (NEDO) to participate in the "Smart Community Demonstration Project in Spain." Based in Malaga (in the Autonomous Community of Andalusia) and consisting primarily of 200 EVs, nine quick charging stations, and an EV management center, the aim of this overseas demonstration project is to build next-generation transportation infrastructure with the potential to make major reductions in CO_2 emissions. System operation commenced on 25, April 2013, and demonstrations are set to continue until the end of December 2015.

The demonstration project will include demonstrations of an energy management system, which has a vital role in ensuring a reliable supply of power for EVs, an ICT platform that provides coordination between the EV infrastructure and energy management system, and a new comprehensive service system based on data collected at the EV management center. Hitachi intends to package the knowledge gained from these demonstrations, and to work with its partners in Japan and Spain to expand its scope of application in Spain and other countries and to deploy the system in other locations with similar lifestyle and culture.

Japan-U.S. Island Grid Project

Hawaii is by far the most oil-dependent state in the USA, with electricity tariffs three times higher than those on the mainland due to the rising price of oil. (As of August 2013, the price of a gallon of gasoline on Maui was \$4.60 compared to \$3.56 on the mainland). Also, because the state depends mainly on imports for fuel and industrial products, consumer prices



µDMS: micro distribution management system

Fig. 3—Smart Grid on Maui.
This demonstration project seeks to combine quality of life (QOL) with the creation of a low-carbon society on the island of Maui in The State of Hawaii.

Fig. 4—EV Chargers on Maui.
Installation of infrastructure on Maui is continuing in preparation for demonstrations.

are roughly 1.5 times higher than the US average, making them the highest in the country. Against this background, a project has been launched on the island of Maui aimed at encouraging the large-scale use of EVs, maximizing use of renewable energy, and ensuring the security of electric power supply. Together with the State of Hawaii, the County of Maui, Hawaiian Electric Company, Inc., Maui Electric Company, Ltd., the University of Hawaii, and US National Laboratories, Hitachi has been entrusted by NEDO to participate in its Japan-U.S. Island Grid Project in Maui (project name: JUMPSmartMaui) (see Fig. 3) (System operation commenced on 17, December, 2013, and demonstrations are set to continue until the end of March 2015).

The project is helping to establish the infrastructure for EVs on the island by installing quick charging stations at 20 locations, and will use the energy storage capacity of EVs for excess energy absorption and to stabilize renewable energy. There are also plans to expand the project to include a VPP function that contributes to the energy supply and demand balance for the islandwide of Maui through the integrated management of a decentralized energy resource (see Fig. 4).

CONCLUSIONS

People's way of life is coming to a turning point, with the era in which prosperity could be pursued without regard for the limited nature of energy resources coming to a close, and society recognizing that there is a limit to how long we can continue to take energy for granted. The electricity shortages that Japan has faced since the Great East Japan Earthquake have directed considerable attention toward smart cities.

Although debate so far has focused primarily on technical considerations, the scope is now expanding to include non-technical discussions with a central role for consumers, covering such matters as customer value creation, supply chain management, and customer engagement, and also discussions focusing on what to do about things like systems and regulations. As a result, smart cities are moving on from the planning and demonstrating phases of the past to the phase in which business models are established and actual work proceeds.

Hitachi is proceeding with the fusion of automotive technology with energy and social infrastructure, establishing solution packages that take advantage of things like the characteristics of EVs through leading-edge examples such as the demonstration projects in Spain, Hawaii, and elsewhere, and seeking to deploy these globally. In the future, it is anticipated that new social value will be created by fusing these with a wide range of social infrastructure, including fuel cells and autonomous driving systems.

REFERENCE

(1) Nikkei BP Clean Tech Institute et al., "The World's Smart Cities 2012," Nikkei Business Publications, Inc. (Oct. 2011) in Japanese.

ABOUT THE AUTHORS

Fumitoshi Emura
New Business Promotion Department, Smart City Project Division, Social Innovation Business Project Division. He is currently engaged in coordinating business planning for smart cities.

Mitsumasa Takayama
New Business Promotion Department, Smart City Project Division, Social Innovation Business Project Division. He is currently engaged in business planning for smart cities. Mr. Takayama is a member of the Society of Automotive Engineers of Japan.

Hiroaki Sugita
New Business Promotion Department, Smart City Project Division, Social Innovation Business Project Division. He is currently engaged in business planning for smart cities.

Kouichi Hiraoka
Infrastructure Systems Engineering Department, Power Information & Control Systems Division, Infrastructure Systems Company. He is currently engaged in business development for smart cities.

Takamasa Yamazaki
Department 3, Embedded Solutions Division, Industrial & Distribution Solution Business Division, Industrial & Distribution Systems Business. He has been seconded to Hitachi, Ltd. since 2012. He is currently engaged in business planning for smart cities.